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Energy and resource use in kerbside collection of source segregated food waste

by

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ABSTRACT

FACULTY OF ENGINEERING AND THE ENVIRONMENT

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ENERGY AND RESOURCE USE IN KERBSIDE COLLECTION OF SOURCE SEGREGATED FOOD WASTE

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The collection of source segregated household food waste is becoming increasingly popular, because of its potential to divert biodegradable materials from landfill, increase recycling rates and provide a contaminant-free feedstock for anaerobic digestion. Various types of kerbside household food waste collection systems are operating in the UK and in Europe; however, studies on the energy consumption of integrating source separated food waste with collection of other waste fractions are very limited. A mechanistic model was developed in this research as a waste collection assessment tool (WasteCAT) for scoping and assessment of collection systems. Data collected from six local authorities in England was applied to verify and validate the modelling tool. Fuel consumption and other parameters such as total distance travelled (a proxy for vehicle lifespan), total time spent (a proxy for staffing costs), number of collection vehicles required (a proxy for capital costs), and arrangement of waste types and compartments were also assessed in this research, as these factors may also influence the selection of kerbside waste collection systems. A typical hypothetical town of 25,000 households was chosen to study the performance of separate, co-collection, kerbside-sorted and partially-sorted collection of household waste by different sizes and types of single and compartmentalised collection vehicles at different collection frequencies. Comparing the performance of the four collection systems, kerbside partially-sorted collection required the least fuel, while co-collection of household waste always had the best performance in terms of total travelling distance, time spent and number of collection vehicles required. The difference between the best and the worst systems was up to 156% for fuel use, 131% for distance travelled, 63% for time spent and 141% for vehicles required. Besides that, inappropriate allocation of compartment and waste type could increase fuel use by up to 1.1 times in co-collection, 2.27 times in kerbside-sorted and 3.08 times in kerbside partially-sorted collection. The research shows WasteCAT could provide a powerful tool for exploring alternative options.

Keywords: Waste collection, collection vehicles, fuel consumption, food waste.

Table of Contents

ABSTRACT ..... **i**
List of tables ..... **ix**
List of figures ..... **ix**
DECLARATION OF AUTHORSHIP ..... **xix**
Acknowledgements ..... **xxi**
Abbreviations ..... **xxiii**
Notations xxv

Chapter 1: INTRODUCTION **1**
1.1 Background 1
1.2 Research aims and objectives 4
1.2.1 Aim 4
1.2.2 Objectives 5
1.3 Outline of the thesis 5

Chapter 2: LITERATURE REVIEW **7**
2.1 Legislation and policy on source separate household waste collection 7
2.2 Overview of household and food waste characteristics 10
2.2.1 Overview of household waste composition 10
2.2.2 Overview of food waste 10
2.3 Overview of kerbside household waste collections 15
2.3.1 Kerbside residual and recyclable household waste collections 16
2.3.2 Household food waste collection 17
2.4 Characteristics of household food waste collections 21
2.4.1 Collection operation and systems 21
2.4.2 Collection method 22
2.4.3 Collection rounds arrangement 23
2.4.4 Collection frequency 23
2.4.5 Type of container 24
2.4.6 Refuse collection vehicles 25
2.5 Factors affecting fuel consumption in the waste collection process 29
2.5.1 Driving cycle, driving behaviour and driving pattern 29
2.5.2 Vehicle operation 30
2.5.3 Traffic environment 31
2.6 Previous work related to waste collection 32
2.6.1 Comparison of fuel efficiency in waste collection 32
2.6.2 Fuel consumption in food waste collection 33
2.6.3 Fuel consumption in residual waste and recycling collection 33
2.7 Previous work on modelling and assessment methods 34
2.7.1 Mathematical modelling approaches 35
2.7.2 Geographic Information System approaches 36
2.7.3 Operational research 36
2.7.4 Life Cycle Assessment approach 37
2.8 Conclusions 38

Chapter 3: METHODOLOGY **41**
3.1 Introduction 41
3.2 Research design 42
3.3 Design of waste collection model 43
3.4 Model validation 44
3.4.1 Site selection 44
3.4.2 Field data collection and analysis 46
3.5 Modelling kerbside household waste collection 50
3.5.1 Background to the theoretical study 50

3.5.2 Composition of kerbside collected household waste 50
3.5.3 Setting up scenarios 51
3.6 Sensitivity analysis 53
3.7 Data analysis 54

Chapter 4: WASTE COLLECTION MODEL 57
4.1 Description of conceptual kerbside collection model 57
4.2 Formulation of kerbside household waste collection 59
4.2.1 Quantity of waste, waste allocation and selection of RCV 61
4.2.2 Determination of collection rounds 63
4.2.3 Determination of energy consumption 70
4.2.4 Time efficiency 73
4.3 Model assumptions 74
4.4 Conclusion 75

Chapter 5: DATA COLLECTION AND MODEL VALIDATION 77
5.1 Description of the study sites 77
5.1.1 Flintshire County Council (Flintshire) 77
5.1.2 Broadland District Council (Broadland) 78
5.1.3 London Borough of Lambeth (Lambeth) 80
5.1.4 London Borough of Bromley (Bromley) 81
5.1.5 The Royal Borough of Kingston upon Thames (Kingston) 83
5.1.6 London Borough of Hackney (Hackney) 85
5.2 Data collection and route analysis 88
5.2.1 Flintshire and Broadland 88
5.2.2 Lambeth 88
5.2.3 Bromley 89
5.2.4 Kingston 90
5.2.5 Hackney 92
5.3 Model validation 93
5.3.1 Flintshire and Broadland 93
5.3.2 Bromley 94
5.3.3 Lambeth, Kingston and Hackney 95
5.4 Results 96
5.4.1 Type I study site: Flintshire, Broadland and Lambeth 96
5.4.2 Type II study site: Bromley 99
5.4.3 Type III study site: Kingston 99
5.4.4 Type IV study site: Hackney 101
5.5 Discussion 103
5.5.1 The collection model 103
5.5.2 Limitations in the data collection method 104
5.5.3 Model validation: Prediction of collection rounds 105
5.5.4 Model validation: Fuel consumption 107
5.6 Conclusion 107

Chapter 6: MODELLING KERBSIDE SOURCE SEGREGATED FOOD WASTE COLLECTION: SINGLE ADDITIONAL COLLECTION 109
6.1 Introduction 109
6.2 Methodology 109
6.2.1 Food waste collection rates 109
6.2.2 Collection vehicles 110
6.2.3 Scenarios 110
6.2.4 Collection parameters 111
6.2.5 Sensitivity analysis 112
6.3 Results 113
6.3.1 Fuel consumption in collection and transportation phases 113
6.3.2 Total time spent in collection and transportation of food waste 116

6.3.3 Total travelling distance in collection and transportation ... 117
6.3.4 Total number of RCVs required ... 118
6.3.5 Capacity utilisation of food waste collection vehicles ... 119
6.3.6 Selection of the most suitable collection options in different situations ... 121
6.4 Sensitivity Analysis ... 122
6.4.1 Fuel consumption ... 122
6.4.2 Total time spent ... 124
6.4.3 Total distance travelled ... 124
6.5 Discussion ... 129
6.5.1 Fuel consumption ... 129
6.5.2 Utilisation of collection vehicle and distance travelled ... 130
6.5.3 Total time and number of collection vehicle required ... 132
6.5.4 The most suitable food waste collection schemes ... 132
6.5.5 Sensitivity analysis ... 133
6.6 Conclusions from modelling of single additional food waste collections ... 134

Chapter 7: MODELLING KERBSIDE SOURCE SEGREGATED FOOD WASTE COLLECTION: SEPARATE COLLECTION AND CO-COLLECTION ... 137
7.1 Introduction ... 137
7.2 Methodology ... 138
7.2.1 Composition of kerbside household waste ... 138
7.2.2 Options for collection vehicles ... 139
7.2.3 Scenarios ... 139
7.2.4 Model inputs ... 140
7.2.5 Sensitivity analysis ... 141
7.2.6 Comparison of scenarios ... 143
7.2.7 Reporting units ... 143
7.3 Results ... 144
7.3.1 Effect of capture rates for food waste and recyclables on fuel consumed per tonne of residual waste collected ... 144
7.3.2 Best and worst collection systems ... 145
7.3.3 Comparison of optimal scenarios ... 151
7.3.4 Refuse collection vehicle ... 154
7.3.5 Allocation of compartments ... 158
7.4 Sensitivity analysis for fuel consumption, time and distance travelled ... 159
7.4.1 Fuel consumption in household waste collection ... 159
7.4.2 Total distance travelled ... 160
7.4.3 Total time spent ... 160
7.5 Discussion ... 165
7.5.1 Effect of capture rates for food waste and recyclables on fuel consumption for residual waste collection ... 165
7.5.2 Comparison of optimal scenarios ... 166
7.5.3 Collection vehicle ... 167
7.5.4 Allocation of wastes to compartments ... 168
7.5.5 Sensitivity analysis ... 169
7.5.6 Limitations of this research ... 169
7.6 Conclusions on separate and co-collection of household waste ... 170

Chapter 8: MODELLING KERBSIDE SOURCE SEPARATED COLLECTION OF HOUSEHOLD WASTE: KERBSIDE-SORTED COLLECTION SYSTEM ... 173
8.1 Introduction ... 173
8.2 Methodology ... 175
8.2.1 Composition of kerbside household waste ... 175
8.2.2 Options for collection vehicles ... 175
8.2.3 Arrangement of wastes and compartments ... 176
8.2.4 Scenarios ... 177

8.2.5 Model inputs 177
8.2.6 Sensitivity analysis 179
8.3 Results 181
8.3.1 Best and worst combinations of wastes and compartments 181
8.3.2 Comparison of the best and the worst scenarios 187
8.3.3 Refuse collection vehicle 191
8.3.4 Allocation of compartments 192
8.4 Sensitivity analysis for fuel consumption, time and distance travelled 194
8.4.1 Fuel consumption in food waste and dry recyclables collection 194
8.4.2 Total distance travelled in food waste and dry recyclables collection 199
8.4.3 Total time spent in food waste and dry recyclables collection 203
8.5 Discussion 207
8.5.1 Comparison of different allocation of waste types and compartments in kerbside-sorted collection and kerbside partially-sorted collection 207
8.5.2 Comparison of collection of the whole household waste stream by kerbside-sorted and kerbside partially-sorted collection 208
8.5.3 Allocation of wastes and compartments in the best stillage vehicle 209
8.5.4 Sensitivity analysis for allocation of waste types and compartments in kerbside-sorted and partially-sorted collection systems 210
8.6 Conclusions on collection of household waste by different kerbside-sorted collection systems 211

Chapter 9: COMPARISON OF SEPARATE, CO-COLLECTION AND KERBSIDE-SORTED COLLECTION OF THE WHOLE HOUSEHOLD WASTE STREAM 213
9.1 Introduction 213
9.2 Methodology 213
9.2.1 Composition of household waste, collection vehicle options and scenario setting 213
9.2.2 Model input 215
9.2.3 Comparison of optimal scenarios 216
9.3 Results 217
9.3.1 Fuel consumption in household waste collection by different collection systems 217
9.3.2 Total travelling distance for household waste collection by different collection systems 218
9.3.3 Total time spent in household waste collection by different collection systems 219
9.3.4 Number of vehicles required in household waste collection by different collection systems 221
9.4 Discussion 222
9.4.1 Best collection systems for fuel consumption 222
9.4.2 Best collection systems for number of vehicles required 223
9.4.3 Best collection systems for total travelling distance and time spent 224
9.4.4 Worst collection systems for fuel consumption and other parameters 226
9.5 Conclusions from the comparative work 228

Chapter 10: CONCLUSIONS 229
10.1 Introduction 229
10.2 Specific contributions 230
10.2.1 Model development and validation 230
10.2.2 Scenario studies 230
10.3 Limitations of the research and recommendations for further work 233

Appendices **235**
Appendix A Inputs and outputs of model validation 237
Appendix B Raw data from scenarios in Chapter 7-8 245
Appendix C Kerbside collection model manual 251
Appendix D VALORGAS Deliverable 6.3: Output from an energy and carbon footprint model verified against primary data collected as part of the research 265

List of References **313**

List of tables

Table 2.1 Food waste capture rates in different collection practices in the UK 14
Table 2.2 Percentage of local authorities collecting residual waste by frequency 16
Table 2.3 Percentage of local authorities collecting each dry recyclable waste 17
Table 2.4 Percentage of local authorities offering dry recycling collection schemes 17
Table 2.5 Examples of different types of food waste collection schemes in Europe 20
Table 2.6 Population of local authorities by type of food waste collection service provided in the UK 21
Table 2.7 Classification and characteristics of different types of collection vehicles 27
Table 3.1 Participating local authorities and classification of study sites 45
Table 3.2 Methods used for gathering different type of data 47
Table 3.3 Methods used for data analysis 49
Table 3.4 Composition of kerbside household waste used in modelling 51
Table 3.5 Possible household waste collection scenarios 52
Table 3.6 Types of collection vehicles used in scenarios 53
Table 4.1 Example of waste characterisation and allocation data 61
Table 4.2 RCV characteristics 63
Table 4.3 Pick-up time for different bin types (t_{bin}) 65
Table 4.4 Bulk density of different combinations of waste type 67
Table 4.5 Speed of collection and transport in densely populated area, city, suburb and village 72
Table 4.6 Example of equations used to predict fuel consumption based on laden percentage for different RCV categories 73
Table 5.1 Recycling rates and breakdown of dry and organic recycling in Flintshire 77
Table 5.2 Recycling rates and breakdown of dry and organic recycling in Broadland 79
Table 5.3 Recycling rates and breakdown of dry and organic recycling in Lambeth 80
Table 5.4 Recycling rates and breakdown of dry and organic recycling in Bromley 81
Table 5.5 Recycling rates and breakdown of dry and organic recycling in Kingston 83
Table 5.6 Recycling rates and breakdown of dry and organic recycling in Hackney 85
Table 5.7 Summary of collection schemes at the selected study sites 87
Table 5.8 Analysis of collection routes in Flintshire and Broadland 88
Table 5.9 Analysis of collection routes in Lambeth 89
Table 5.10 Analysis of collection routes in Bromley 90
Table 5.11 Quantity of recyclable material and food waste collected in Kingston 91
Table 5.12 Dimensions and volumes of the compartments 91
Table 5.13 Analysis of collection routes in Kingston 92
Table 5.14 Analysis of collection routes in Hackney 93
Table 5.15 Comparison of predicted and observed values from model and field data in Flintshire .. 97
Table 5.16 Comparison of predicted and observed values from model and field data in Broadland . 98

Table 5.17 Comparison of predicted and observed values from model and field data in Lambeth 98
Table 5.18 Comparison of predicted and observed values from model and field data in Bromley 99
Table 5.19 Comparison of predicted and observed values from model and field data in Kingston . 101
Table 5.20 Comparison of predicted and observed values from model and field data in Hackney .. 102
Table 6.1 Specification of single-compartment vehicles used in hypothetical study 110
Table 6.2 Scenarios for source separated food waste collection... 110
Table 6.3 Input values for modelling kerbside collection in a hypothetical city of 25,000 households 112
Table 6.4 Minimum, maximum and static values of each input parameters.................................... 113
Table 6.5 Fuel consumption in collection and transportation of food waste 114
Table 6.6 Total time to collect food waste in hypothetical area of 25,000 households 116
Table 6.7 Time ratio of weekly/fortnightly collection for different RCVs...................................... 116
Table 6.8 Total travelling distance in collection and transportation in a hypothetical area of 25,000 households 117
Table 6.9 Total number of RCVs required for food waste collection in a hypothetical area of 25,000 households 118
Table 6.10 Laden percentages in weight for RCV in transportation stage 120
Table 6.11 Laden percentages in volume of collection vehicle in transportation stage 121
Table 6.12 Summary of selection of best scenarios at different set-out rates.................................. 122
Table 6.13 Summary of regression coefficients from sensitivity analysis for fuel consumption at set-out rates from 10-100% 123
Table 6.14a Summary of regression coefficients from sensitivity analysis for total time spent for weekly collection at set-out rates from 10-100% 125
Table 6.15 Summary of regression coefficients from sensitivity analysis for total distance travelled at set-out rates from 10-100% 127
Table 7.1 Composition of kerbside household waste used in modelling 139
Table 7.2 Specification of collection vehicles used in modelling.. 139
Table 7.3 Nine scenarios for collection systems... 140
Table 7.4 Input values for modelling kerbside collection of household waste in a hypothetical city of 25,000 households 141
Table 7.5 Minimum, maximum and static values of each input parameter 143
Table 7.6 Summary of fuel consumption for collection of the whole household waste stream under optimal collection options for each scenario 146
Table 7.7 Average distance travelled per week in collecting the whole household waste stream at different capture rates under the optimal collection option for each scenario................. 147
Table 7.8 Time spent per week in collecting the whole household waste stream at different capture rates under the optimal collection option for each scenario 148

Table 7.9 Breakdown and total number of RCVs required for collection of the whole household waste stream at different capture rates under the optimal collection option for each scenario 150
Table 7.10 Best single-compartment collection vehicle with respect to fuel consumption in different collection systems at capture rates from 10-100% 155
Table 7.11 The best single-compartment collection vehicle with respect to total travelling distance in different collection systems at capture rates from 10-100% 155
Table.7.12 Best single-compartment collection vehicle with respect to total time spent in different collection systems at capture rates from 10-100% 156
Table 7.13 The best compartmentalised collection vehicle co-collect the two type of waste at capture rates from 10-100% (Fuel consumption) 157
Table 7.14 The best compartmentalised collection vehicle co-collect the two type of waste at capture rates from 10-100% (Total travelling distance) 157
Table 7.15 The best compartmentalised collection vehicle co-collect the two type of waste at capture rates from 10-100% (Total time spent) 157
Table 7.16 Summary of the results of sensitivity analysis for fuel consumption in separate or co-collection of household waste at capture rates from 10-100% 161
Table 7.17 Summary of the results of sensitivity analysis for total travelling distance in the separate collection or co-collection of household waste at the capture rate from 10-100% 162
Table 7.18 Summary of the results of sensitivity analysis for total time spent in separate or co-collection of household waste at the capture rate from 10-100% 163
Table 8.1 Composition of kerbside household waste used in the modelling 175
Table 8.2 Specification of stillage vehicles used in collection model 175
Table 8.3 Allocation of wastes and compartments for kerbside-sorted system 176
Table 8.4 Allocation of wastes and compartments for partially-sorted collection system 176
Table 8.5 Scenarios for different kerbside-sorted and partially-sorted collection system 177
Table 8.6 Input values for modelling kerbside-sorted collection system in a hypothetical city of 25,000 households 179
Table 8.7 Minimum, maximum and static values of each input parameter for kerbside-sorted system 180
Table 8.8 Summary of fuel consumption for collection of food waste and kerbside-sorted dry recyclables by optimum collection vehicle for each combination 181
Table 8.9 Summary of fuel consumption for collection of food waste and kerbside partially-sorted collection of dry recyclables by optimum collection vehicle for each combination 182
Table 8.10 Distance travelled per week in the collection of food waste and kerbside-sorted dry recyclables at different capture rates under the optimum collection vehicle for each combination 183

Table 8.11 Average distance travelled per week in the collection of food waste and kerbside partially-sorted dry recyclables at different capture rates under the optimum collection vehicle for each combination 183
Table 8.12 Total time spent per week in the collection of food waste and kerbside-sorted dry recyclables at different capture rates under the optimum collection vehicle for each combination 184
Table 8.13 Total time spent per week in the collection of food waste and kerbside-sorted dry recyclables at different capture rates under the optimum collection vehicle for each combination 185
Table 8.14 Number of vehicles required in the collection of food waste and kerbside-sorted dry recyclables at different capture rates under the optimum collection option for each combination.. 186
Table 8.15 Number of vehicles required in the collection of food waste and kerbside partially-sorted collection of dry recyclables at different capture rates under the optimum collection option for each combination.. 187
Table 8.16 Summary of the best collection option on the litre diesel consumed in collecting whole household waste stream per week 188
Table 8.17 Summary of the best collection option for each scenario with respect to distance travelled per week in collecting the whole household waste stream at different capture rates 189
Table 8.18 Summary of the best collection option for each scenario with respect to total time spent per week in collecting whole household waste stream at different capture rates 190
Table 8.19 Summary of the best collection option for each scenario with respect to number of vehicles used in collecting whole household waste stream at different capture rates 190
Table 8.20 Best stillage vehicles with respect to fuel consumption in kerbside-sorted collection systems at capture rates from 10-100%... 192
Table 8.21 Best stillage vehicles with respect to fuel consumption in kerbside partially-sorted collection systems at capture rates from 10-100% 192
Table 8.22 Summary of laden percentage of vehicle and volume percentage of compartments of the best stillage vehicle used in kerbside-sorted collection system at capture rates for recyclables and food waste from 10-100%... 193
Table 8.23 Summary of laden percentage of vehicle and volume percentage of compartments of the best stillage vehicle used in kerbside partially-sorted collection at capture rates of recyclables and food waste from 10-100%... 194
Table 8.24 Summary of results of sensitivity analysis for fuel consumption for kerbside-sorted collection at capture rates from 10-100%.. 196
Table 8.25 Summary of results of sensitivity analysis for fuel consumption for kerbside partially-sorted collection at capture rates from 10-100% 198

Table 8.26 Summary of results of sensitivity analysis for total travelling distance for kerbside-sorted collection at capture rates from 10-100% 200
Table 8.27 Summary of results of sensitivity analysis for total travelling distance for kerbside partially-sorted collection at capture rates from 10-100% 202
Table 8.28 Summary of results of sensitivity analysis for total time spent for kerbside-sorted collection at capture rates from 10-100% 204
Table 8.29 Summary of results of sensitivity analysis for total time spent for kerbside partially-sorted collection at capture rates from 10-100%... 206
Table 8.30 Breakdown of fuel consumption of the collection of household waste stream per week in Scenarios C2-S1 and C2-S3... 209
Table 9.1 Summary of scenarios for kerbside household waste collection..................................... 214
Table 9.2 Specification of all single-compartment and compartmentalised collection vehicles used in modelling 215
Table 9.3 Model inputs for running all scenarios in a hypothetical city of 25,000 households....... 216
Table 9.4 Summary of the best collection options for different collection systems with respect to fuel consumption for collection of the whole household waste stream at capture rates 10-100% 217
Table 9.5 Summary of the best collection options for different collection systems with respect to total travelling distance for collection of the whole household waste stream at capture rates 10-100% 219
Table 9.6 Summary of the best collection options for different collection systems with respect to total time spent in collection of the whole household waste stream at capture rates from 10-100%.. 220
Table 9.7 Summary of the best collection option for different collection systems based on number of collection vehicles for collection of the whole household waste stream at capture rates from 10-100% 221
Table 9.8 Summary of the best and worst collection systems and scenarios for different output parameters.. 222
Table 9.9 Cost assessment of the best and the worst in co-collection and kerbside partially-sorted collection systems 224

List of figures

Figure 2.1 Composition of kerbside household waste by weight, (a) in 2006/7, (b) in 2010/11 10
Figure 2.2 Composition of UK household food waste by weight 12
Figure 2.3 Difference between kerbside, selective and HWRC collections...................................... 16
Figure 2.4 Classification of food waste collection systems in Europe 19
Figure 2.5 Collection point options (a) Kerbside food waste collection in Bromley, (b) Food waste collection at designated collection point, photo taken in Bromley (c) Communal bin is being used for food waste collection in estates, photo taken in Hackney 22
Figure 2.6 The driving cycle of the collection vehicle, speed plot against time 30
Figure 3.1 Outline of the research methodology 43
Figure 3.2 Process flow diagram for the field study site selection 45
Figure 3.3 Location of study sites 46
Figure 3.4 GPS data loggers used in tracking the data (a) Qstarz BT-Q1000XT and (b) GlobalSat DG-100 48
Figure 3.5 Examples of the speed profile of the collection route logged. (a) In Hackney. (b) In Bromley 49
Figure 4.1 Illustration of terms for a complete collection in a city 57
Figure 4.2 Schematic showing different options for a collection round 59
Figure 4.3 Flow chart of the construction of kerbside collection model 60
Figure 4.4 Schematic showing segments of travel 64
Figure 5.1 Locations and aerial views of Alltami depot and waste transfer station in Buckley......... 78
Figure 5.2 Container and vehicle used in Flintshire (a) Food waste caddy (b) Single-compartment vehicle for food waste collection round 78
Figure 5.3 Locations and aerial views of Brookside depot and composting plant in Edgefield 79
Figure 5.4 Container and vehicle used in Broadland (a) Food waste container (b) Single-compartment vehicle for food waste collection round 80
Figure 5.5 Locations and aerial views of depot in Brixton and compositing plant in Mitcham 81
Figure 5.6 Container and vehicle used in Bromley (a) Food waste container for kerbside collection, (b) Food waste communal bin used in estates and flats, (c) Two-compartment vehicle to collect food waste and paper 82
Figure 5.7 in Bromley and Beckenham and of the waste transfer station in Bromley 83
Figure 5.8 Container and vehicle used in Kingston (a) Food waste container, (b) Stillage vehicle for kerbside-sorted collection 84
Figure 5.9 and transfer station in Kingston 84
Figure 5.10 Locations of depot in Homerton and London Waste Eco Park in Edmonton 86
Figure 5.11 Container and vehicle used in Hackney (a) Food waste communal bin using in estate, (b) Single-compartment vehicle for food waste collection in flat rounds............................... 86
Figure 5.12 Configuration of compartments in stillage vehicle 91

Figure 6.1 Fuel consumption of food waste collection with different set-out rates and RCVs, (a) weekly (b) fortnightly 114
Figure 6.2 Fuel consumption in collecting one tonne of food waste with different set-out rates and RCVs, (a) Weekly (b) fortnightly 115
Figure 6.3 Comparison of total fuel consumption in weekly and fortnightly food waste collection 115
Figure 6.4 Total times spent in food waste collection with different set-out rates and RCVs, (a) weekly (b) fortnightly 117
Figure 6.5 Total travelling distances in food waste collection with different set-out rates and RCVs, (a) weekly (b) fortnightly 118
Figure 6.6 Total number of vehicles required for the food waste collection, (a) Weekly, (b) Fortnightly 119
Figure 6.7 Variation in laden percentage by weight of different RCV in weekly collection (in transportation), (a) Weekly, (b) Fortnightly 120
Figure 6.8 Variation in laden percentage by volume of different RCVs in fortnightly collection (in transportation), (a) Weekly, (b) Fortnightly 121
Figure 7.1 Fuel consumption for collection of one tonne of residual waste at different capture rates for food waste and recyclables (Weekly collection) 144
Figure 7.2 Fuel consumption in collection one tonne of residual waste at different capture rate for food waste and recyclables (Fortnightly collection) 145
Figure 7.3 Fuel consumption for household waste collection at different capture rates under optimal collection options for each scenario 146
Figure 7.4 Distance travelled in household waste collection at different capture rates under the optimal collection option for each scenario 148
Figure 7.5 Time spent in collection of the whole household waste stream at different capture rates under the optimal collection option for each scenario 149
Figure 7.6 Number of RCVs required for collection of the whole household waste stream at different capture rates under the optimal collection option for each scenario 150
Figure 7.7 Comparison of fuel consumption for collection of the whole household waste stream in single collection and co-collection (a) weekly and (b) fortnightly; effect of permutations of waste type and compartment in weekly co-collection along with (c) fortnightly collection and (d) weeklyly collection 152
Figure 7.8 Comparison of total travelling distance for collection of the whole household waste stream in single collection and co-collection (a) weekly and (b) fortnightly; effect of permutations of waste type and compartment in weekly co-collection along with (c) fortnightly collection and (d) weekly collection 153
Figure 7.9 Comparison of total time spent for collection of the whole household waste stream in single collection and co-collection (a) weekly and (b) fortnightly; effect on permutations

of waste type and compartment in (c) weekly co-collection and (d) fortnightly co-collection 154
Figure 7.10 Change in laden percentage of vehicle and volume percentage of different compartments in different permutations of waste type and compartment at capture rates of recyclables and food waste from 10-100%, (a) Weekly co-collection of recyclables and residual waste; (b) Fortnightly co-collection of recyclable and residual waste; (c) Weekly co-collection of recyclable and food waste; (d) Weekly co-collection of residual waste and food waste; (e) AWC of recyclables and food waste; and (f) AWC of residual waste and food waste. 159
Figure 8.1 Fuel consumption for food waste and dry recyclable collection at different capture rates under optimum collection options for each combination, (a) Kerbside-sorted collection, (b) Kerbside partially-sorted collection 182
Figure 8.2 Total distances travelled for food waste and dry recyclables collection at different capture rates under optimum collection options for each combination; (a) Kerbside-sorted collection, (b) Kerbside partially-sorted collection 184
Figure 8.3 Total time spent for food waste and dry recyclable collection at different capture rates under optimum collection options for each combination, (a) Kerbside-sorted collection, (b) Kerbside partially-sorted collection 185
Figure 8.4 Number of vehicles required for food waste and dry recyclable collection at different capture rates under optimum collection options for each combination, (a) Kerbside-sorted collection, (b) Kerbside partially-sorted collection 187
Figure 8.5 Fuel consumption for household waste collection at different capture rates under optimum collection options for each scenario 188
Figure 8.6 Distance travelled in household waste collection at different capture rates under the best collection option for each scenario 189
Figure 8.7 Minimum number of working hours per week to collect the whole household waste stream at different capture rates under the best collection option for each scenario....... 190
Figure 8.8 Minimum number of vehicles required for collection of the whole household waste stream at different capture rates under the best collection option for each scenario....... 191
Figure 8.9 Laden percentage of vehicle and volume utilisation percentage of compartment at capture rates of recyclables and food waste from 10-100% for vehicle KS2 in combination KSP11 (Kerbside-sorted collection system).. 193
Figure 8.10 Laden percentage of vehicle and volume utilisation percentage of compartment at capture rates of recyclables and food waste from 10-100% for vehicle CWS1 and combination P1 (Kerbside partially-sorted collection system) 194
Figure 9.1 Fuel consumption in different optimal whole household waste collection systems at capture rates 10%-100% 218

Figure 9.2 Total travelling distance for different optimal whole household waste collection systems at capture rates from 10-100%..219
Figure 9.3 Total time spent in collection for different optimal whole household waste collection systems at capture rates from 10-100%..221
Figure 9.4 Number of vehicle required for different optimal whole household waste collection systems at capture rates from 10-100%..222

DECLARATION OF AUTHORSHIP

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declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

Energy and resource use in kerbside collection of source segregated food waste

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
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5. I have acknowledged all main sources of help;
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7. Parts of this work have been published as:

- T.W. Chu, S. Heaven & L. Gredmaier (2013) Modelling fuel consumption in kerbside source segregated food waste collection: Separate collection and co-collection, *Proceedings of the International Conference on Solid Waste 2013 - Innovation in Technology and Management*. 5–9 May 2013, 196-199
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- VALORGAS (2013a) D2.7: Results from LCA and energy footprint modelling for optimisation of collection methods and equipment. [Online]. Available: http://www.valorgas.soton.ac.uk/deliverables.htm [Accessed 5 May 2014].
- VALORGAS (2013b) D6.3: Output from an energy and carbon footprint model verified against primary data collected as part of the research [Online]. Available: http://www.valorgas.soton.ac.uk/deliverables.htm [Accessed 5 May 2014].

Any work reported in the VALORGAS reports and deliverables which is also reported in this thesis was carried out by myself.

Signed:..

Date: ....

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Abbreviations

ABPR	Animal By-product Regulations
AWC	Alternate Weekly Collection
AD	Anaerobic Digestion
BVPI	Best value performance indicators
EEA	European Environment Agency
EU	European Union
FW	Food Waste
GIS	Geographic Information Systems
GPS	Geographic Positioning System
GHG	Greenhouse Gas
GVW	Gross Weight Vehicle
HDV	Heavy Duty Vehicles
HWRC	Household Waste Recycling Centre
LCA	Life Cycle Assessment
MRF	Material Recycling Facility
MSW	Municipal Solid Waste
OFMSW	Organic Fraction of Municipal Solid Waste
RCV	Refuse Collection Vehicle
RM	Recyclable material
RW	Residual waste
RFID	Radio Frequency Identification
SORT	Separate Out Recyclables Today
TDP	Treatment or disposal point
UK	United Kingdom
US	Unloading Site
VFG	Vegetable, Fruit and Garden
VRPTW	Vehicle Routing Problem Time Window
VRP	Vehicle Routing Problems
WMC	Waste management contractor
WRAP	Waste Resources Action Programme

Notations

ahwg	Average household waste generation (kg HH^{-1} day^{-1})
avhd	Average households visited per day (HH day^{-1}) and is rounded up to the nearest integer
avWTi	Average weight of a load of waste type i, corresponding to BW, RM and RW for single and twin compartment vehicles and RMi for multi-compartment vehicles (tonne)
BW (or RM or RW)	Amount of biowaste (or recyclable material or residual waste) to be collected from a household on the collection day (kg HH^{-1})
ccf	Concurrent collection factor (no.)
CompV	Volume of compartment in RCV (m^3)
CR	Waste presented for separate collection as a proportion of total household waste put out at the kerbside
DA	Accumulation day (days)
dc2us	Distance between collection area and unloading site (km $collection^{-1}$)
dcol	Total distance travelled in collection area (km $collection^{-1}$)
dd2c	Distance between depot and collection area (km $collection^{-1}$)
dHH	An 'average' or representative distance between households (km)
dint	Total distance in intermediate trips to unloading site (km $collection^{-1}$)
dtotal	Total travelled distance in collection and transportation phases (km $collection^{-1}$)
dtran	Total distance involved in transportation phase (km $collection^{-1}$)
dus	Distance to unloading site from part way around the collection (km $collection^{-1}$)
dus2d	Distance between unloading site and depot (km $collection^{-1}$)
DWi	Density of waste type i (kg m^{-3})
FCTotal	Total fuel consumption per collection (L $collection^{-1}$)
maxhc	Maximum no. of households that can be served per day based on RCV capacity (weight or volume) (HH day^{-1})
maxhd	Maximum no. of households that can be served per day based on the limiting factor (time or RCV capacity) (HH day^{-1})
maxhd	Maximum no. of households that can be served per day based on the Limiting factor (time or RCV capacity) (HH day^{-1})
maxht	Maximum no. of households to be served based on service time (HH $round^{-1}$)
maxhu	Maximum no. of households before unloading (volume or weight basis) (HH $round^{-1}$)
maxhv	Maximum no. of households before unloading (volume basis) (HH $round^{-1}$)
maxhvi	Maximum no. of households before unloading (volume basis) for waste type *i* (HH $round^{-1}$)
maxhw	Maximum no. of households before unloading (weight basis) (HH $round^{-1}$)
n	Number of recyclable materials separately collected in the same vehicles
ncd	Number of collection districts (no.)
ncol	Number of collectors in crew (no.)
nfld	Number of full loads per day (no.), which is rounded down to the nearest integer

noh	Number of households to be served in a collection (HH collection^{-1})
nsort	Number of extra compartments used in kerbside sorting of mixed recyclables (no.)
nveh	Number of RCVs required (no.) and is rounded up to the nearest integer
p	Proportion percentage of waste (%)
RCVload	Maximum payload of RCV (tonne)
Scol	Speed in collection (km hour^{-1})
SOR	Number of households setting out this waste category as a percentage of total no of households
tact.work	Actual working hours per round (hour round^{-1})
tbin	Time to collect bin (s)
tbreak	Time spent on break (mins round^{-1})
TBW (or TRM or TRW)	Total amount of biowaste (or recyclable material or residual waste) collected in a whole collection (tonnes collection^{-1})
tc2us	Travel time from collection area to unloading site (mins round^{-1})
tcrew	Time spent in picking up the crew (mins round^{-1})
td2c	Travel time from depot to collection area (mins round^{-1})
tfuel	Time spent in fuelling RCV (mins round^{-1})
tic	Time in collection (hour)
tiu	Time for intermediate unloading (mins)
tph	'Average' time per household (s)
tsort	Sort time for mixed recyclables (s)
ttotal	Total time required for whole collection (hour collection^{-1})
ttp	Time to pick up a waste(s)
ttraffic	Time spent in traffic congestion (mins round^{-1})
ttv	Travel time to visit a household (s)
tunload	Time spent in unloading (mins round^{-1})
tunload	Time spent unloading (mins round^{-1})
tus	Travel time to unloading sit from part way around the collection (mins round^{-1})
tus2d	Travel time from unloading site to depot (mins round^{-1})
twork	Working hours per round (hour round^{-1})
WTi	Waste type i, corresponding to BW, RM and RW for single and twin compartment vehicles and RMi for multi-compartment vehicles.
$y_{tran.0}$	Fuel consumption in transportation phase when the RCV is empty (g km^{-1})
x_{col}	Laden percentage in collection phase (%)
x_{tran}	Laden percentage in transportation phase (%)
y_{col}	Fuel consumption in collection phase (g km^{-1})
y_{tran}	Fuel consumption in transportation phase when the RCV is loaded (g km^{-1})

Chapter 1: INTRODUCTION

1.1 Background

In the past two decades, there has been a dramatic change in kerbside household recycling collection services in the United Kingdom. Up to the 1990s, household recycling collections were typically run on a voluntary basis with low coverage and participation rates (Jesson and Stone, 2009). After the introduction of the Household Waste Recycling Act 2003, the proportion of households provided with a kerbside recycling collection increased significantly, from 30% in 1996 to 90% in 2009 (Thomas and Sharp, 2013). According to the Act, local authorities have a high degree of flexibility in how they organise waste collection services, but must provide separate collection of at least two recyclable materials, which may include food waste (Defra, 2005). In the early stages after implementation of the Act, the provision of 'dry recyclables' collections (e.g. paper, cans and plastics) was most popular amongst local authorities. In view of the high proportion of food waste remaining in the general waste stream, a number of local authorities received funding to run trial kerbside household food waste collection programmes between 2007 and 2009 (WRAP, 2009a). Uptake of the concept was rapid, and by 2011, 47% of local authorities in the UK already offered some form of source separated food waste collection to households. More local authorities are expected to roll out new food waste collection schemes in the near future in order to further improve their recycling rates (WRAP, 2013a).

Food waste can be defined as material that has been thrown away as not used or partly used in the preparation of meals, plus any food that is not consumed (WRAP, 2009b). It is one of the major components of municipal solid waste in developed countries. 89 million tonnes of food waste is generated every year in the EU (House of Lords, 2014), while 7 million tonnes per year of food waste is produced by households in the UK (WRAP, 2013d). In the UK, food waste is the largest single fraction of household waste (Eunomia, 2007a), with biodegradable items such as fruit, vegetables, cooked and processed food making up approximately 22% of the waste stream (Bench et al., 2005). The wastage of large amounts of food, however, represents a loss to the economy at both individual and national scales; while disposal of this material to poorly-designed or poorly-operated landfill sites may have a range of adverse effects on the environment (Nahman et al., 2012).

In view of this, a wide variety of instruments is either being implemented or is under discussion to tackle the food waste problem. Direct and indirect measures being considered include changes in current legislation, the enforcement of landfill bans, increases in landfill tax and the development of alternative treatment systems (Defra, 2011b, PDM Group, 2011). The concept of the waste hierarchy is also being applied to food waste management. In order to reduce food waste generation from different sectors, since 2007 the UK government has launched a series of food waste reduction programmes such as Love Food Hate Waste (WRAP, 2011d). At the same time it is understood that, however effective minimisation programmes may become, there will always remain a residue for disposal (WRAP, 2011e, Vision 2020, 2013, Letsrecycle, 2014); and kerbside household food waste collections are therefore being proactively introduced. These measures are driven by the EU Landfill Directive (1999/31/EC) and the Waste Framework Directive (2008/98/EC), which play an essential role in promoting the separate collection and handling of biodegradable wastes in the UK. In 2012, the Scottish Government amended its Waste (Scotland) Regulations to be in line with EU waste directives and boost the recycling of all wastes. The new regulations ban the disposal of household and commercial biodegradable wastes, including food waste, to landfill. In addition, local authorities are required to collect food waste from households by the end of 2015 (Scottish Parliament, 2012). The Department of the Environment in Northern Ireland also released a consultation paper in September 2013 which follows Scotland's model (Department of Environment, 2013). Similar measures are under consultation in Wales following the recommendation by the Welsh Assembly that household food waste should be separated at source for collection (Welsh Government, 2013). No consultation on a landfill ban for food waste is being undertaken in England as yet, but this issue is being debated among political parties and related industries (Materials Recycling World, 2012, Materials Recycling World, 2013, LocalGov, 2014). Although the segregation of food waste is not a mandatory requirement in England, the pressure for implementation of separate food waste collections is gradually increasing as the government sets priorities to increase the recycling and recovery rates for food waste through anaerobic digestion (Defra, 2011a, Defra, 2011b). The legislation being implemented or proposed in Scotland, Wales and Northern Ireland also facilitates local authorities in providing better and more effective collection systems for dry recyclables as well as food waste from households.

Apart from the legislative pressure, the demand for contaminant-free food waste from the anaerobic digestion industry provides a further push to implement source segregation of household food waste. Anaerobic digestion of food waste has been a fast-growing industry in the past decade in the UK, with 55 anaerobic digesters with a total capacity of 79440 kWe constructed between 2002 and 2014 (NNFCC, 2014), and source segregated domestic food waste can provide a consistent feedstock for this purpose. At the same time, the methane gas generated from the process can maintain the operation of the digestion plant, and produce surplus energy for transfer to the electricity and gas grid, for direct use in heating or as a transport fuel; whilst the digestate can be used as bio-fertiliser on local farms (Wang et al., 2002, Kim et al., 2004, Zhang et al., 2007, Banks et al., 2011). Separation of food waste from the rest of the waste stream not only reduces the burden on landfill and minimises the emission of greenhouse gases, but also provides an alternative energy source helping to achieve renewable energy generation targets and the targets for use of biofuels in transport set in the EU Renewable Energy Directive (2009/28/EC). As noted by the European Commission (COM (2010) 235), improved recycling and recovery of food and related municipal biowastes may thus offer the most cost-effective solution to meeting a range of environmental objectives.

A variety of systems for collection of source segregated household food waste and co-mingled food and garden waste have been implemented in Europe (Slater and Frederickson, 2001, Gallardo et al., 2012). The choice between separate and co-mingled collection depends on the treatment method used. Composting of the biowaste allows co-mingled collection of food waste and garden waste, while separately collected food waste is most suitable for anaerobic digestion. Separate collection schemes themselves can be categorised into kerbside and centralised collection systems. The former collect food waste at the doorstep, while the latter require individuals to bring food waste to designated collection points, and are usually used for multi-storey buildings or areas of high-density housing (Eunomia, 2007b, WRAP, 2008a). A large variety of household food waste collection schemes are operating in the UK, but they can be divided into three main types: separate collection, co-collection with co-mingled recyclables and co-collection with source separated recyclables. Each type of system, however, may operate with different collection frequencies and use different types of collection vehicle, including single-compartment and multi-compartmentalised vehicles. In this research, the main focus is on kerbside collection of source segregated household food waste, in view of its potential as a feedstock for energy and resource recovery through anaerobic digestion. Therefore, co-mingled food waste and garden waste collections and centralised collection systems are outside the scope of the study.

Major studies have been carried out to evaluate the performance of household food waste collections in urban and rural areas and in different housing types. These have looked at factors such as the participation rate, capture rate and collection yield of food waste, as well as household perceptions on food waste recycling collections (WRAP, 2009a, Tai et al., 2011, Bernstad, 2012). The performance of different types of collection systems collecting different categories of source separated household waste has also been compared (Dahlén et al., 2007, Gallardo et al., 2010, Gallardo et al., 2012). In general these studies did not pay a great deal of attention to energy usage but focused mainly on collection efficiency e.g. in terms of participation rate, separation rate and capture rate. If food waste is to be used as a feedstock for renewable energy production through anaerobic digestion, however, there is a need to understand the full energy balance of the process, from collection to through to beneficial utilisation or disposal (VALORGAS, 2013b). An efficient collection system is expected to minimise the energy used in collection and transport, thus reducing the energy input into the overall process and increasing the net energy yield.

There have been a number of studies on fuel consumption in waste collection, including source separated systems. Tanskanen and Kaila (2001) modelled the fuel used in the collection of source separated household dry recyclables and biowastes in Finland. Maria and Micale (2013) evaluated fuel consumption in the collection of recyclables and biowaste from residential and commercial areas in Italy. Larsen et al. (2009) measured the diesel consumption for different household waste collections in two municipalities in Denmark. Everett et al. (1998) and Everett and Shahi (1996) studied time spent in kerbside collection of recyclables and yard wastes. In the field of transportation, extensive research has been carried out on logistics and route optimisation to minimise fuel consumption, although the majority of this has considered distribution rather than waste collection.

On the other hand, a number of studies have attempted to use life cycle assessment methods to examine the performance of collection of recyclables by different systems such as door to door, mobile pneumatic, bring site and recycling centre (Iriarte et al., 2009, Larsen et al., 2010). This approach is interesting but can be data-hungry, and is not practicable in terms of a providing a generalised decision support system for local authorities and other organisations responsible for introducing food waste collections (VALORGAS, 2013a). Little or no work appears to have been carried out to date on developing simple and robust methods to allow selection of the optimum collection system or benchmarking and comparison of performance of real schemes. There is thus a need for systems that give readily-interpretable quantitative outputs in terms of energy and resource use for use as scoping tools to support the decision-making process. As food waste and may be collected either separately or in compartmentalised vehicles with other waste fractions, such a method would be of benefit in assessing the energy and resource use associated with recovery and recycling of the whole municipal waste stream.

1.2 Research aims and objectives

1.2.1 Aim

The aim of this research was to develop a model able to calculate the energy and resource use in the source segregated collection of household food waste, as one component in the overall energy balance from anaerobic digestion of this feedstock. As food waste collection cannot be considered in isolation from the rest of the municipal waste stream, the modelling tool would also provide a robust methodology for assessing and optimising the performance of kerbside collection systems for food waste, dry recyclables and residual waste in terms of working time, total travelling distance, utilisation of compartments and number of refuse collection vehicles required.

1.2.2 Objectives

A number of objectives were set in order to fulfil the aims of the research:

- To review and categorize source separated food waste collection systems currently used in the UK and other European countries.
- To develop a deterministic waste collection model able to calculate the fuel consumption, working time, travelling distance, utilisation of compartments and fleet sizes, as a tool for the selection of optimal collection systems.
- To gather information from local authorities and service providers/waste management contractors on fuel consumption, tonnage of waste collected and characteristics of collection rounds from different household waste collection schemes running in the UK.
- To verify, validate and calibrate the collection model using the collected data.
- To assess the fuel consumption and other performance parameters in the 'single additional collection' mode of source segregated food waste at different set-out rates and collection frequencies by different sizes of single-compartment collection vehicles.
- To assess the fuel consumption and other performance parameters in kerbside household waste collection systems for co-collection of co-mingled recyclables with source segregated food waste at different capture rates in weekly and fortnightly collection using two-compartment collection vehicles.
- To assess the fuel consumption and other parameters in kerbside household waste collection systems for co-collection of food waste and different source separated fractions of recyclables at different capture rates in weekly and fortnightly collection using multi-compartmentalised collection vehicles.
- To identify optimum solutions by comparing the possible scenarios studied in different combinations of collection systems.

1.3 Outline of the thesis

The thesis consists of nine chapters. Chapter 1 provides an overview of the research and of the motivation for studying energy use in the source separated collection of food waste from households. Detailed background information on related legislation, food waste collection practices and different waste collection models and assessment tools are provided in the literature review in Chapter 2. Chapter 3 presents the methodologies used for development of the waste collection assessment tool for the collection of data for model validation and for conducting sensitivity analyses. A detailed description and formulation of the assessment tool is presented in Chapter 4. The information on data collection in different study sites and the work on model validation are presented in Chapter 5. In Chapters 6-8, different kerbside source segregated food waste collection systems are modelled to examine the performance in terms of fuel consumption and other parameters: systems considered include the single additional collection, separate collection, and co-collection with co-mingled recyclables or residual waste as well as co-collection with source segregated recyclables. In Chapter 9, the optimal collection systems are selected by comparing all the results obtained in previous chapters. The main findings are summarised and recommendations for future work are presented in Chapter 10.

Chapter 2: LITERATURE REVIEW

The first part of this chapter provides information on current legislation and policies related to separate household waste collection, the composition and quantity of household waste, current practice in food waste collection schemes and fuel consumption in waste collection. The second part reviews previous research relevant to household waste collection, and the models and tools used for the assessment of fuel consumption in waste collection.

2.1 Legislation and policy on source separate household waste collection

The European Union (EU) has established a number of Directives that provide the framework for the EU member states to implement national and regional legislation and policies on solid waste management: these directly influence local authorities in managing their waste. Currently, the EC is promoting the concept of turning waste into resources and minimising residual waste (European Commission, 2011). The requirements of the EU Landfill Directive (1999/31/EC) and EU Waste Framework Directive (2008/98/EC) have assisted the United Kingdom in setting strategic plans to work towards a resource-efficient economy.

The EU Landfill Directive (1999/31/EC) was established to reduce the amount of biodegradable waste going to landfill, and thus minimise the associated environmental impacts. To achieve this, it set specific targets of reduction by 25%, 50% and 65% of 1995 levels by 2010, 2013 and 2020 (European Commission, 1999). The revised Waste Framework Directive (2008/98/EC) provides a framework for Member States to establish policies favouring recycling, such as introducing the separate collection of dry recyclables and encouraging the separate collection of biowaste. In response to the revised Directive, 50% of household waste is targeted to be recycled in the UK by 2020 (Defra, 2010b). The UK has successfully achieved the first biodegradable waste diversion target in 2010 and is progressing towards the household waste recycling target, having reached 43.3% in England in 2013 (Defra, 2010c, Defra, 2013b).

A number of waste acts and regulations have been implemented in England, Wales, Scotland and Northern Ireland in order to achieve compliance with the requirements and statutory targets set in both Directives. The Household Waste Recycling Act 2003 aimed to increase the recycling rate, and required all local authorities to collect at least two recyclables from households in England. According to the Act, recyclables are defined as any household waste that could be recycled or composted, including batteries, garden waste, glass, food waste, metals, papers, plastics, textiles, wood, and hazardous liquid wastes as well as electrical and electronic equipment (Defra, 2005). To boost recycling rates further, the Waste (England and

Wales) Regulations were amended in 2012 and require waste collection authorities to offer separate household collection of paper, plastics, metals and glass from 2015 (Environment Agency, 2012b, Defra, 2013a). The Scottish Government also made an amendment to the Waste (Scotland) Regulations in 2013. This takes forward the mandatory requirement not only to collect dry recyclables separately, but also to source segregate and separate household food waste for collection. Local authorities are required to start providing receptacles for the collection of source separated food waste by 2014, and to offer full coverage by 2016 (National Archives, 2012). Similar measures for separate food waste collection are also under consultation in Northern Ireland and Wales (Welsh Government, 2013, Department of Environment, 2013)

The Scottish Government has published a waste policy that proposes to set a challenging target to recycle 70% of all waste in Scotland by 2025. In addition, it has put forward the idea of a landfill ban, especially to ban food waste going to landfill by 2020 (Natural Scotland, 2010). The Government also published a review document on waste policy in England in 2011 that committed it to work on the minimisation of food waste generation, and to increase the recycling and recovery rate for food waste as well as promoting the use of anaerobic digestion as an alternative waste treatment method (Defra, 2011b). At present, collection of food waste is not mandatory in England under the Waste (England and Wales) Regulations 2011 (Environment Agency, 2012b). Although a ban on food waste is still being discussed between government, political parties and the waste industry in England, increasing the landfill tax also provides momentum to divert food waste from landfill. According to HM Revenue & Customs (2012), the landfill tax will increase by £8 per tonne every year up to £80 in 2014. This not only provides a financial incentive to look for alternative treatment methods, but could also be a driving force for implementation of source segregated household food waste collections. In order to divert more food waste from the household waste stream, it has even been suggested that tax on different materials sent to landfill should be charged at different rates (Coggins and Mcllveen, 2009).

Two further regulatory changes which had an impact on waste collection and management practices were the introduction of Best Value Performance Indicators (BVPI) and of the Animal By-Products Regulations (ABPR). BVPI (now replaced by the National Indicator Set) were introduced in England and Wales under the Local Government Act 1999 which placed a duty on local authorities to achieve continuous improvements in local services. BVPI were in place between 2000/01 and 2007/08 and required local authorities to report the percentage by weight of household waste sent for recycling, composting or anaerobic digestion, with each authority given a statutory target. These were set in the context of the national Public Service Agreement

(PSA) target to recycle or compost 25% of household waste by 2005/06, 30% by 2010 and 33% by 2015 (Audit Commission, 2007). As green waste is a dense material, setting up a green waste kerbside collection provided a rapid means for local authorities to meet their recycling targets. As a result, the amount of household green waste recycled increased from 3% of the total waste stream in 2001 to 17% in 2012, equivalent to 30-41% of the total household recycling rate (Personal communication, Chris Coggins, 2015). Green waste thus became a major component in the separately collected waste stream, compared to food waste which forms only 1.3% of total household waste (Defra, 2015), has had relatively little effect on recycling rates. Animal by-products regulations, on the other hand, refer directly to food wastes. They were introduced by Regulation EC 1774/2002 (now amended and consolidated as EU 142/2011) to protect human and animal health and the environment by regulating the collection, transport, storage and treatment process of animal by-products. The ABPR are implemented in England by the Animal By-Products (Enforcement) (England) Regulations 2011, and by similar regulations in the rest of the UK. Animal by-products are categorised into three types, based on their potential risk to human and animal health (Netregs, 2015). Food waste is classified as Type 3 which needs to be treated in an approved composting or anaerobic digestion plant with a pasteurisation process (Defra, 2014). This influences both the type of collection scheme chosen for food and garden waste, and its operational practice, as garden waste alone can be composted without special procedures while material including or consisting of food waste needs to be treated in accordance with the requirements of the ABPR.

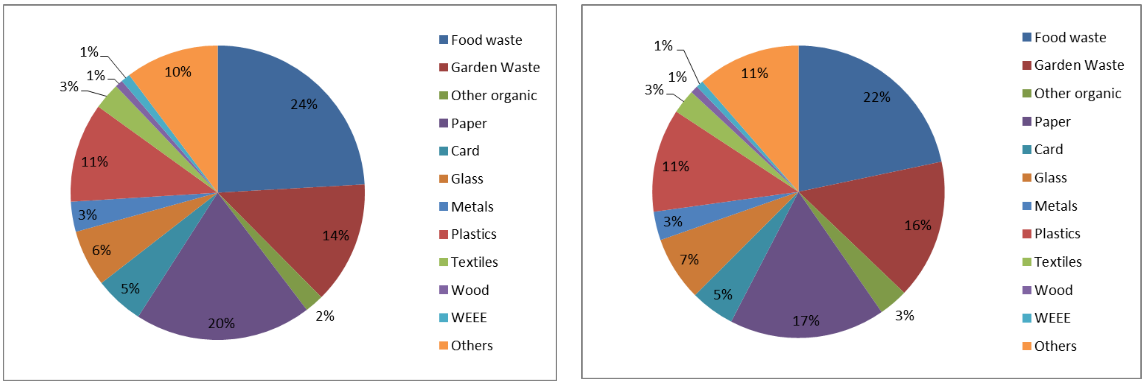
In addition to waste management legislation, EU energy policies also provide another indirect impetus to separate collection of food waste. For example, the EU Renewable Energy Directive (2009/28/EC) set a target for generation of 20% of EU energy demand from renewable sources by 2020 (Department of Energy & Climate Change, 2010). The Directive sets a mandatory target for 15% of UK energy to be produced from renewables by 2020 (Department of Energy & Climate Change, 2011). In order to fulfil the target, it is estimated that at least 10% of electricity must be generated from biomass, including e.g. anaerobic digestion of food waste, while 12% of heat must come from renewable sources (Renewable Energy Association, 2011).

Current UK energy and waste policies formed to implement these directives provide a momentum for source segregated household waste collection. The energy policies encourage energy recovery from biodegradable materials such as food waste and wood (Renewable Energy Association, 2011). Meanwhile, the waste policies emphasise the need for food waste reduction and the diversion of food waste from landfills (European Environment Agency, 2009a, The Scottish Government, 2011). These policies are considered to influence current practice in household waste collection, especially if separate food waste collection is going to be mandatory.

2.2 Overview of household and food waste characteristics

2.2.1 Overview of household waste composition

Household waste refers to the waste collected from household collection rounds, but also includes waste from bulky waste collections, litter collections and civic amenity sites (National Statistics, 2014). In 2012, approximately 27 million tonnes of household waste was generated in the UK (National Statistics, 2013b, National Statistics, 2013a, Scottish Environment Protection Agency, 2013, Department of the Environment, 2013). About 89% of household waste in England was collected from household collection rounds in 2012/13 (Defra, 2012b). The composition of kerbside collected household waste in England as reported by Defra (2008, 2012a) is shown in Figures 2.1a and 2.1b: to reduce the number of waste categories displayed in the graphs, hazardous waste, sanitary, mattresses, miscellaneous combustible and non-combustible waste, soil, fines and other uncategorised waste are grouped as 'Others'. From Figure 2.1 it can be seen that paper and plastics are the two largest fractions in dry recyclable waste on a weight basis, while food waste is the single largest fraction in kerbside household waste. As food waste collection is the main focus of this research, the characteristics of food waste are considered in more detail in the following sections.



(a) (b)

Figure 2.1 Composition of kerbside household waste by weight, (a) in 2006/7 adapted from Defra (2008), (b) in 2010/11 adapted from Defra (2012a)

2.2.2 Overview of food waste

Food wastage brings significant environmental problems to society. Traditionally, household food wastes were mixed with residual wastes and sent either to landfill or for incineration. Like other biodegradable waste, food waste can produce high-strength organic leachates which require proper control and management to prevent pollution. Also, the methane which is released during the degradation of food waste in landfill is a powerful greenhouse gas, with 25 times the impact of carbon dioxide (Brook Lyndhurst, 2009), and can contribute to climate change (Williams, 2005). Due to its high moisture content, however, food waste contributes little or no energy in the incineration process. As a result, recycling of food waste by anaerobic digestion is considered a preferable option to reduce the burden on the environment and the cost of waste treatment (Lai et al., 2009).

2.2.2.1 Definitions of food waste

There is no common definition of food waste among European countries. Some countries take into account food wastage in the supply chain, rather than simply considering food wasted in the final consumption stages (House of Lords, 2014). In addition, different countries use different terms which may have similar meanings but cover slightly different categories of materials (VALORGAS, 2012a). For example, Matavfall is used in Sweden and Bioavfall is used in Finland (Skellefteå Kommun, 2012, Helsinki Region, 2012). Matavfall does not include paper towels and napkins, however, but Bioavfall does. GFT (Groente- Fruit- en Tuinafval = Vegetable, Fruit and Garden waste) is used in Belgium and the Netherlands to describe food waste co-mingled with garden waste (VALORGAS, 2012a). In this research, the UK definition of food waste is used, which is material that has been thrown away, not used or partly used in the preparation of meals and any food that is not consumed (WRAP, 2009b). In addition, only source segregated household food waste is considered in this study: collection of food waste mixed with garden waste and other degradable materials is outside the scope of the current work.

2.2.2.2 Composition and proportion of food waste

Food waste is a major component of municipal solid waste (MSW) in most countries throughout the world. In Taiwan, Singapore and Japan, food waste is about 20-47% of the household waste stream (Bai and Sutanto, 2002, Lai et al., 2009). For Asian countries where source separation of food waste is not implemented, however, the fraction in solid waste could reach up to 71% (Tai et al., 2011). In developing countries the proportion of food waste in the domestic waste stream may be high for a number of reasons, including the tendency to buy more raw or unprocessed products that generate peels, seeds and other waste during home preparation; lack of packaging and refrigeration leading to greater wastage; and the smaller amount of non-food waste packaging and other items making up the rest of the waste stream (Kusch, 2013). In developed countries, food processing, packaging and distribution systems may help to reduce the quantity of spoiled or damaged food (Alter, 1989, Marsh and Bugusu, 2007), but may also lead to unnecessary wastage due to over-reliance on sell-by dates (see section 2.2.2.3 below). The high proportion of packaging adds to the residual waste stream, and may also contribute to contamination of source segregated food waste (Lebersorger and Schneider, 2011). In European countries such as the UK and Italy, food waste typically accounts for 25-50% by weight of total MSW waste generation (Bidlingmaier et al., 2004, Tawatsin, 2014). A study of household waste in Sussex, UK found that approximately 22% by weight was composed of fruit, vegetables, cooked and processed food (Bench et al., 2005).

A food waste compositional analysis carried out in the UK in 2000 for 7 consecutive days in 13 households found that fruit, vegetables, and bread and cereals made up 30%, 23% and 16% respectively (Langley et al., 2010). Very extensive studies on the composition of food waste in the UK have since been carried out by the Waste Resources Action Programme (WRAP) (WRAP, 2009c, WRAP, 2012b): the composition of UK household food waste in 2012 based on the most recent of these studies is shown in Figure 2.2.

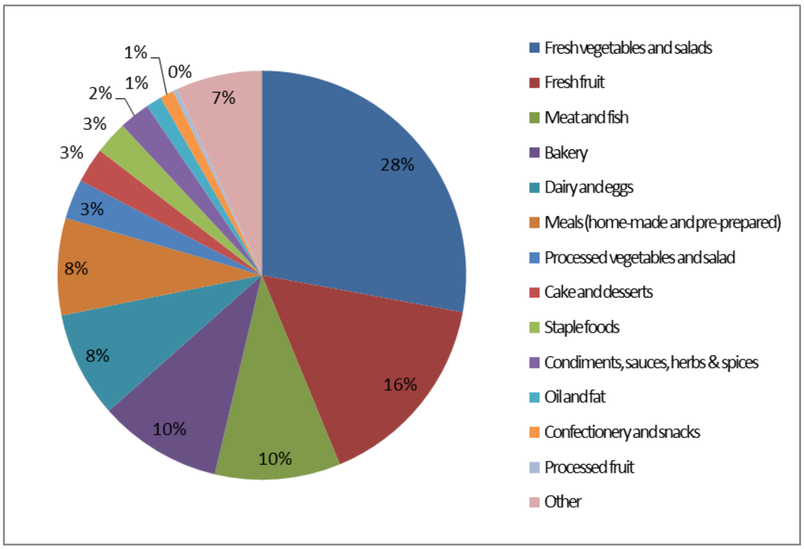


Figure 2.2 Composition of UK household food waste by weight, adapted from WRAP (2013c)

A study conducted in Cyprus showed that there were variations in food waste composition in urban and rural areas. In the urban area, bread and cakes, lemon peel and salad were the largest three components in household food waste, at 14.8%, 11.3% and 10.4% respectively. Rural families disposed of more potato peelings, watermelon and pasta, making up 16.4%, 14.5% and 11.3% of the food waste composition (Skourides et al., 2008). A recent study by WRAP (2012c) found that there appeared to be no significant seasonal variation in food waste quantity in the UK. A food waste characterisation study carried out for the FP7 VALORGAS indicated that the biochemical composition of food waste in terms of proteins, lipids and carbohydrates and other analytical parameters was similar in different European countries (VALORGAS, 2011).

2.2.2.3 Generation rates for household food waste

The quantity of food waste generated per household or individual varies from one place to another, and a number of studies have shown that socio-economic and behavioural factors contribute to this variation. These include household size, income, and number of children in a family, eating habits and the frequency of having meals in restaurants (Hui et al., 2006, Lee et al., 2007, Skourides et al., 2008, Tai et al., 2011). In studies carried out by WRAP in the UK, the average quantity of collected food waste per household covered by the collection scheme ranged from 1.0 to 2.2 kg $week^{-1}$, while the average quantity of collected food waste per household setting the material out was between 2.5 and 4 kg $week^{-1}$ (WRAP, 2009b). Ranges for the amount of captured food waste per household per week in different situations in the UK are shown in Table 2.1. The results indicate that both the housing type and the frequency of collection of residual waste can affect the amount of food waste collected. For example, slightly more food waste per household is captured in weekly food waste collections running alongside fortnightly collections of refuse compared to weekly refuse collection (WRAP, 2009a). The food waste collection method also affects the amount collected. WRAP (2009a) reported that the Index of Multiple Deprivation (IMD) of the area is one of the factors that affects the amount of food waste collected: areas with higher IMD tend to have lower yields of food waste collected than less deprived areas as a result of low participation rates and lower average household sizes in the more deprived areas. Apart from the relationship between IMD and housing, other factors such as the amount of food purchased, and meal preparation and consumption habits could also explain the influence of food waste yields. VALORGAS (2012a) noted that the average IMD of areas with food-waste only collection was lower than the average IMD for England.

Table 2.1 Food waste capture rates in different collection practices in the UK

		Amount of collected food waste (kg week^{-1})	References
General	From participating household	1.0-2.2	WRAP (2009b)
	From setting out household	2.5-4	WRAP (2009b)
Collection type	Food waste collection only	1.6-2.2	Brook Lyndhurst (2009)
	Mixed food waste and garden waste	0.5-1.0	Brook Lyndhurst (2009)
Housing type	From multi-occupancy housing	0.24-0.54	WRAP (2008a)
	From high density housing	0.99-1.69	WRAP (2008b)
	From low and medium density housing	1.50-2.17	WRAP (2008d)
Refuse collection frequency	Weekly food waste collection, fortnightly residual waste collection	1.7	WRAP (2009a)
	Weekly food waste collection, weekly residual waste collection	1.4	WRAP (2009a)

Recent initiatives on food waste in the UK and elsewhere have focused on minimisation, and these may affect both composition and quantity. One particular target is food retailers and especially supermarkets, as current practices in date labelling and storage instructions may increase the amount of useable food that is thrown away unnecessarily (WRAP, 2012a). As a result, labelling and packaging is gradually changing to include the use of resealable bags, intelligent packs for fresh fruit and vegetables, and vacuum packed fresh meat to maintain freshness and prevent over-ripening (WRAP, 2013b). With the introduction of waste reduction campaigns like Love Food Hate Waste, household food waste in the UK has reduced by 21% in five years (WRAP, 2012b). Data gathering and monitoring is thus essential to ensure accurate information is available to support decision-making during periods of dynamic change.

2.2.2.4 Bulk density of food waste

Reliable data on the bulk density of food waste is difficult to obtain. In a study by WRAP (2009a), the bulk density of food waste ranged between 400 and 600 kg m^{-3}. WRAP (2010) conducted a comprehensive study on bulk density of different waste types, and found that the average for food waste was 290 kg m^{-3} in individual kerbside containers and 500 kg m^{-3} in non-compaction collection vehicles. Skourides et al. (2008) reported that the average bulk density of food waste in urban and rural areas of Cyprus was 505 and 470 kg m^{-3} respectively. This variability could explained by a number of factors such as the size of container, the way in which the material is put into the container, the composition of the food waste and the use of compaction (WRAP, 2009a, UNEP, 2010, WRAP, 2010).

2.2.2.5 Biogas production and energy potential of food waste

Anaerobic digestion of food waste produces biogas, which is mainly composed of methane and carbon dioxide and can be burned directly to generate electricity and heat, or upgraded for grid injection or use as a vehicle fuel. Banks et al. (2011) studied the biogas and methane production from anaerobic digestion of UK source segregated food waste in a full-scale digestion plant, and found values of 642 m^3 $tonne^{-1}$ VS and 402 m^3 $tonne^{-1}$ VS, respectively. In laboratory studies, Zhang et al. (2012) reported a methane yield of 441-463 m^3 $tonnes^{-1}$ VS, slightly higher than the value in the study by Banks et al. (2011). Compared to the methane yield from cow manure (166.3 m^3 $tonne^{-1}$ VS) and full ripeness maize (268-286 m^3 $tonne^{-1}$ VS) (Amon et al., 2007), food waste thus has a higher specific methane yield that makes it an attractive feedstock for anaerobic digestion. As the energy yield of methane is 39.84 MJ m^{-3} (higher heat value) (Rincón et al., 2012), the maximum energy potentially available from food waste as raw biogas is around 15-18 GJ $tonne^{-1}$. Banks et al. (2011) found about 405 kWh $tonne^{-1}$ was available as net recoverable energy from anaerobic digestion of food waste in a commercial AD plant after allowing for parasitic energy demands for plant operation. More extensive studies in VALORGAS (2013b) also showed net positive energy yields under a wide range of conditions after taking into account all collection and pre- and post-processing requirements.

2.3 Overview of kerbside household waste collections

Household waste is collected at the kerbside, via selective collection systems, and at household waste recycling centres. The main difference between these three types of collection method is the distance between the waste source and the collection point, as illustrated in Figure 2.3. Kerbside collection requires a collection crew to collect the waste from at or near at the doorstep (Knipe, 2007). Selective collection systems require householders to bring their waste to designated collection points, and are usually applied to multi-occupancy or high density housing (WRAP, 2008c). The designated collection point for a source segregated waste collection is usually referred to as a ‘bring site’ or communal bin, and is within walking distance of users, in contrast to a household waste recycling centre (HWRC) which usually requires transport to access it. If a HWRC is used, then the energy consumed by private vehicles in travelling to the HWRC has to be included in any overall energy assessment. The following sections look briefly at recycling and residual waste collection, while source segregated food waste collection is considered in more detail in section 2.3.2.

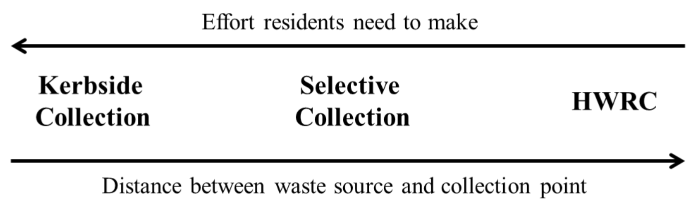


Figure 2.3 Difference between kerbside, selective and HWRC collections

2.3.1 Kerbside residual and recyclable household waste collections

Weekly and fortnightly collections of residual waste are the most widely-operated forms in the UK, with more than 70% of UK local authorities providing fortnightly residual waste collection. Local authorities in Northern Ireland also favour fortnightly collection, while Scottish authorities prefer weekly collection of residual waste (WRAP, 2013e). Table 2.2 shows the percentage of local authorities collecting residual waste by interval. The total is greater than 100% as each local authority may apply more than one type of scheme.

Table 2.2 Percentage of local authorities collecting residual waste by frequency (WRAP, 2013e)

	More than weekly	**Weekly**	**Fortnightly**
England	3%	53%	69%
Wales	0%	27%	91%
Scotland	9%	66%	84%
Northern Ireland	0%	8%	96%

For household dry recyclables, more than 90% of UK local authorities provide kerbside collection for cans, paper, cardboard and plastic bottles. Collection of textiles and household rigid plastic packaging is less common, with these services offered by 33% and 58% of local authorities respectively (WRAP, 2013b). Table 2.3 shows the percentage of local authorities collecting each dry recyclable waste in 2013. It can be seen that Welsh and Northern Ireland local authorities currently provide more comprehensive recycling collection services than authorities in England and Scotland, with more than half of the dry materials collected by 100% of the authorities.

Table 2.3 Percentage of local authorities collecting each dry recyclable waste (WRAP, 2013e)

	England	Wales	Scotland	Northern Ireland
Glass	83%	91%	78%	65%
Cans	99%	100%	97%	100%
Paper	100%	100%	97%	100%
Cardboard	91%	100%	91%	100%
Plastics Bottles	96%	100%	97%	100%
Rigid plastics packaging	56%	73%	63%	58%
Textiles	32%	36%	34%	46%

The UK Government categorises collection schemes into four types according to the degree of sorting by households and/or the way the collection crew collects the waste. These are multi-stream, co-mingled, two-stream and single material collections. Multi-stream means recyclable waste is segregated by householders into different streams, or separated by a crew at the kerbside during collection. Co-mingled and two-stream collection requires comparatively less effort from the household to separate materials, but involves downstream sorting (e.g. in a material recycling facility). In the former system all recyclable materials are collected in the same compartment, while in the latter recyclables are collected in two streams. Collection of only one material without any post-sorting is called single material collection (WRAP, 2014a). Table 2.4 presents the percentage of local authorities offering these types of dry recycling collection scheme in 2012/13. Currently, local authorities are only required to report on the dry recyclable materials listed in Table 2.3 (WRAP, 2013e). Therefore, current practice in household kerbside food waste collection is reviewed separately in Section 2.3.2.2.

Table 2.4 Percentage of local authorities offering dry recycling collection schemes (WRAP, 2013e)

	England	Wales	Scotland	Northern Ireland
Multi-stream	35%	55%	38%	23%
Two stream	28%	18%	37%	0%
Co-mingled	46%	27%	41%	85%
Single materials	1%	0%	16%	0%
Others	1%	5%	3%	0%
No schemes	0%	0%	3%	0%

2.3.2 Household food waste collection

2.3.2.1 Household food waste collections in Europe

A wide variety of schemes for source segregated household food waste have been implemented in Europe (Slater and Frederickson, 2001, Brook Lyndhurst, 2010, VALORGAS, 2012a). Generally, these are based on two main operating modes: grinding the food waste for disposal down the kitchen sink, and source separation by the household for collection. In some European countries such as Iceland and Sweden, food waste disposal units or food waste grinders are commonly used: in 2005 in the UK, Herefordshire Council and Worcestershire County Council launched the "Sink Your Waste" campaign to promote the use of food waste disposers (FWD) (Worcestershire County Council, 2011). A FWD is an electro-mechanical device that fits under the kitchen sink. Food waste is spun onto an abrasive ring with cold water, to avoid the accumulation of fat and grease on sewer walls as well as cooling the electric motor. Food waste is ground by the abrasive ring and turned into fine particles less than 2 mm in diameter, then either flushed down the kitchen drain to the wastewater treatment plant or stored in septic tanks before collection for anaerobic digestion (Evans, 2007, Iacovidou et al., 2012b, Bernstad et al., 2013). A number of recent studies have compared the advantages and impacts of introducing food waste disposers (Marashlian and El-Fadel, 2005, Bernstad and la Cour Jansen, 2012, Iacovidou et al., 2012a, Schiettecatte et al., 2014), but without reaching a consensus, and more research may be needed (Schiettecatte et al., 2014).

For source separated collection, food waste is generally collected at the kerbside or at a bring site. In the UK, the local authority tends to provide a kerbside collection service for households in low and medium density housing areas, while bring site collection systems are sometimes used for multi-occupancy housing (WRAP, 2008a, WRAP, 2008d, WRAP, 2009a). Mixing food waste and garden waste in the same bin for the collection is common practice in parts of Finland, Belgium, Netherlands and Northern Ireland (VALORGAS, 2012a). Some municipalities in Norway provide plastic and paper bags to contain the food waste, but these are placed in the bin with garden waste for collection (City of Stavanger, 2008). The collection of source separated food waste only is widespread in Sweden, where 76% of the population receive this service from the municipality. It was observed that the implementation of food-waste only collections is growing rapidly in the UK (VALORGAS, 2012a). A flowchart for classification of household food waste collection systems is shown in Figure 2.4, while some examples of current food waste collection schemes in Europe are summarised in Table 2.5. Details of collection schemes in the UK are described in Section 2.3.2.2.

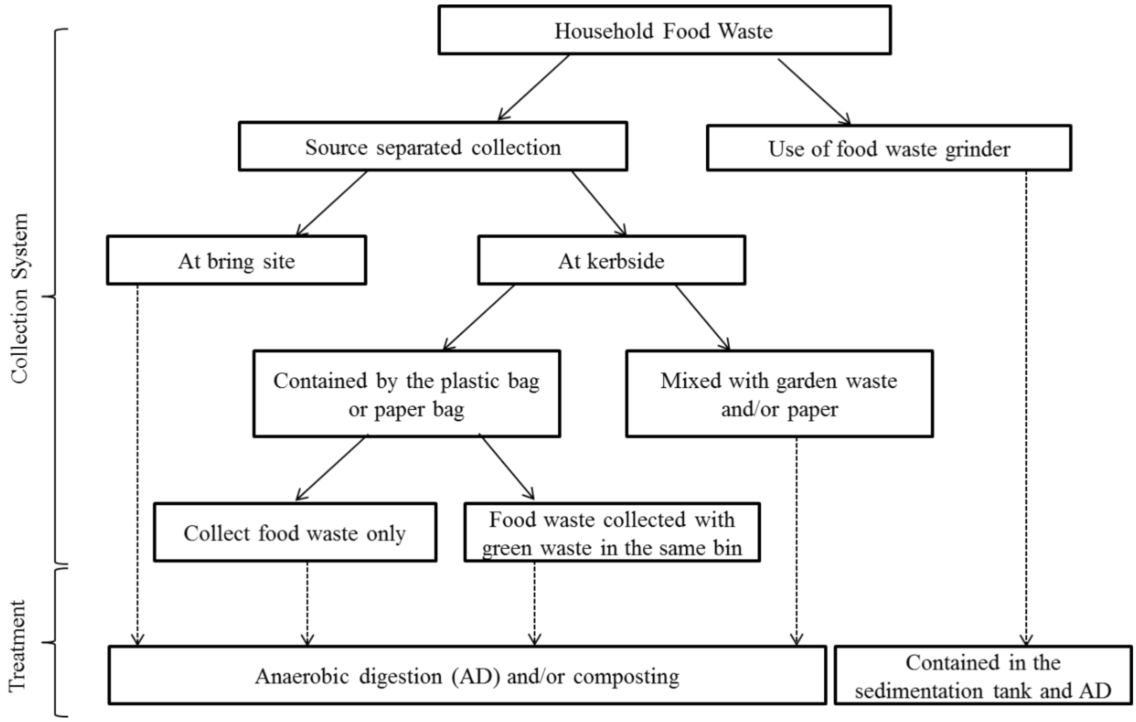


Figure 2.4 Classification of food waste collection systems in Europe

Table 2.5 Examples of different types of food waste collection schemes in Europe

City/Country	Type of scheme and method	References
Taunton, UK	Weekly kerbside collection - 5-litre kitchen caddy and lockable bin is provided, 3-way split vehicle is used to collect food waste, plastic bottles and cardboard at the same time. Source separated food waste is sent to an anaerobic digestion plant.	SWP (2011)
Hackney, UK	Weekly centralised collection – 7-litre kitchen caddy and liners are provided for each household; food waste is collected in centralised wheeled bins near the building. 7.5-tonne refuse collection vehicle empties the bins every week and send to an in-vessel composting plant.	WRAP (2008c)
Copenhagen, Denmark	Weekly kerbside collection – kitchen waste is contained in paper bag with wire baskets in the kitchen and transferred to brown plastic containers or paper sack placed outdoor. Food waste is then transported to an anaerobic digestion plant.	Carey et al. (2005)
Jyväskylä, Finland	Centralised collection – 120 or 140-litre collection bins, located at each building, used to collect kitchen waste. In some residual areas, 1300-litre Molok deep collection systems are used. The collected kitchen wastes were treated by a windrow composting plant.	Koivula et al. (2000)
Cupello, Italy	Kerbside collection – biodegradable bags are used to contain the kitchen waste and placed in buckets or bins. It is collected three times a week using bulk lorries with a capacity of 3 m^3. Kitchen waste was sent then to a composting plant.	EC (2000)

2.3.2.2 Source separated food waste collection in the United Kingdom

According to a study carried out by VALORGAS (2012a), co-mingled collection of food waste with garden waste or food-waste only collections were the most common practices in the UK. 41% of the population lived in local authorities that offered source separated food waste collection, while 23% had their food waste collected with garden waste. Approximately 36% of the UK population did not yet receive a separate food waste collection service.

Table 2.6 shows the proportion of different types of food waste collection services provided in England, Wales, Scotland and Northern Ireland. In Wales, all households receive some form of separate collection of food waste, while around one third of the population in England and Scotland receive food-waste only collection. In Northern Ireland, only one local authority is running a trial food-waste only collection scheme, while collection of food waste with garden waste is widespread. The study by VALORGAS (2012a) suggested that local authorities prefer to set up food-waste only collection schemes in areas that are relatively small and more densely populated.

Table 2.6 Population of local authorities by type of food waste collection service provided in the UK (VALORGAS, 2012a)

	England	Wales	Scotland	Northern Ireland
Separate food-waste only collection	37%	91%	31%	15%
With garden waste	23%	9%	20%	58%
No separate food waste collection	40%	0%	49%	27%

2.4 Characteristics of household food waste collections

2.4.1 Collection operation and systems

Collection systems are sometimes categorised into two types, as hauled container or stationary container systems (Tchobanoglous et al., 1993). A hauled container system is based on picking up the container from a collection point, transferring it to a disposal site and then returning the emptied container either to the original point or to the next collection point (Nemerow et al., 2009). It is usually applied to the collection of large containers scattered across a relatively wide area. For kerbside food waste collection, stationary container systems are more common, in which the container is returned to its original place after being picked up and unloaded into a collection vehicle (Tchobanoglous et al., 1978, Nemerow et al., 2009). In practice, however, collectors may apply a hybrid form of these two systems at the same time, e.g. in the collection of source separated food waste in blocks of flat or estates. In this case the container at the first location is exchanged with an empty bin which is brought from the depot; its contents are unloaded into the collection vehicle, and the bin is brought to the next location for the next in a sequence of such exchanges (Personal fieldwork observation, Chu, 2013).

2.4.2 Collection method

In practice, the method of collecting household food waste differs from one local authority or municipality to another, and generally depends on the available collection equipment and on the housing type. In the UK, local authorities usually provide kerbside collection services for households living in street-level properties, as shown in Figure 2.5a. Those who live on estates or in blocks of flats are generally required either to bring their food waste containers to a designated collection point, or to deposit the food waste in communal bin, as shown in Figure 2.5b and 2.5c respectively. Some local authorities also provide 'kerbside' or door-to-door collection for food waste in multi-storey buildings. In this case, the food waste bin is collected at the doorstep and emptied into a 'slave bin' which is then loaded into the collection vehicle (WRAP, 2008a). Compared to the use of a communal bin, this approach is both time-consuming and labour intensive, and is therefore being phased out in most places. In terms of logistics, it can be classified as a centralised collection system even though the food waste is picked up at the door step.

(a)

(b)

(c)

Figure 2.5 Collection point options (a) Kerbside food waste collection in Bromley, (b) Food waste collection at designated collection point, photo taken in Bromley (c) Communal bin is being used for food waste collection in estates, photo taken in Hackney

2.4.3 Collection rounds arrangement

Only a very limited amount of literature specifically reviews the arrangement of food waste collection rounds. Summarising the findings from WRAP reports and local authority websites, it can be observed that source separated food waste collection rounds for street level properties and for blocks of flats are always carried out separately, due to considerations such as the location of bins, the type of vehicles available and the accessibility of alleyway in estates (ADEPT, 2010). Having separate dedicated food waste collection rounds for flats and for houses can give increased flexibility in arranging collection services, but the total driving distances for collection from a mixed area of household and flats are likely to be higher. In some cases councils such as Bromley collect food waste from flats and houses in the same collection rounds, which reduces the total travelling distance for the collection.

The quality of food waste may be a problem, however, as contamination is frequently an issue in communal bins. The contamination mainly arises from the use of plastic bags to contain food waste, and can be improved by provision of appropriate bin liners by local authorities (WRAP, 2014c). On the other hand, some local authorities have also started to collect food waste from schools (WRAP, 2011b): council such as Hackney operate a combined collection service for schools and flats. This may also not be ideal in terms of the quality of the collected food waste, however, because food waste from school canteens is often contaminated by cutlery (WRAP, 2011a).

2.4.4 Collection frequency

Generally, the frequency of food waste collection depends on the regional climate and on public acceptability (Holiwast, 2006, Eunomia, 2007b). In southern European countries such as Italy, food waste is typically collected two to four times per week due to the Mediterranean climate; while in northern Europe, source separated food waste is collected once a week or even less frequently. In Finland, for example, source segregated food waste may be collected every four weeks in winter when the material remains frozen in the bin (VALORGAS, 2012a). In the UK, all of the local authorities in England and Wales that provide source separated food-waste only collections do so on a weekly basis. In Scotland, 75% of those served by food waste collections receive weekly food waste collection service. The majority of co-mingled food waste and green waste collections in the UK operate once a fortnight (VALORGAS, 2012a). Considering household waste collection as a whole, the most common arrangements for local authorities collecting food waste, dry recyclables and residual waste are as follows (Holiwast, 2006, VALORGAS, 2012a):

- Weekly food waste collection running alongside Alternate Weekly Collection (AWC) of residual waste and dry recyclables
- Weekly collection of food waste and recyclables with fortnightly residual waste collection
- Weekly food waste and residual waste collection with dry recyclable once a fortnight.

Alternate weekly collection is gaining popularity in England, with more than 59% of English local authorities adopting AWC of household waste (Bennett, 2013). For example, Rushcliffe Borough Council collects paper, card and green waste on one week and residual waste on the alternate week (Mee and Clewes, 2004). The observed advantages of AWC are that recycling rates increase, the overall waste generation rate may reduce, and especially that the refuse collection frequency can be reduced to every two weeks (McLeod and Cherrett, 2008, Sheward and Williams, 2011, Bennett, 2013).

2.4.5 Type of container

The type of container used depends on the type of collection scheme to be implemented. There are four main types of container: kitchen caddy, kerbside food waste container, wheeled bin and deep collection container. The kitchen caddy and kerbside food waste container are usually used together in kerbside source separated food-waste only collections, while wheeled bins or deep collection containers are generally used in centralised collections. In the UK, a small kitchen caddy (5-7 litres) and a medium-sized collection bin (20-30 litres) is normally provided by the local authority responsible for a kerbside collection scheme. The kitchen caddy, usually used with a liner, is used to contain food waste in the house. Once the caddy is full food waste is transferred to the larger bin, which is often lockable, and this is placed at the doorstep or in front of the house (Wilson, 2007). In Italy and some cities in the UK, wheeled bins are used to collect source separated household food waste in areas of high-rise buildings and high-density estates. About 15-20 households typically share one bin (WRAP, 2008c). Some wheeled bins used in Sweden and Denmark are partitioned into two sections, with food waste placed in one section and residual waste in the other (VALORGAS, 2012a). In the UK, a similar split bin system was introduced as part of the Leeds ‘Separate Out Recyclables Today’ (SORT) scheme (Kerrell and Briggs, 1991, Unsworth, 2004).

Deep collection containers are used for biowaste collection in Portugal and Finland (Koivula et al., 2000, Goulart, 2003). One third of the container is at ground level while two thirds is below ground. Because of the high bulk density of food waste, it can compact naturally into the lower part of the container. This is said to reduce odours, as the temperature inside the container is slightly lower than the surrounding air temperature and this slows down the decomposition of organic materials (Goulart, 2003, Molok, 2009). Use of this system to collect source separated food waste alone is rare, however, and it is mainly used for the selective collection of dry recyclables and mixed biowastes.

2.4.6 Refuse collection vehicles

Refuse collection vehicles (RCV) can be categorised according to the loading method used: e.g. manual or mechanical. Manual loading into the collection vehicle can be done by direct emptying of the container or with the assistance of a bin lifting system (Tchobanoglous et al., 1978). Bin lifting systems are commonly used in handling household waste during collection. When the bins are taken to the vehicle and loaded mechanically by a bin lifter, this can be further classified as partial mechanical loading. For mechanical loading and emptying, a mechanised collection vehicle is used which is equipped with a crane handling system for lifting deep collection containers, or with an automated arm to lift wheeled bins (Tchobanoglous et al., 1993). The advantage of mechanical loading is that it involves less human effort, but it requires more cooperation from household than manual loading because the bins need to be placed accurately on the roadside. Manual loading is much more flexible, as it allows the collection crew to pick up bins even when they are not well set out. There is, however, a greater risk of injury to collectors during carrying and lifting (Tchobanoglous et al., 1978).

Various types of RCV are used in household waste collection, with a wide range of payloads. RCVs can be classified into three main types: single-compartment, two-compartment and multi-compartment vehicles (Lund, 2000). Two-compartment vehicles can be further divided into two types: rear-loaded split bodied RCV, and rear-loaded RCV with a pod that is side loaded. Both types can be used to co-collect e.g. food waste and dry recyclables at the same time. Rear-loaded split bodied RCV are typically manufactured with a 70/30 or 50/50 split by volume. Alternatively, the body of the RCV may be further subdivided into 3 to 10 compartments. Only limited information on compartmentalised RCV is available in the literature, but Table 2.7 summarises the general characteristics of different types of collection vehicle based on information provided by the manufacturers.

Wilson (2007) and Holiwast (2006) agreed that the most economical and flexible option for source segregated household food waste collection is the use of a small non-compacting non-compartmentalised vehicle. This is because food wastes have a high bulk density and can be self-compacting in containers and collection vehicles; therefore, an expensive RCV equipped with compactor is not required. Beullens et al. (2004) reported, however, that using a single-compartment vehicle is less efficient in terms of fuel consumption and carbon emissions when hauling small amounts of waste. In the UK, an increasing number of local authorities are adopting compartmentalised vehicles (Avfall Sverige, 2012, McLeod and Cherrett, 2008, WRAP, 2009a). The multi-compartment RCV is used in areas that have a high degree of waste fraction separation at the household. In this system the crew picks up the recycling box and sorts the dry recyclables in situ. Compared to loading other RCVs, this approach is more labour intensive but allows the collection of high quality recyclables, and may thus save on the capital and operating cost of material recycling facilities (MRFs) (Personal communication, A. Bond, 4R Environmental Ltd, 2012). The use of split-bodied or multi-compartment collection vehicles often causes practical problems, however, when one compartment fills up quickly while another is under-utilised (Smyth, 2010). Nevertheless, McLeod and Cherrett (2007) found that the co-collection of residual and recyclable waste using split-bodied RCVs was more efficient in terms of travelling distance and time required than using standard RCVs to collect the same wastes separately on a weekly basis. Although McLeod and Cherrett (2007) studied the co-collection and AWC of residual waste and dry recyclables, the potential benefit or otherwise of AWC integrated with source separated food waste collection is unknown. Hence, this aspect is explored in the current research.

Table 2.7 Classification and characteristics of different types of collection vehicles (Dennis-Eagle, 2004, CWS, 2012, FARID, 2012a)

Number of compartments	Type of RCV		Description
Single compartment	-		The single-compartment RCV is referred to as the traditional/standard RCV in some publications. The gross weight of the vehicle ranges from 3.5 to 26 tonnes. The 26-tonne RCV is most commonly used in refuse collection.
Two compartments	Rear split-bodied		The rear split-bodied RCV also known as the twin bodied RCV. 30/70 and 50/50 splits are available in the market. The bin is lifted at the rear.
	Single pod		The body of the RCV is split into two parts: front and rear. The front compartment is called a pod and waste is loaded from one side. The rear compartment is equipped with a compactor.
Three compartments	Rear split-bodied with single pod		A pod is installed at the front. Waste can be loaded from one or both sides. Rear compartment is split into two bodies and equipped with a rear loading system. *Photo credit: http://www.macqueeneq.com/work/heil/

Cont. Table 2.7 Classification and characteristics of different types of collection vehicles (Dennis-Eagle, 2004, CWS, 2012, FARID, 2012a)

Number of compartments	Type of RCV		Description
Three compartments	Three identical		The compartment is split into three sections identical in size. Waste is loaded from one or both sides in the front and middle compartments while the bin can be lifted from all three sides at the rear compartment.
Multi-compartment (up to 12 compartments)	Kerbsider		The vehicle can be partitioned into up to 12 small compartments, the size of which is adjustable and controlled by a computerised system. The compartment at the top is usually equipped with a compacter.
	Stillage		The size of the compartment is fixed, and the number of compartments can be changed according to need. Usually, the RCV is equipped with 6 removable compartments of identical size in the middle; and a small and large compartment located at the front and rear respectively. A forklift is used to empty the waste from the removable compartments.

2.5 Factors affecting fuel consumption in the waste collection process

In Europe and the US refuse collection vehicles are classified as heavy duty vehicles (HDVs) according to their gross weight (Agar et al., 2007, Harrington and Krupnick, 2012). In most cases the engines used in RCVs were originally designed for HDVs, which typically travel at higher speeds than those achieved in refuse collection (Maimoun, 2011). Based on a comparison of values reported by Agar et al. (2007) and the US Environmental Protection Agency (1998), the fuel efficiency in RCVs could be 2.85 times lower than in HDVs, due to the particular driving cycle of RCVs (i.e. stop-and-go pattern). Apart from the driving cycle, several other factors can influence fuel consumption, including the driving pattern, vehicle operation and traffic environment (Brundell-Freij and Ericsson, 2005).

2.5.1 Driving cycle, driving behaviour and driving pattern

The driving cycle is defined by the series of data points that record the vehicle speed and gear selection versus time (Barlow et al., 2009). Running the engine when the vehicle is stationary is called idling, and is one of the factors that consumes fuel and reduces the overall fuel efficiency (O'Keefe et al., 2007, New West Technologies, 2011). As mentioned above, the driving cycle in a RCV differs from that for a typical HDV not only due to the speed, but also the time spent and the manner of idling. Long-haul HDVs are idled when the drivers are in a rest period, and the engine is on to maintain the heating or air-conditioning system and keep the engine warm in cold weather (Hickman, 1999, USEPA, 2002). For a refuse collection vehicle, 50-70% of the time may be spent in idling for compacting waste and loading it from the bins to the vehicle (An et al., 1999, Maimoun, 2011). The energy consumed during RCV operation is discussed in more detail in Section 2.5.2.

Generally speaking, driving behaviour depends on the driver's age, driving experience, cultural background and attitude to driving (Brundell-Freij and Ericsson, 2005). De Vlieger (1997) studied how fuel consumption in passenger cars is affected by calm, normal and aggressive driving conditions. It was reported that fuel use in aggressive driving with sudden acceleration and heavy braking in a city environment was about 20-40% higher than in normal driving. Although the driving cycles of passenger cars and RCVs are not the same, the results of this study give an indication of the relationships between fuel use and driving behaviour.

Driving pattern is related to the driving behaviour, vehicle, weather, traffic, street environment and travel behaviour (Ericsson, 2000). Each factor is interlinked with other factors that also affect the driving pattern, but do not necessarily have a significant influence on the fuel consumption. Fuel consumption is mainly affected by the driving behaviour, driving cycle, vehicle acceleration and gear shift (Ericsson, 2001, O'Keefe et al., 2007, European Commission, 2012).

2.5.2 Vehicle operation

US researchers have investigated the on-road driving cycle of RCVs, in studies where the fuel efficiency was monitored by a dynamometer measurement system, and vehicle speed and time were also recorded (An et al., 1999, O'Keefe et al., 2007, New West Technologies, 2011, Maimoun et al., 2013). Figure 2.6 shows an example of the speed profile of the collection vehicle: the 'stop-and-go' pattern can be observed in the graph. When the vehicle speed equals zero in the repetitive pattern, this means the RCV has stopped for waste compaction or emptying of bins (Maimoun, 2011).

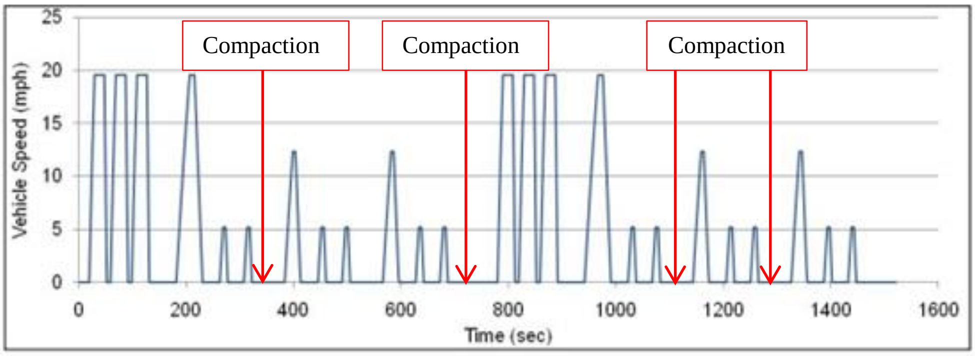


Figure 2.6 The driving cycle of the collection vehicle, speed plot against time (New West Technologies, 2011, Maimoun, 2011)

New West Technologies (2011) studied the distribution of fuel consumption and distance travelled, and showed that 48% of total fuel consumption was used in travelling between the collection area and unloading site, which represented 75% of the total travelled distance; while 52% of the fuel was consumed in the collection process which involved driving, idling and waste compaction and unloading. O'Keefe et al. (2007) also commented that the fuel used at a standstill during the collection period is more than that used in driving. When considering the 'stop-and-go' driving conditions in waste collection, Betsy et al. (2007) suggested including an average fuel consumption of 3.1 L $hour^{-1}$ in idling to compensate for the extra energy consumed in frequent use of the brake, in acceleration and in loading containers.

In the early 1980s, Ferreira (1982) studied the effect of cold start of the engine in passenger cars, and found that fuel consumption during warm-up was around 30% higher in summer and 60% higher in winter than under normal conditions. Despite improvements in car engine technology, Darnton (1997) noted that the fuel used during engine warm-up still remains 13-

17% higher than when the engine is at a fully-warm condition. Cold weather starting causes increased fuel consumption to reach the light-off temperature of the engine. The fuel efficiency of vehicles is also being affected by vehicle Euro emission standards. The most recent emission standard is Euro 6 which came into effect on 1 January 2014. The newer the vehicle, the lower the expected fuel consumption due to improvements in engine design to give better fuel economy (King et al., 2005).

Vehicle load and distance travelled are among the major factors affecting fuel usage (European Commission, 2012). A vehicle of higher weight will require more fuel to run the engine than a light duty vehicle (Hickman, 1999). In a study of route optimisation for the collection of glass waste, Beijoco et al. (2011) showed that a 25% reduction in distance travelled could reduce fuel usage by 28%. In order to reduce fuel consumption, a considerable amount of research in the past decade has focussed on methods for route optimisation (see section 2.7.3 below).

2.5.3 Traffic environment

Vehicle fuel consumption is affected by the traffic environment i.e. road type, road gradient, road surface, traffic congestion, density of junctions and traffic lights (Hickman, 1999, Brundell-Freij and Ericsson, 2005). The travelling speed, acceleration and deceleration of the vehicle are related to the road type, density of junctions and traffic congestion. The road surface is linked to the rolling resistance, and fuel consumption increases with increasing roughness of road surfaces. The road material, vehicle loads and air pressure in the tyre may also affect the fuel consumption (Sandberg, 2001, Beuving et al., 2004).

Road gradient has been shown to affect fuel consumption: Boriboonsomsin and Barth (2009) measured the fuel use of light duty vehicles in flat and hilly routes, and found that up to 20% less fuel is used in driving on a flat route than hilly routes. The same researchers also pointed out, however, that there could be not much difference in overall fuel use on flat and hilly routes because the different fuel usages in driving the uphill and downhill segments should compensate one another.

Most UK local authorities collect kerbside household waste between 7am and 2pm, when a certain degree of traffic congestion may be experienced in the inner city during the peak hour. Traffic congestion affects fuel economy because of the low travel speed and the need for instantaneous acceleration and deceleration. Sivak and Schoettle (2011) reported that a 20-40% reduction in fuel economy would be expected for traffic congestion compared to fast driving on the highway. De Vlieger et al. (2000) also showed that more fuel is used in congested city traffic conditions: the fuel use under normal and congested conditions was 9.3±0.2 L per 100 km and 10.4±0.5 L per 100 km respectively. Although these studies did not look at the fuel consumption of collection vehicles under congested driving conditions in urban streets, the results clearly demonstrated that congestion could significantly increase the fuel use.

2.6 Previous work related to waste collection

2.6.1 Comparison of fuel efficiency in waste collection

When considering fuel consumption or fuel efficiency in waste collection, a distinction is generally made between the collection and transportation phases. Eisted et al. (2009) defined collection as an activity that involves the picking up of waste in a residential, commercial or industrial area by a RCV. Transportation describes the movement of collected waste from one place to another by RCV, and includes the initial journey from the depot to the collection area even though the RCV is empty at this point.

Very few values for the specific fuel consumption of different types of RCV can be found in the literature. Even where these are reported they may not be representative, as the values can be site or route specific. WRAP (2009a) reported that a 7.5-tonne and a large RCV consumed about 18.8-23.5 and 47.1-94.2 L diesel per 100 km respectively, with the latter range too wide to be of much practical use for estimation purposes. Nguyen and Wilson (2010) estimated that 180 litres and 126 L of diesel per 100 km were consumed by two-compartment vehicles and normal packer trucks, including both the transportation and collection phases. In the absence of information on the RCV specifications and with the combination of the fuel consumed in the two phases of collection, it is impossible to compare these studies other than to observe that there is are significant differences between the reported consumption values.

Betsy et al. (2007) estimated that the fuel efficiency of a RCV ranged from 74.6-217.4 litres diesel per 100 km, again representing a very broad range of performance. For the collection and transportation phases, higher fuel efficiency is observed in transportation because the collection phase involves a ‘stop-and-go' travelling pattern. The values for transportation and collection used in a life cycle assessment tool for waste collection were 3 km L^{-1} and 1.25 km L^{-1} respectively (Diaz and Warith, 2006), while Tanskanen and Kaila (2001) used 4 km L^{-1} as the fuel efficiency in transportation for their assessment. Lópezet al.(2009) reported the consumption of diesel fuel for an actual household waste collection route in the city of Madrid as 0.77 L km^{-1}, equivalent to 1.30 km L^{-1}.

2.6.2 Fuel consumption in food waste collection

There is only a limited amount of research investigating the energy consumption in collection and transportation of household source separated food waste. Evans (2012) studied the energy used in the collection of source separate food waste using multi-compartment collection vehicles. As the time spent in on-site sorting is longer than for traditional RCV, it was assumed that an extra 22% of energy is consumed during idling. The research found that 2.53-6.89 L of diesel were consumed to collect one tonne of food waste from households. Gredmaier (2011) calculated the diesel consumption during collection and transportation by collecting data on fuel use, quantity of food waste collected and distance travelled for a source segregated domestic food waste collection scheme in Flintshire, UK. In this study, 7.5-tonne single-compartment RCVs were used for collection, and 10.9 and 9.9 L of diesel per tonne of collected food waste was consumed in the collection area and for transportation from the bulking point to an AD plant, respectively.

Willis (2010) considered the energy consumption in four source separated food waste collection schemes in the UK. An equation from EMEP/CORINAIR Emission Inventory Guidebook was adopted to calculate the energy consumption of RCVs during collection and transportation. To allow for the use of the hydraulic bin lifting system, it was assumed that an additional 35% of fuel was required in the collection phase, and based on this the estimated fuel use ranged from 4.32 to 10.33 litres per tonne of collected food waste. Comparison of the studies by Willis (2010) and Evans (2012) provides a general idea of the energy consumption of single-compartment and compartmentalised RCV: it appears that the multi-compartment RCV consumes less fuel per tonne of material collected than the standard RCV in the collection of source separated food waste. On the other hand, Chu (2010) used a simplified theoretical model for kerbside and centralised source separated food waste collection systems to assess the energy usage and greenhouse gas (GHG) emission, and showed that both collection frequencies and type of RCV affected the performance in terms of energy consumption.

2.6.3 Fuel consumption in residual waste and recycling collection

Apart from food waste collections, a number of studies have looked at energy consumption in the collection of household residual waste at the kerbside (Larsen et al., 2009, Eisted et al., 2009), and of glass via bottle banks (Edwards and Schelling, 1999, Dacombe et al., 2005). Eisted et al. (2009) found that the energy used in transportation is higher than in the collection and transfer stages. Larsen et al. (2009) studied fuel consumption in the waste collection and transportation phases, and related this to the housing type and amount of waste collected. Fuel consumption was found to range from 1.4 to 10.1 L diesel per tonne of residual waste collected.

Collection from apartment buildings consumed the least fuel per tonne because of the short distance between stops and the large amount of material picked up per stop. Rural areas required more energy as the travel distance between the collection points is longer. Another study by Di Maria and Micale (2013) considered how fuel consumption was affected by the source segregation intensity of dry recyclables and organic waste using different collection methods in a medium-sized city in Italy. It was found that the fuel required for collection of one tonne of waste increases with increasing intensity of source segregation of materials, ranging from 3.33 to 3.80 L $tonne^{-1}$.

2.6.3.1 Comparison of different collection systems

A number of studies have compared energy use in different types of collection systems, including door-to-door and pneumatic waste collection (Gallardo et al., 2012, Punkkinen et al., 2012); kerbside and bring site collection (Gallardo et al., 2012, Gredmaier et al., 2013); and pneumatic, kerbside and bring collection systems altogether (Iriarte et al., 2009). When comparing kerbside and centralised collection systems, Vidal et al. (2001) and Iriarte et al. (2009) found that kerbside collection of household waste had a higher total energy demand than the bring site collection system. Vidal et al. (2001) stated that the same amount of fuel was used in the collection stage for the two systems; however, the fuel consumption doubled in the bring site system. This implies that more fuel was used in transportation rather than in the collection phase, despite the 'stop-and-go' pattern involved, in contradiction to the work of Betsy et al. (2007). Iriarte et al (2009) found that the total energy used for a door-to-door system for organic waste, dry recyclable and general refuse in a theoretical urban area with population density of 5000 inhabitants km^{-2} was 57% higher than for bring sites due to the longer collection routes. Gredmaier et al. (2013) compared the energy used for food waste-only collection at kerbside, low and high density bring sites. The energy used in kerbside collection was significantly higher, at 10.9-12.9 L diesel per tonne for kerbside collection and 4.1-4.4 L diesel per tonne for bring-site collection system. Although more energy is generally used in kerbside collection, it may be the preferred system as a high proportion of waste is captured and low contamination is found in the bins (Gallardo et al., 2012).

2.7 Previous work on modelling and assessment methods

In reviewing the previous work on modelling and assessment methods for waste collection systems, it was noted that several researchers have used mathematical modelling approaches to estimate fuel consumption. In the past decade, a growing number of studies have applied Geographic Information Systems (GIS) to model waste generation and collection. Life Cycle Assessment (LCA) methods have also considered the energy consumption in collection and transportation when assessing the environmental consequences of whole waste management system. In addition, operational approaches have been used to improve waste collection by optimising the collection distance and cost.

2.7.1 Mathematical modelling approaches

A number of waste collection and transportation models have been used to estimate fuel consumption and greenhouse gas emissions. The models developed by Everett and Shahi (1997), Sonesson (2000) and Di Maria and Micale (2013) used deterministic approaches to estimate the time and/or fuel required in household waste collection.

Everett and Shahi (1996, 1997) and Everett et al. (1998) constructed a model based on the time spent in collecting material in order to study the kerbside collection of yard waste. The model could estimate route time based on time between stops, time spent on non-productive tasks, walking and sorting time. The output was useful for comparing the efficiency of different collection methods for identical collection routes, and for predicting the size of the fleet and the effect of changing some parameters such as set-out rate. However, this model did not address fuel consumption or GHG emissions.

Sonesson (2000) highlighted the limitations of existing models in waste assessment tools, and developed a mathematical model using MATLAB/SIMULINK software to calculate fuel consumption and time during waste collection. Number of stops, collection frequency, fuel consumption during hauling, collection and stopping points were taken into account for the calculation of energy consumption. Only the payload of the collection vehicle was considered, however, which may lead to errors when the number of pick-up points is limited by the volume of an RCV compartment.

Di Maria and Micale (2013) developed a model based on the time spent in transport and collection. The time spent in transport was derived from average vehicle speed and travelling distance, while the time in the collection area is calculated from the number of collection points and the pick-up time at each point. Fuel consumption is calculated from the number of vehicles required, total travelling distance and the fuel efficiency of different vehicle sizes. The model assumed, however, that compartment volume was the limiting factor. Although the above models have different limitations, the approaches used are suitable for outline scheme design and assessment purposes as only a small amount of site-specific data is required.

2.7.2 Geographic Information System approaches

Geographic Information Systems are increasingly used to estimate the fuel consumption, determine the optimal route and allocate the collection facilities. Due to the lack of real data on fuel consumption of RCVs, however, assessing and reducing the energy usage of collection schemes is problematic. Nguyen and Wilson (2010) used a Geographic Positioning System (GPS) device to collect data on idling time and distance travelled for each collection route, and estimated the fuel consumption and GHG emissions in different processes, such as travel to the collection area, in collection, to and within the transfer station and finally back to the depot. Compared to the modelling approaches described in section 2.7.1 above, far greater amounts of site-specific data are required and hence more time must be spent on data collection. However, relatively precise estimates of fuel consumption can be made.

Cheng et al. (1997) presented a mathematical model integrated with a GIS function and also demonstrated the application of the model using data collected in Taiwan to calculate total distance, cost and time used in waste collection. It was reported that the model could help users to select the optimum waste collection system among alternative scenarios. Tavares et al. (2009) developed a GIS 3D model to find the optimal collection routes in 2D and 3D models for MSW collection. The model considered the effects of road gradient and vehicle weight. The results suggested that the optimal collection route in terms of fuel consumption is not necessarily the shortest route. Generally, there are a number of possible parameters to optimise on, including the lowest fuel consumption, shortest working time, and smallest numbers of vehicles and collection bins. The preferred option may vary in different circumstances.

Energy consumption during collection can be minimised by optimising the location of containers. Zamorano et al. (2009) used GIS to optimise the location of containers for collecting organic and residual waste and calculated the shortest collection routes. Both time and distance were reduced, especially the collection distance, which fell by 40.6%. Unfortunately, only distance was optimised and not fuel consumption. With this limitation, Chalkias and Lasaridi (2009) used ArcGIS Network Analyst to re-allocate the location of waste collection bins. The choice of collection route was based on the travel time and distance, and CO_2 emissions were also taken into account as well as fuel consumption.

2.7.3 Operational research

There are well-developed algorithms for optimisation of vehicle routing problems (VRP) in different real situations such as goods delivery, spreading of salt on roads and waste collection services (Bodin, 1990, Chang et al., 1997, Xing et al., 2010). These use combinational optimisation which combines the use of mathematics and computation to find the minimum cost to cover all road networks (Corberán and Prins, 2010). Waste collection VRPs can be divided into two types: arc routing problems and node routing problems (Toth and Vigo, 2002). The arc routing problem is commonly applied to solve household waste collection problems, i.e. to search for the shortest path visiting all the collection points by traversing roads at least once in order to reduce the travelling distance (Kim et al., 2006, McLeod and Cherrett, 2008). In particular, this approach is suitable for kerbside collection in densely populated areas (Nuortio et al., 2006).

Nuortio et al. (2006) used a node routing algorithm to optimise the vehicle route and scheduling for waste collection in a thinly populated area. McLeod and Cherrett (2007) used the LogiX commercial node vehicle routing and scheduling software to maximise collection efficiency in the domestic sector by optimising the collection round, distance and time. Kim et al. (2006) developed a capacitated clustering-based algorithm called Vehicle Routing Problem with Time Windows (VRPTW) to address multiple disposal trips and include the drivers' lunch break. Although it did not consider the fuel consumption or GHG emissions, the study pointed out that the balance between vehicle capacity and collection is crucial and a fundamental concept for waste collection transport. Fırıncı et al. (2009) studied the minimisation of travelling distance by combining GIS techniques and a greedy algorithm. Palmer (2007) combined the concepts of transportation science and environment modelling to develop a vehicle routing model which calculates the time, distance and carbon dioxide emissions of vehicle routes with consideration of the traffic environment and other factors reviewed in Section 2.5. Though this optimisation tool has not yet been applied to waste collection, the concepts used in development of this model could potentially be adapted for this purpose. The fact that it is based on routing approaches, however, means it is more precise but less flexible than the approach adopted in the current work, and is thus less suitable as a general scoping and benchmarking tool.

It should also be noted that drivers usually tend to organise their route according to schedules and routines, and also based on practical experience; This may include factors which can easily be included in optimisation such as road gradients; but also those that are more difficult to encode, such as the effect of school runs and holidays on local congestion (Ford, 1999). Therefore, practical implementation of mathematically-based approaches to route optimisation may be difficult to achieve in waste collection activities.

2.7.4 Life Cycle Assessment approach

Several life cycle assessment tools have been used to assess the environmental impacts of waste management system in different countries, including WISARD (WS Atkins, 2000), WRATE

(VALORGAS, 2012a, Tawatsin, 2014, Golder Associates (UK) Ltd, 2014), EASEWASTE (Christensen et al., 2007, Zhao et al., 2009) and WASTED (Diaz and Warith, 2006). Schott (2012) used a life cycle approach to conduct a study of the environmental performance of household food waste management in Sweden. The overall net avoidance of primary energy consumption achieved by using food waste grinders in a kitchen sink and vacuum system was better than collecting the source separated food waste in paper bags with energy gains from anaerobic digestion of the waste. Chen et al. (2008) used the WASTED model to analyse the fuel consumption from collection and transportation, and estimated that 5.96 L per tonne of kitchen waste was used in collection area and transport to the treatment plant. Salhofer et al. (2007) combined GIS and LCA to assess the environmental performance of waste disposal systems. The influence of transport on the recycling of white goods, paper and plastics was studied, but food waste collection was not considered.

2.8 Conclusions

This chapter has reviewed the key waste legislation and policies that are driving the implementation of household source separated food waste collection. To comply with waste regulations, a higher degree of waste fraction separation at source is expected in the near future, and this will lead to a need for effective tools for evaluating, planning and managing household waste collections in terms of their frequency, use of collection vehicles and choice of separated fractions.

Current practices in food waste collection systems are described, and the factors affecting fuel consumption of collection vehicles are reviewed in detail, to provide supporting information for the development of waste collection models and as a basis for understanding the scenario studies carried out in the current work. In order to increase the accuracy of estimates of energy consumption in waste collection, there is a need to find more appropriate fuel consumption values for different types of collection vehicle. Data derived from operational studies interpreted in conjunction with a robust mechanistic collection model could be used in deriving these values.

The energy used in the collection of food waste, recyclables and residual waste in a number of different types of collection systems has been studied by various authors. In comparison, very little research has looked at the energy consumption specifically associated with kerbside collection of household food waste, although this is potentially an important consideration in the overall energy balance for anaerobic digestion of this material. The benefits and disadvantages of integrating source separated food waste collections with collections of other fractions at low and high separation of waste fraction are also unknown. Therefore, the current research will focus on contributing to this important area.

Finally, the different methods and approaches used to assess and minimise the energy use in the waste collection and transportation process have their own advantages and disadvantages. The waste collection model developed by Everett and Shahi (1997) could calculate the route time and number of vehicles, thus allowing the user to design new collection systems and compare collection methods. This model, however, did not address fuel consumption. The models developed by Sonesson (2000) and Di Maria and Micale (2013) could estimate fuel consumption as a function of the type of collection system, but did not consider the constraint of vehicle volume or payload. These models have the advantage that theydo not demand a large amount of site-specific data and are suitable for the use in initial screening studies. On the other hand, as noted by VALORGAS (2013a), LCA tools are generally data-demanding and not easy to apply to real collection activities. It is certainly true that GIS and operational research approaches could minimise fuel consumption, travelling distance and time by route optimisation; however, these techniques require very detailed input data (Sonesson, 2000) and necessarily ignore many factors that are important in real life. Moreover, the users need to be trained before using route optimisation software. Such systems are therefore insufficiently flexible for use in preliminary studies. For these reasons, a mechanistic approach was adopted in developing the waste collection model as it combines the advantages of being a less data-hungry but still robust method for estimating the energy consumption and resource requirements of different options in waste collection, and is ideally suited to scoping and screening studies. This type of model could make a specific contribution to this research area by eliminating the limitations in the Sonesson (2000) and Di Maria and Micale (2013) models and including enhancements such as the use of modified fuel consumption equations. Further details of the modelling approach adopted are given in Chapters 3 and 4.

Chapter 3: METHODOLOGY

This chapter presents the research methodology and its application in the model development, data collection, model validation and analysis of the results. Section 3.1 lists the research questions addressed. In Section 3.2, the general approach to conducting the research is presented. The concept of the waste collection model is briefly described in Section 3.3. The methodology used in data collection for model validation is presented in Section 3.4. The background of the theoretical study is presented in Section 3.5. The technique used for sensitivity analysis and proposed analysis of the data are described in Sections 3.6 and 3.7.

3.1 Introduction

As mentioned in Section 2.7, various different tools have been used to assess the environmental performance of household waste collection systems. Relatively few have been developed, however, to study the performance of the kerbside collection system itself in terms of its energy and resource use. On the other hand, multi-compartment collection vehicles are now widely used in the UK and elsewhere, and these require higher degrees of source separation, leading to increasing complexity in the kerbside household waste collection system. In this research, the performance of household waste collection systems is considered mainly in terms of their energy consumption, as this is potentially an important factor in the overall energy balance from collection and processing of food waste as part of a combined waste management and renewable energy production system. In order to determine this for food waste collections, however, it is necessary to look at collection of the whole household waste stream since an increase in the energy required to collect one fraction may be offset by a reduction in another. While energy is a major focus of interest, the approach adopted also gives information on the use of other resources, such as staff time and the number of vehicles required for alternative systems, and allows estimation of total travelling distance in each case. These outputs can also provide a robust basis for cost assessment for research and planning purposes, although this has not been conducted in the current work.

The research addresses the following questions in a series of studies in chapter 6-9:

- What is the relative fuel use in different food waste collection systems in relation to the collection frequency, type of collection vehicle used and capture rates?
- What kind of food waste collection systems have the best performance in terms of the different output parameters considered?

- Which types of collection vehicle and which arrangements of compartment and waste type are most suitable for use in household waste collections with different degrees of source separation?

3.2 Research design

The research involved the development and application of a theoretical model for energy and resource use in kerbside food waste collection systems, and a series of steps were undertaken to acquire the necessary underpinning information. In order to find the optimal system(s) for source separated food waste collection, a series of reviews were carried out in the previous chapter on food waste collection systems, the composition of kerbside household waste, collection frequency and the type of refuse collection vehicles as a basis for construction of a kerbside collection model. Current food waste collection systems were reviewed in order to categorise them using a logistics approach, while excluding co-mingled green waste and food waste collection. An understanding of kerbside household waste composition, collection frequency and specification of RCVs is important both for development of the collection model and for setting up possible scenarios for household waste collection. Generation rates for source separated food waste are needed for the study of single additional food waste only collection. When considering collection of the whole household waste stream (including food waste, recyclable materials and residual waste), the amount of each waste to be collected is determined based on the composition of kerbside collected household waste and the capture rates for each material. A database of different refuse collection vehicles was compiled and used in setting up scenarios for collection of both co-mingled and source separated dry recyclables in combination with food waste and residual waste collections.

Based on the above data, a deterministic model for waste collection was created. Real life data on waste quantities, fuel consumption and other collection parameters were also collected in order to verify and validate the model. A set of scenarios was then defined, based on a typical 'theoretical' city of 25,000 households. Each scenario was based on a combination of collection frequencies, waste types and collection vehicles. The outputs from scenario modelling were used to assess and select the optimal collection system(s) at different capture rates. Finally, all optimised scenarios were compared in order to determine which scenario(s) consume the least fuel and to identify their other requirements in terms of distance, time and vehicle numbers.

An outline of the research methodology is shown in Figure 3.1. The green boxes are the review work presented in Chapter 2. The area within the red dotted line concerns the formulation of the kerbside collection model. The model was validated prior to use in the studies of the energy consumption of each scenario, as shown in the orange boxes. The blue boxes with shadow are the outputs used to select the optimal collection system(s) considering the results for all scenarios.

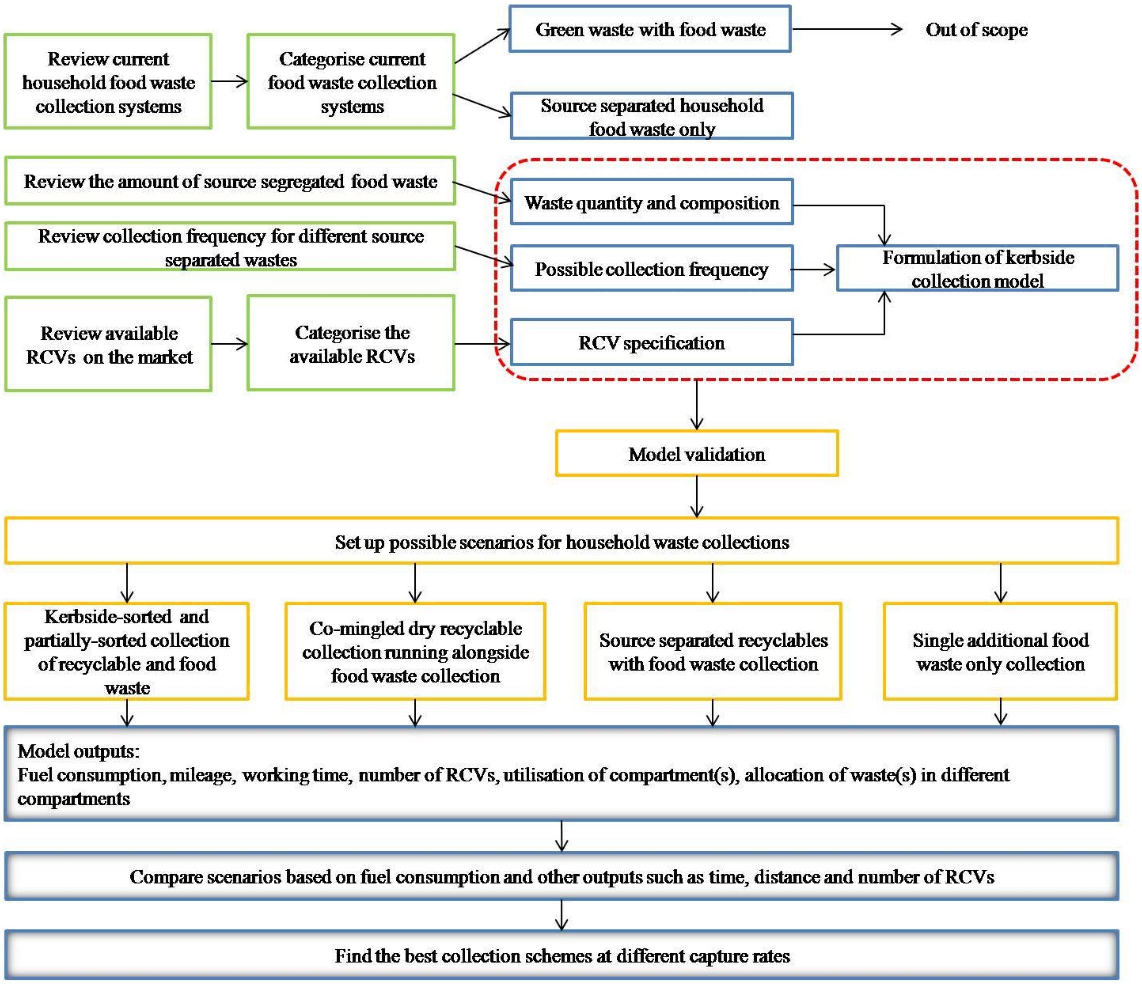


Figure 3.1 Outline of the research methodology

3.3 Design of waste collection model

As mentioned in Chapter 2, several waste collection models have been constructed by other researchers in order to study garden waste collection or for general use. These models, however, have limitations when multi-compartment collection vehicles are involved. To address these, in the first stage of the model development a kerbside waste collection model was set up based on Everett's and Sonesson's models (Everett and Shahi, 1997, Sonesson, 2000) with some modifications, and was implemented in Microsoft® Excel. The upgraded model took both the service time and the volume or load capacity of a collection vehicle into consideration. In the final stage of the work, the Monte Carlo simulation program @Risk® was integrated with the spreadsheet model for scenario analysis. Full details of the formulation of the model are presented in Chapter 4.

3.4 Model validation

Before the waste collection model could be used as an assessment tool, verification and validation needed to be carried out. Model validation is a technique used to test the validity of a model by comparing the system output and model output when the model inputs are known (Maria, 1997). This section describes the criteria used in selection of sites for the collection of model validation data, and the methods and equipment used for data collection and analysis.

3.4.1 Site selection

Four types of collection scheme were modelled during the research. Type I uses a single-compartment vehicle for the kerbside collection of source separated food waste only. Type II and Type III provide kerbside household food waste collection in two-compartment and multi-compartmentalised vehicles respectively. Finally, Type IV uses a centralised collection system to collect food waste from blocks of flats and multi-storey buildings.

In order to validate the waste collection model, it was necessary to gather field data on at least one example of each type of scheme. Data collection is time and resource-consuming, however, so for practical reasons the number of sites that could be examined in detail was limited. Several criteria were therefore set in order to pick the right sites for the field studies. These included whether the collection was of source segregated food waste only: in other words, if food waste is collected with garden waste, the site was unsuitable for this study and was rejected. Another consideration was the arrangement of the food waste collection rounds: if food waste was collected from houses and blocks of flats in the same collection round, the site was also eliminated from the study. Possible sites were then further categorised according to the type of collection vehicle used. The site selection process is illustrated in the flow diagram in Figure 3.2.

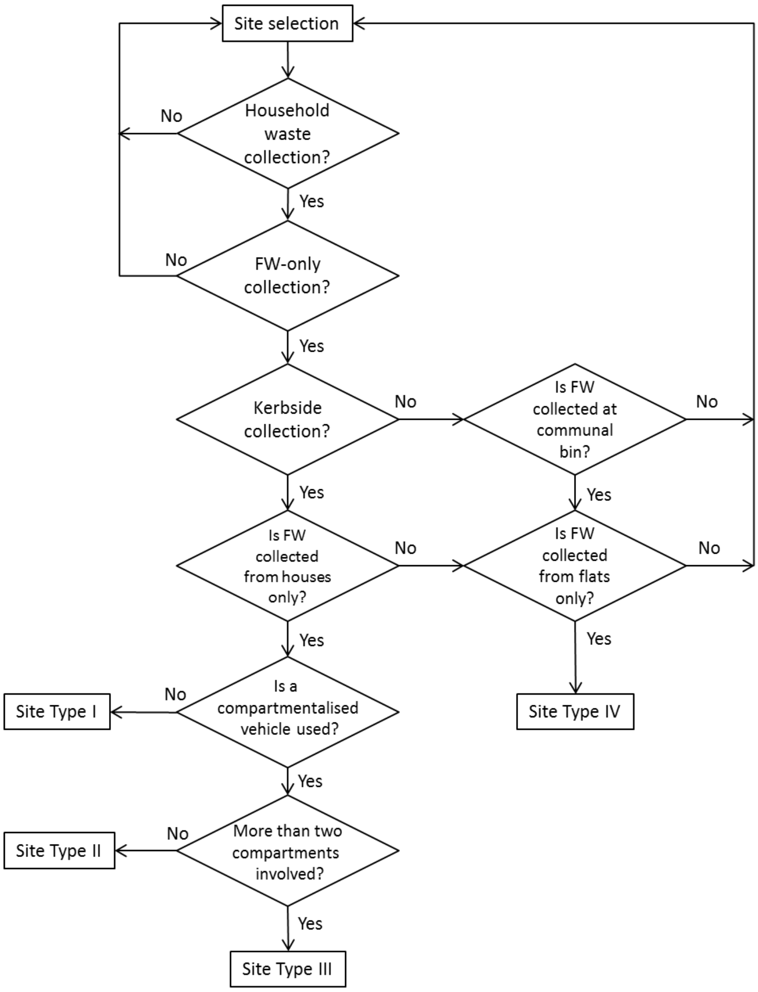


Figure 3.2 Process flow diagram for the field study site selection

Based on these selection criteria, and on the accessibility of data and advice from the waste and recycling collection teams, collection schemes in six local authorities in England were selected for site studies to obtain validation data for the waste collection model. The local authorities participating in the studies and their respective site types are listed in Table 3.1 and shown in Figure 3.3. Apart from the six study sites, preliminary data collection was also carried out for Tower Hamlets, but the collection scheme was found to be unsuitable for the current study as garden waste and kitchen waste are co-collected by single-compartment vehicles; however, some of the data obtained was used to supply missing values in the selected sites.

Table 3.1 Participating local authorities and classification of study sites

Participating Council	**Type of field study site**
Flintshire County Council	I
Broadland District Council	I
London Borough of Lambeth	I
London Borough of Bromley	II
The Royal Borough of Kingston upon Thames	III
London Borough of Hackney	IV

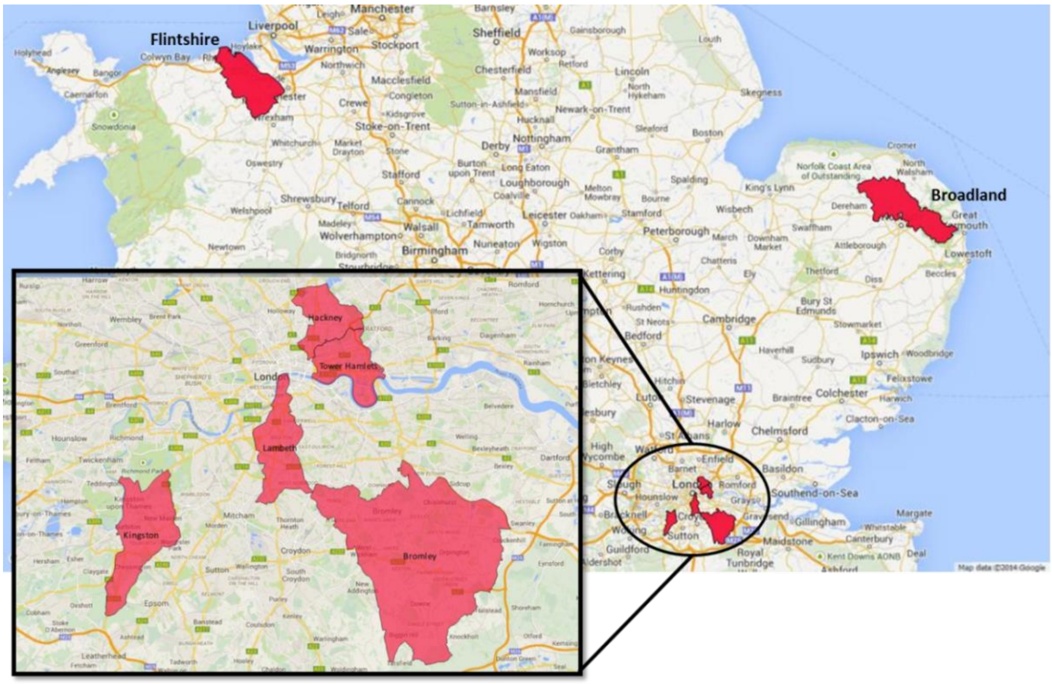


Figure 3.3 Location of study sites (Quantum GIS, 2014)

3.4.2 Field data collection and analysis

At the time of writing, some local authorities still do their own collection, but many contract this service out to a waste management contractor (WMC). This means data is held by two parties: local authorities and contractors, and the need for consultation and approval can add considerably to the time required for the data collection process. In this research, the original selection of sites was based on data provided by Veolia Environmental Service UK Ltd (Veolia) to the FP7 VALORGAS project on food waste collection services operated by the company; as it was necessary to have at least one example of each scheme type, however, and as Veolia did not operate any Type IV schemes, an example run by another service provider/local authority was identified. A Type I scheme operated by Flintshire was also included.

Validation of the kerbside collection model required two types of information, classified as general information on the collection scheme and specific characteristics of the collection round. In general these data were provided by the local authorities and by Veolia, respectively. Veolia provided the operational information such as tonnages of waste collected and number of households in the collection round, while parameters such as speeds and distance between households were measured on site by the researcher. Methods used for the data collection are explained in Table 3.2.

Table 3.2 Methods used for gathering different type of data

Parameters	Description of method	Data sources[b]
Number of participating households[a]	Taken from local authority's database.	LA/WMC
Number of households served per round	Recorded on the collection round sheet.	WMC
Number of collectors	By observing the number of staff involved in picking up household waste. Decimal fractions are accepted as driver may not involve in picking up bins all the time.	MOS
Set-out rate[a]	In some cases local Recycling Officers monitor the percentage of households setting out the food waste container over a period of time on selected collection rounds. If this data was not available, values from historical records or published in the literature were used.	LA/Lit
Tonnage of waste collected per vehicle	The weight of the collection vehicle before and after tipping the waste was measured by weighbridge at the transfer station or treatment plant. The difference between two readings is the net tonnage of waste collected.	WMC
Distance travelled	Initial and final readings taken from the odometer, and calculation of the difference.	MOS
Fuel use per round	Initial reading recorded after the fuel tank was filled up prior to leaving the depot. Final reading taken after the tank was filled up again after returned to depot when job is done. The difference in initial and final reading is the fuel used per round.	MOS, WMC
Speed	Taken from the Global Positioning System (GPS) data logger.	MOS, WMC
Working hours[a]	Taken from the GPS data logger.	MOS
Pick-up time for bin[a]	Taken by digital stopwatch, based on the time taken for the collector to leave the cab, walk to the house, pick up the bin, empty and return it to the original location and go back to the cab.	MOS
Time taken for sorting the mixed recyclables	Digital stopwatch used to measure the time taken for the collector to sort the recyclables and empty the bin.	MOS
Specification of collection vehicle[a]	Gross weight, payload and volume capacity of the collection vehicle provided by the waste management contractor. In stillage vehicles the dimensions of compartments were measured using a steel tape in order to determine the sizes.	WMC, MOS

[a] Input of the waste collection model

[b] LA=local authority, WMC=waste management contractor, MOS=measured on site and Lit = literature study carried out by researcher

In order to determine the vehicle speeds and the average time taken and distance per stop, GPS data loggers (Qstarz BT-Q1000XT and GlobalSat DG-100) were placed on the collection vehicle to log the longitude, latitude, elevation, travelling speed and the time of the reading. The data were sampled every second from the time the collection vehicle left the depot until it returned. Qstarz BT-Q1000XT can also record the position of the collection bins; all of this information was used to separate the speeds in the collection and transportation phases. Figure 3.4 shows the GPS data loggers used in the study: the loggers were placed near the windscreen to ensure good reception of satellite data.

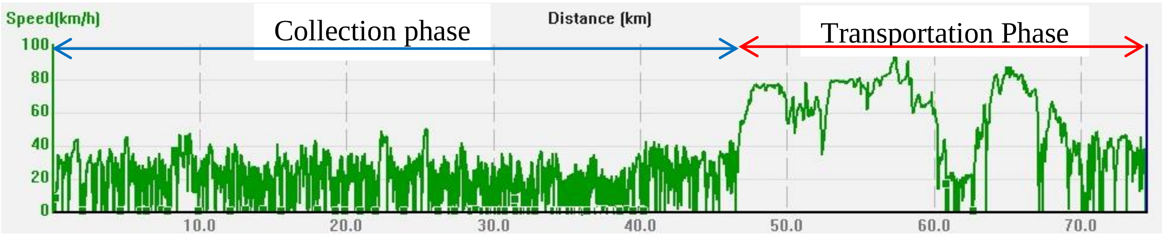
(a)

(b)

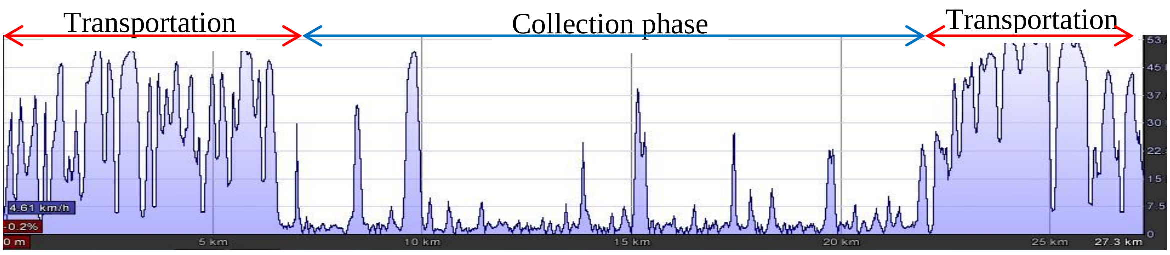
Figure 3.4 GPS data loggers used in tracking the data (a) Qstarz BT-Q1000XT and (b) GlobalSat DG-100

After the tracking, GPS data were imported and analysed using Google Earth or commercial software including Racelogic Performance Box Tools, Data logger PC Utility and QTravel to show the speed profile of the collection vehicle. Speed was plotted as a function of time and of distance, in order to find the speed in the collection area and in transportation, as well as the distance between properties.

The collection and transportation phases were distinguished from the speed profile and stopping pattern. Examples of speed profiles tracked in two different types of study site are shown in Figure 3.5 to illustrate the collection and transportation phases. QTravel software was used to show the speed profile of the collection round in Hackney (Site Type IV) in Figure 3.5a. Figure 3.5b shows the results for Bromley (Site Type II) using Google Earth to display the speed profile. The two phases were distinguished by visual inspection of the graphs: continuous high peaks usually represent the transportation phase, as the vehicle is driving at high speed on main roads; while the collection phase involves continuous low peaks with a stopping pattern. Some high peaks occasionally appear in the collection phase as the vehicle travels from one residential area to another one. In order to calculate the speeds and distance between properties precisely, various techniques were applied during the data collection. Details of these and other methods applied for analysing the collected data are presented in Table 3.3.



(a)



(b)

Figure 3.5 Examples of the speed profile of the collection route logged. (a) In Hackney. (b) In Bromley.

Table 3.3 Methods used for data analysis

Parameters	**Description of method**
Household waste generation rate[a]	Divide the tonnage of waste collected per vehicle by the number of set-out households served on that particular collection round. When the set-out rate is not available from council, the literature data (e.g. past performance audit report) was used to complete the calculation.
Speed in collection area[a]	Record the time of arrival at the first collection point and the time of leaving the last collection point. The software automatically calculates the speed in that period of time.
Speed/time/ distance in transportation phase[a]	Record the time of leaving depot, the time of arrival at unloading site and depot. The software does the calculation automatically when that period of time is highlighted in the speed profile.
Distance between properties[a]	Calculated by dividing the total distance for collection by the number of households served. The total distance in the collection area could be obtained from the software.
Time at unloading site[a]	Record the arrival and departure time at unloading site, the difference is the net time spent at unloading site.
Time taken for sorting each recyclable[a]	Record the time taken for sorting mixed recyclable and the number of types of recyclables placed in the container. Resulted obtained by dividing time taken for sorting by number of types of recyclables.

[a] Input of the waste collection model

3.5 Modelling kerbside household waste collection

3.5.1 Background to the theoretical study

The scenario studies in this research were based on a hypothetical group of 25,000 households, corresponding to a typical medium-sized town in Europe (Baumgart et al., 2004). On average, each household was assumed to generate 788.5 kg year^{-1}of kerbside-collected waste, equivalent to 2.16 kg household^{-1} day^{-1} (Office for National Statistics, 2011b, Defra, 2012a). The quantity of food waste, recyclables and residual waste collected was based on the percentage composition of kerbside-collected household waste, the capture rate and the set out rate for each waste type. Capture rate can be defined as the amount of waste presented for separate collection as a proportion of total household waste put out at the kerbside (WRAP, 2009a). The set out rate simply represents the proportion of households participating in the scheme. Specific details of the values selected in each case are given in the methodology sections in Chapters 7 and 8.

3.5.2 Composition of kerbside collected household waste

The composition of the household waste was taken from the England and Wales municipal waste composition report (Defra, 2012a), which is based on a detailed compositional survey of household residual and recyclable waste at the kerbside, at household waste recycling centres (HWRC) and in street bins. Kerbside household waste is classified into more than ten categories, which include: Paper and card, Food waste, Garden & other organic waste, Plastics, Glass, Metals, Wood, Textiles, and Waste Electrical and Electronic Equipment (WEEE). The composition of household waste used in this research was re-calculated from the Defra report (2012) based on kerbside household waste only (i.e. household waste collected via bring systems was excluded). The classification and composition of household waste used is shown in Table 3.4.

Table 3.4 Composition of kerbside household waste used in modelling (Adapted from Defra, 2012)

Composition	Proportion in waste % weight
Food waste	21.70
Garden Waste	15.45
Other organic	3.23
Paper	17.25
Card	4.90
Glass	7.13
Metals	3.17
Plastics	11.43
Textiles	2.69
Wood	0.83
WEEE	0.82
Hazardous	0.51
Sanitary	4.27
Furniture	0.09
Mattresses	0
Misc combustible	1.39
Misc non-combustible	1.72
Soil	0.51
Other waste	1.51
Fines	1.42

3.5.3 Setting up scenarios

Possible scenarios were developed from the combination of sorting categories, type of refuse collection vehicles and collection frequency. In the first stage of the scenario study, the waste collection model was applied to investigate the energy consumption of a single additional weekly collection of source separated food waste with weekly and fortnightly collections of other wastes. As weekly food waste collection is preferred in the UK, fortnightly food waste collection was not considered when setting up these scenarios. The scenarios considered are shown in Table 3.5, arranged in order of the degree of segregation of the household waste.

Table 3.5 Possible household waste collection scenarios

Case	Type	Primary sorting	Secondary sorting
0	Single additional	Food Waste	--
1	Co-mingled	Recyclables	Mixed plastic
			Paper
			Cans
			Glass
		Residual waste	--
		Food waste	--
2	Partially source segregated	Recyclables	Mixed plastic
			Cans
		Glass	--
		Mixed paper	--
		Residual waste	--
		Food waste	--
3	Source segregated	Mixed plastic	--
		Cans	--
		Glass	--
		Mixed paper	--
		Residual waste	--
		Food waste	--

Case 0 illustrates the additional kerbside collection of household food waste added to any existing household waste collection. All recyclables are co-mingled in Case 1, while all recyclables are source separated in Case 3. This set-up allows consideration of the effect of the degree of separated collection on fuel consumption. In this research, the collection of Wood, Textiles, WEEE, and Garden & other organic waste was excluded as it was assumed these materials are collected in bring systems or by other dedicated services, or are transferred to a household waste recycling centre.

The types of collection vehicles used in modelling are listed in Table 3.6. The selection of collection vehicle was made according to the waste type, degree of separation at source and the characteristics of the vehicle. For example, a single-compartment collection vehicle is suitable for separate collection of all waste types. In practice, however, a stillage collection vehicle will not be used to collect residual waste with other source separated materials.

Table 3.6 Types of collection vehicles used in scenarios

Type of collection vehicle	Code	Description
Single compartment	3.5t Single	FARID Mini-micro
	7.5t Single	FARID MicroL
	12t Single	FARID PN10
	15 Single	FARID PN13
	18t Single	FARID PN15
	26t Single	WRATE 6x4 RCV Fleet
Two compartments *(Pod + rear loader)*	Duo1	Phoenix 2 Duo - 12W + Combi7
	Duo2	Phoenix 2 Duo - 12W + Combi9
	Duo3	Phoenix 2 Duo - 15W + Combi9
Two compartments *(Split rear loader)*	Twin1	Phoenix TwinPack 50/50
	Twin2	Phoenix TwinPack15 70/30
	Twin3	Phoenix TwinPack20 70/30
Stillage	MKS1	Mini Kerbsider Stillage DAF FA LF45
	CWS1	CWS 410 series DAF FA LF 45
	KS2	Kingston stillage vehicle
	MKS4	Mini Kerbsider Stillage Iveco ML130E18

The collection frequency was selected from weekly, fortnightly and alternate weekly collection. There is no difference between fortnightly and AWC if a single-compartment collection vehicle is used for collection, as the waste is picked up once every fortnight. When considering co-collection using a compartmentalised vehicle, AWC will affect the collection cycle, waste quantity and compartment allocation. The complexity of the collection system increases and more matrix tables are required for full development of the possible scenarios. Based on the waste type to be collected, collection frequency and type of collection vehicle used, the required scenarios can then be set up for the study. Detailed descriptions of the scenarios used are given in the methodology sections in Chapters 6, 7, 8 and 9.

3.6 Sensitivity analysis

Sensitivity analysis was carried out to determine the scale of changes in model output with variations in the input data (Palisade Corporation, 2012a). Some input values for the model, such as the pick-up time for food waste containers and speeds in collection and transportation, are uncertain; while the density of residual waste is one of the uncertainties in modelling co-collection and kerbside-sorted collection. The uncertainty in the inputs is mainly due to the range of possible parameter values found in the literature, when no suitable specific value can be used as an input to the collection model. Therefore, Monte Carlo simulation was carried out to conduct a sensitivity analysis. In this research, the commercial software @Risk® (Palisade Corporation, 2012b) was chosen to determine the regression coefficient value range and the minimum, mean and maximum values. The regression coefficient is automatically generated in the form of Tornado graphs, and the larger the coefficient, the greater influence on the specific input on the output (Palisade Corporation, 2014). The mean values for fuel consumption, working time, travelled distance and other output parameters was used to report on and compare scenarios in each case.

To start with, the probability distributions of each uncertain input are defined according to a range of possible values found in the literature and on understanding of the uncertain input. Different sets of random numbers based on the probability function are then automatically and repeatedly selected by the software to run the model. Finally, the simulation results are used for data analysis and reporting. In this research, uniform and triangular probability distributions were commonly used (Palisade Corporation, 2012b):

- Uniform – All values have an equal probability of occurring. This distribution requires the least information to define it: usually only the minimum and maximum value of variables is required.

- Triangular – Compared to the uniform probability distribution, more understanding of the variables is required. The minimum, most likely, and maximum values must be defined and a higher probability of occurrence is expected around the most likely value.

Specific details of the selection of the probability distributions selected for each uncertain input are given in the detailed methodology sections in Chapter 6-8.

3.7 Data analysis

As mentioned in Section 3.6, the mean value of the model outputs was used to report on and compare scenarios. The outputs of the model include:

- Total energy consumption
- Energy consumption per tonnage of waste collected
- Energy consumption ratio of transport and collection
- Number of rounds per collection
- Number of refuse collection vehicles
- Total collection distance
- Percentage utilisation of compartments in volume
- Percentage utilisation of vehicle in load
- Time efficiency (counted as round)
- Total time spent per collection

This research mainly focused on the total energy consumption and the energy consumption per tonne of waste collected, but the remaining outputs were also used in analysis and interpretation of the findings. For example, the time taken for the whole collection (related to staff time) and the fuel consumption could be considered as proxies for the running cost, while the number and type of vehicle required could be considered as a basis for the capital cost. All outputs from different scenarios are reported in Chapters 6-8. The best optimised scenarios in each case were then taken forward to Chapter 9 for a comparative study.

Chapter 4: WASTE COLLECTION MODEL

The model presented in this chapter was constructed in order to provide an estimate of the energy consumption in the collection and transportation phases of kerbside collection. Section 4.1 describes the conceptual model for kerbside collection of household waste. Section 4.2 presents the equations used to formulate the model. Section 4.3 describes the assumptions made in modelling and a conclusion is presented in Section 4.4.

4.1 Description of conceptual kerbside collection model

Waste management involves a series of processes that start with collection, followed by transportation, sorting, treatment and final use or disposal. This research focused specifically on the energy and resources consumed in the collection and transportation process.

Districting is a commonly-used technique in the implementation of collection schemes for large areas. For example, a city of a certain number of households is usually divided into districts according to the number of working days per week. Each district is allocated a similar number of collection rounds, which will depend on the RCV capacity and working hours. Based on these two factors, the size of the collection round can be estimated. One collection round is defined as the whole activity including travel from the depot to the collection area, collection and unloading of the waste, and travel back to the depot by the RCV. For example, if it is assumed there are 4 collection days in a week (i.e. the city could be divided into 4 districts), and that 4 collection rounds are assigned to each district, a total of 16 routes is required to complete the whole collection for that city. This concept is illustrated in Figure 4.1.

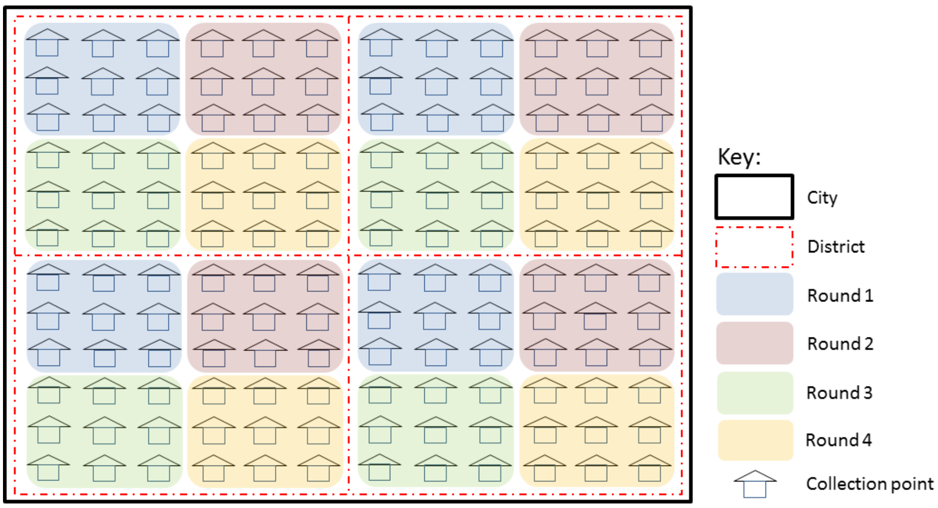


Figure 4.1 Illustration of terms for a complete collection in a city

Using one collection round as a unit, a conceptual kerbside collection model was built up as presented in Figure 4.2. Typical collection activity begins at the depot and includes travel to the designated collection area. The RCV collects the set-out waste from every collection point within the collection area: in kerbside collection schemes these collection points often correspond to individual households, but they could also represent groups of properties etc. When the RCV reaches its maximum capacity or the maximum service time is reached, it travels to the unloading site. This may be a transfer station where the collected waste is bulked and sent for treatment or disposal (Figure 4.2a); or if the collection area is close to the treatment plant or disposal point, the RCV may transport waste there directly (Figure 4.2b). An RCV may become fully loaded before finishing the collection round for that day: in this case, the RCV travels to the unloading site (transfer station, treatment plant or disposal point) to deposit material and then goes back and continues to collect until the round is completed (Figure 4.2c and 4.2d). Once the waste has all been collected and unloaded, the RCV returns to the depot. These options are shown schematically in Figure 4.2. Blue and red arrows indicate the direction of travel of RCV: blue for transport, red for collection. Green arrows indicate the transport of bulked waste by lorries (not included within the system boundary). The length of the lines shown is not proportional to the distance between collection points, unloading site, treatment or disposal point.

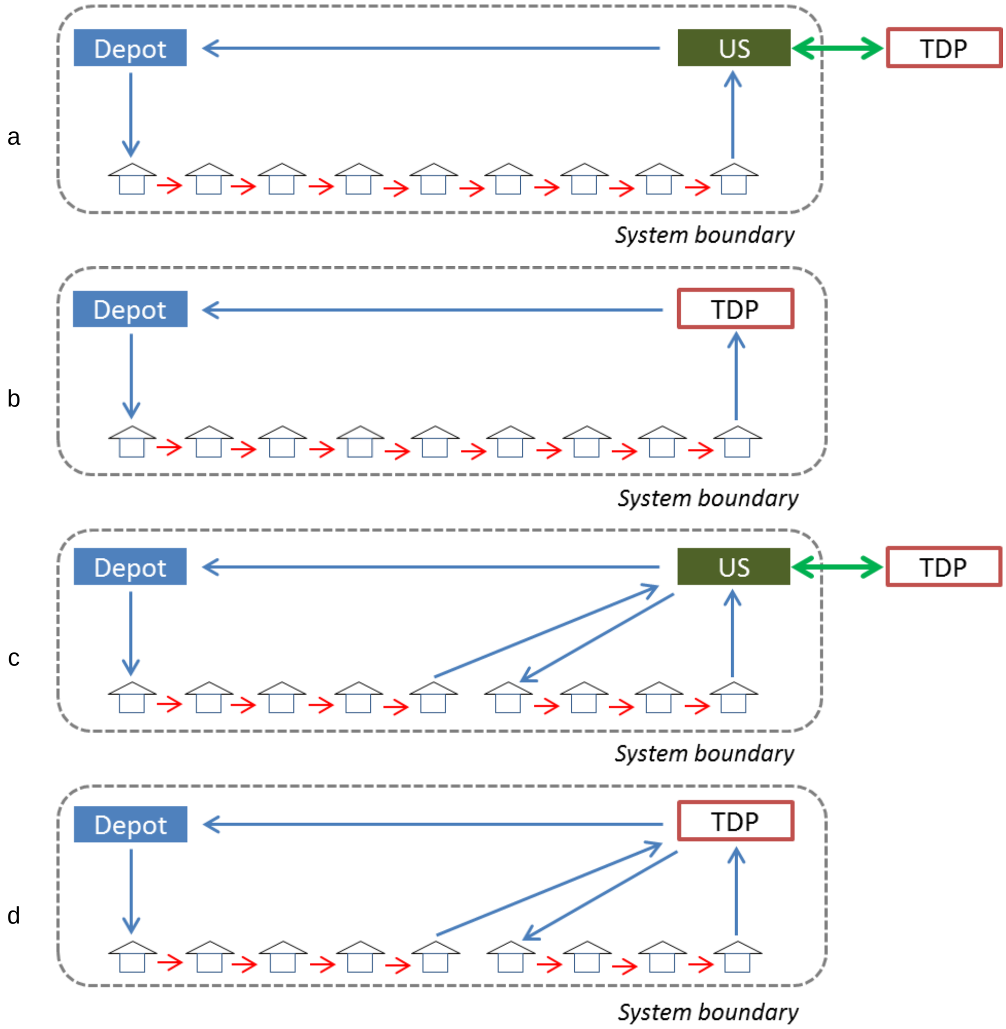


Figure 4.2 Schematic showing different options for a collection round. US = unloading site or bulking point, TDP = Treatment or disposal point (e.g. AD or composting plant, materials recovery facility or processing plant, incinerator or landfill site)

4.2 Formulation of kerbside household waste collection

A deterministic model was constructed based on the conceptual model described in section 4.1. The model consists of two main parts: determination of collection rounds, and calculation of energy consumption and other parameters. As the current study concerns source segregated collection of domestic waste, the collection unit is based on households. Input to the model includes: number of households setting out waste, amount and type of waste collected per household, number of collectors, collection frequency, productive and non-productive working time, time spent per pick-up, speed in collection and transportation stages, distance between collection points and to treatment facilities. The outputs are fuel consumption per collection, total mileage, utilisation of RCV compartments in terms of volume and load, total number of collection routes, total time taken, and the number of RCVs required. The components of the model are explained in more detail below and presented in a flow chart in Figure 4.3.

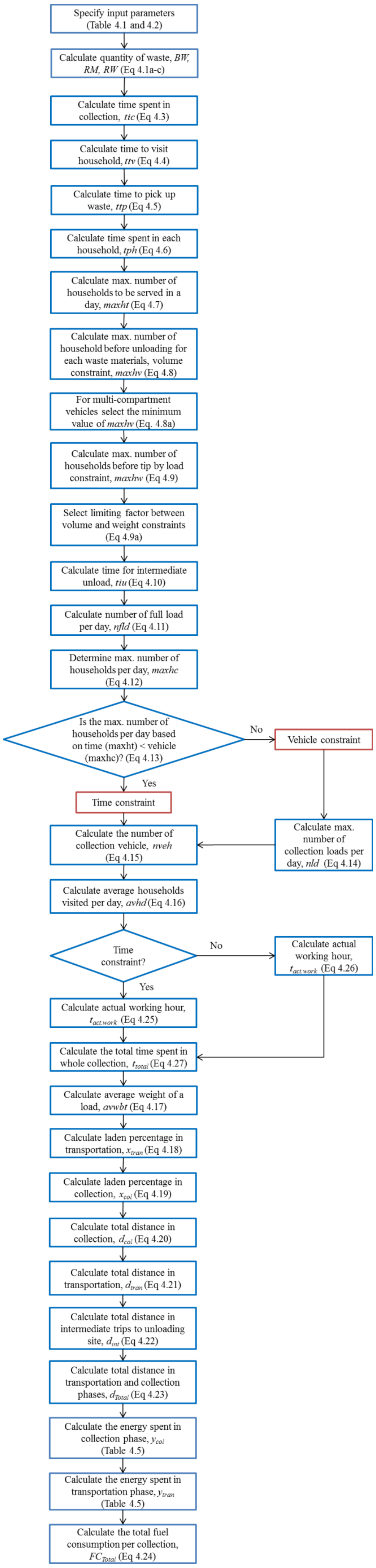


Figure 4.3 Flow chart of the construction of kerbside collection model

4.2.1 Quantity of waste, waste allocation and selection of RCV

4.2.1.1 Quantity of waste

The quantity of a waste material that is captured for collection depends on the proportion in the household waste stream and the average capture rate for that waste material. Table 4.1 gives an example of typical composition and capture rates. For collection purposes the model assumes that all waste materials are assigned to one of three waste categories: recyclable material, residual waste and biowaste (e.g. food waste, but may also include garden waste and household paper in some types of collection scheme). In this research, biowaste specifically refers to food waste.

Table 4.1 Example of waste characterisation and allocation data

Waste material	Proportion [a] % weight	Capture rate[b] %	Waste category
Food waste	21.70	50	Biowaste
Paper and card	22.15	50	Recyclable
Garden & other organic waste	18.67	50	Not collected
Plastics	11.43	50	Recyclable
Glass	7.13	50	Recyclable
Metals	3.17	50	Recyclable
Wood	0.83	50	Recyclable
Textiles	2.69	50	Residual
WEEE	0.82	50	Residual
Others	11.42	50	Residual

[a] Based on Defra (2012a); [b] Waste presented for separate collection as a proportion of total household waste put out at the kerbside (WRAP, 2009a)

The average amount of biowaste (or recyclable material) captured from a household per day is calculated by multiplying the proportion of each waste material by its capture rate and summing this for all materials identified as biowaste (or recyclable material); then multiplying this by the average household waste generation rate for kerbside collected household waste. The total quantity of biowaste (or recyclable material) to be collected depends on the number of accumulation days between collections and the set-out rate (defined as the proportion of households setting out that waste category out of the total number of households). The number of accumulation days depends on the collection frequency: if waste is collected weekly and fortnightly, for example, the accumulation days are 7 and 14 respectively. The biowaste, recyclable material and residual waste to be collected in each category is calculated from Equation 4.1a, 4.1b and 4.1c respectively. To ensure that the whole waste stream is collected it is assumed that all waste not collected as recyclable material or biowaste goes into the residual collection with an average set-out rate of 100%.

$$BW = \frac{ahwg \times p \times CR \times SOR \times DA}{10000} \quad (4.1a)$$

$$RM_i = \frac{ahwg \times DA \times (p_i \times CR_i \times SOR_i)}{10000} \text{ and } RM = \sum_1^n RM_i \qquad (4.1b)$$

$$RW = (ahwg \times DA \times SOR) - BW - RM \qquad (4.1c)$$

Where:
ahwg = average household waste generation (kg HH^{-1} day^{-1})

BW (or *RM or RW*) = amount of biowaste (or recyclable material or residual waste) to be collected from a household on the collection day (kg HH^{-1})

p = proportion percentage of waste (%)

CR = waste presented for separate collection as a proportion of total household waste put out at the kerbside

SOR = number of households setting out this waste category as a percentage of total no of households

DA= accumulation day (days)

i = type of recyclable material collected separately in the same vehicle

n = number of recyclable materials collected separately in the same vehicle

The total quantity of kerbside collected biowaste (or recyclable material or residual waste) to be collected is calculated by multiplying the number of households to be served in a collection and the amount of biowaste (or recyclable material or residual waste) collected from a household on the collection day, as shown in Equation 4.2. The following example is for the calculation of total amount of biowaste collected; the same equation is used for recyclable material and residual waste.

$$TBW = \frac{BW \times noh}{1000} \qquad (4.2)$$

Where:
TBW (or *TRM or TRW*) = total amount of biowaste (or recyclable material or residual waste) collected in a whole collection (tonnes $collection^{-1}$)

noh = number of households to be served in a collection (HH $collection^{-1}$)

4.2.1.2 Selection of RCV

The type of RCV used is specified by the user, according to the parameters in Table 4.2.

Table 4.2 RCV characteristics

Term	**Description**
GVW:	Gross weight of the collection vehicle (tonnes)
Payload:	Maximum load capacity of vehicle (tonnes)
Number of compartments:	Total number of vehicle compartments (no.)
Total volume:	Maximum volume capacity of vehicle (m^3)
Compartment:	Volume capacity of each compartment (m^3)

4.2.2 Determination of collection rounds

4.2.2.1 Determination of round size by time constraint

The time available for waste collection on a collection round is equal to the working hours minus the time spent in transportation, unloading and non-productive time (Equation 4.3). Non-productive time includes breaks, delays due to traffic congestion, pick-up of collection crews and RCV fuelling.

$$tic = t_{work} - \frac{t_{d2c} + t_{c2us} + t_{us2d} + t_{unload} + t_{break} + t_{traffic} + t_{crew} + t_{fuel}}{60} \qquad (4.3)$$

Where:
tic = time in collection (hour)

t_{work} = working hours per round (hour $round^{-1}$)

t_{d2c} = travel time from depot to collection area (mins $round^{-1}$)(see [1] in Figure 4.4)

t_{c2us} = travel time from collection area to unloading site (mins $round^{-1}$) (see [4] in Figure 4.4)

t_{us2d} = travel time from unloading site to depot (mins $round^{-1}$) (see [5] in Figure 4.4)

t_{unload} = time spent in unloading (mins $round^{-1}$)

t_{break} = time spent on break (mins $round^{-1}$)

$t_{traffic}$ = time spent in traffic congestion (mins $round^{-1}$)

t_{crew} = time spent in picking up the crew (mins $round^{-1}$)

t_{fuel} = time spent in fuelling RCV (mins $round^{-1}$)

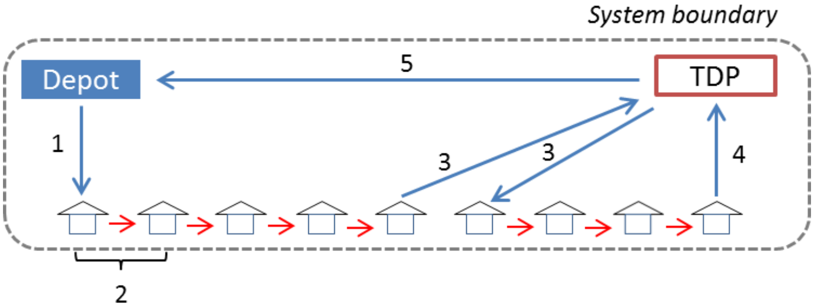


Figure 4.4 Schematic showing segments of travel: [1] = depot to collection area; [2] = distance between collection points; [3] = distance between collection area and unloading site for intermediate unloading; [4] = collection area to unloading site; [5] = unloading site to depot

The round size, in terms of the maximum number of households that can be served based on service time, can be calculated from the time in the collection area and the average time required per household. The average time per household depends on the travel time required to visit a household, which can be estimated from the average distance between households and the speed of travel in the collection area (Equation 4.4); and on the time spent in picking up waste.

$$ttv = \frac{3600 \times d_{HH}}{S_{col}} \qquad (4.4)$$

Where:
ttv= travel time to visit a household (s)

d_{HH}= an 'average' or representative distance between households (km) ([2] in Figure 4.4)

S_{col} = speed in collection (km hour^{-1})

Equation 4.5 gives the time spent in picking up waste. This is calculated from the time required to pick up a bin plus, in the case of mixed recyclables sorted at the kerbside by the collection crew, the additional time required to sort the bin contents into one or more additional compartments.

$$ttp = t_{bin} + nsort \times t_{sort} \qquad (4.5)$$

Where:
ttp = time to pick up a waste(s)

t_{bin} = time to collect bin (s)

nsort = number of extra compartments used in kerbside sorting of mixed recyclables (no.)

t_{sort} = sort time for mixed recyclables (s)

Values reported in the literature for the time required to pick up different types of bin are shown in Table 4.3 and can be used to estimate *ttp* and t_{bin} if real data are not available.

Table 4.3 Pick-up time for different bin types (t_{bin})

	Value	Unit	Reference
Food waste caddy	21.58	sec	WRAP (2008f)
Kerbside collection with 1 container	25	sec	Zamorano et al. (2009)
Kerbside collection with 1-2 containers	33	sec	Tchobanoglous (2002)
Kerbside collection with 3-4 containers	45	sec	Tchobanoglous (2002)

If two or more waste types are collected concurrently from a household, some saving in time generally occurs, e.g. due to a reduction in walking distance or to the crew member bringing several bins to the RCV at the same time. This was modelled using a concurrent collection factor equal to the number of bins emptied at one time. For example, if food waste and mixed recyclables are collected at the same time the concurrent collection factor is 2; the time to pick up the two bins is then estimated by multiplying the time for a single bin by the square root of the concurrent collection factor. Where the pick-up time for the two bins is different, the longer of the times is used. The average time per household for the whole collection area can then be calculated from the time to visit, plus the time to pick up waste multiplied by the set-out rate (to take into account the proportion of households setting out that material) and divided by the number of collectors in the crew (Equation 4.6).

$$tph = ttv + \frac{\text{SOR}}{100}\frac{ttp \times \sqrt{ccf}}{ncol} \tag{4.6}$$

Where:
tph = 'average' time per household (s)

ccf = concurrent collection factor (no.)

ncol = number of collectors in crew (no.)

The maximum size of a round on a time basis is calculated using Equation 4.7, with the result rounded down to the nearest integer.

$$maxht = \frac{3600 \times tic}{tph} \tag{4.7}$$

Where:
maxht = maximum n number of households to be served based on service time (HH round^{-1})

4.2.2.2 Determination of round size by vehicle constraint

The maximum number of households that can be served on one round is also constrained by the volume and weight capacity of the RCV. The calculation of round size based on vehicle constraints must be carried out for each combination of waste type and compartment to identify the limiting condition. The maximum number of households that can be served based on the volume of the RCV compartment is calculated from Equation 4.8. Table 4.4 gives examples of the bulk density for different waste types in different conditions, which can be used if site specific data are not available.

$$maxhv_i = \frac{CompV \times D_{Wi}}{WT_i} \qquad (4.8)$$

Where:

$maxhv_i$ = maximum number of households before unloading (volume basis) for waste type i (HH $round^{-1}$)

$CompV$= volume of compartment in RCV (m^3)

D_{Wi} = density of waste type i (kg m^{-3}) (See Table 4.4)

WTi = waste type i, corresponding to *BW*, *RM* and *RW* for single and twin compartment vehicles and *RMi* for multi-compartment vehicles.

Equation 4.8a is then used to calculate the limiting value for the maximum number of households based on compartment size:

$$maxhv = minimumof(maxhv_1\, , maxhv_2, \ldots .\, maxhv_n) \qquad (4.8a)$$

Where:

$maxhv$ = maximum number of households before unloading (volume basis) (HH $round^{-1}$)

Table 4.4 Bulk density of different combinations of waste type (WRAP, 2008f, WRAP, 2009a, WRAP, 2010)

Waste type	**Type of vehicle**	**Value** kg m^{-3}
Food waste	Traditional vehicle	470
Newspaper and magazine	Kerbsider (no compaction)	305
Newspaper and magazine	Caged stillage (no compaction)	279
Mixed paper and card	Rear End Loader (compacted)	431
Mixed paper, card and drink cartons	Rear End Loader (compacted)	366
Mixed glass	Rear End Loader (compacted)	265
Mixed glass	Kerbsider (no compaction)	456
Mixed cans	Kerbsider (no compaction)	63
Mixed cans	Caged stillage (no compaction)	56
Plastic bottles	Rear End Loader (compacted)	158
Plastic bottles	Kerbsider (no compaction)	16
Plastic bottles	Kerbsider (MVR compaction)	44
Plastic bottles	Stillage (builder dump sacks)	26
Mixed plastic (no film)	Rear End Loader (soft pack)	79
Mixed plastic (no film)	Rear End Loader (split back)	106
Mixed plastic (no film)	Kerbsider (MVR compaction)	29
Mixed plastic (no film)	Stillage (builder dump sacks)	25
Mixed plastic (with film)	Rear End Loader (soft pack)	116
Mixed plastic (with film)	Rear End Loader (hard back)	197
Mixed plastic (with film)	Kerbsider (MVR compaction)	47
Mixed plastic (with film)	Stillage (builder dump sacks)	28
Drink cartons	Caged stillage (no compaction)	26
Food waste	Caged stillage (no compaction)	500
Food and garden waste	Rear End Loader	338
Food, garden and card	Rear End Loader	502
Co-mingled: Plastic bottles, paper and cans	Rear End Loader	310
Co-mingled: Plastic bottle and cans	Rear End Loader	184
Co-mingled: Plastic bottles, paper, cans and glass	Rear End Loader	405
Co-mingled: Plastic bottles, cans and glass	Rear End Loader	450
Residual waste	Rear End Loader	348

Equation 4.9 is used to calculate the maximum number of households that can be served on a weight basis.

$$maxhw = \frac{1000 \times RCV_{load}}{(BW+RM+RW)} \quad (4.9)$$

Where:
maxhw = maximum number of households before unloading (weight basis) (HH $round^{-1}$)

RCV_{load} = maximum payload of RCV (tonne)

If a single-compartment collection vehicle is used, two of the three waste types (*BW*, *RM* and *RW* are equal to zero. If more than one compartment is used then the sum of the weights of collected waste must be considered. For example, if a two-compartment collection vehicle is used for the collection of food waste and residual waste, the total amount of waste collected from a household on the collection day is equal to BW plus RW.

Equation 4.9a is then used to identify the limiting factor between volume and weight constraints.

$$maxhu = minimum\ of\ (maxhv, maxhw) \qquad (4.9b)$$

Where:
maxhu = maximum number of households before unloading (volume or weight basis) (HH round^{-1})

If the round size is constrained by RCV capacity (i.e. *maxhu*<*maxht*), there may be time for the RCV to leave the collection area and unload, then return to continue collecting waste (Figure 1c and d). The time required for this additional trip to the unloading point is calculated from Equation 4.10.

$$tiu = 2 \times t_{us} + t_{unload} \qquad (4.10)$$

Where:
tiu = time for intermediate unloading (mins)

t_{us} = travel time to unloading site from part way around the collection (mins round^{-1})(see [3] in Figure 4.4)

t_{unload} = time spent unloading (mins round^{-1})

The number of full loads that can be collected and deposited per day is obtained from Equation 4.11.

$$nfld = \frac{(60 \times tic) + tiu}{tiu + (maxhu \times \frac{tph}{60})} \qquad (4.11)$$

Where:
nfld = number of full loads per day (no.), and is rounded down to the nearest integer.

The time for collection plus additional trips must be less than the total time available for collection, as shown in Equation 4.11a. The factor (*nfld* - 1) appears because the final visit to unload has already been accounted for in calculating *tic* (Equation 4.3).

$$(nfld - 1) * tiu + nfld * maxhu * \frac{tph}{60} < 60 * tic \qquad (4.11a)$$

The round size allowing for intermediate unloading is then determined from Equation 4.12.

$$maxhc = \text{maximum of } (maxhu \times nfld,\ \frac{3600 \times tic - 60 \times nfld \times tiu}{tph}) \qquad (4.12)$$

Where:
maxhc = maximum number of households that can be served per day based on RCV capacity (weight or volume) (HH day^{-1})

4.2.2.3 Selection of round size based on time and capacity constraints

The size of the round is finally determined by comparing the limiting values based on time and capacity constraints, and selecting the minimum of these (Equation 4.13).

$$maxhd = minimum\ of\ (maxht, maxhc) \qquad (4.13)$$

Where:
maxhd = maximum number of households that can be served per day based on the limiting factor (time or RCV capacity) (HH day^{-1})

4.2.2.4 Determination of number of loads deposited per day

If RCV capacity is the limiting factor, it may be possible for a single RCV to drop off more than one load per day: this affects the calculation of the average load. In this case the number of loads per day is calculated from Equation 4.14.

$$nld = if(maxhd = maxhu \times nfld, nfld, nfld + 1) \qquad (4.14)$$

Where:
nld = number of loads per day (load day^{-1})

When service time is the constraint, an RCV completes one round per day and deposits a single load, i.e. $maxhd = maxht$ and *nld* = 1.

4.2.2.5 Determination of number of RCVs

The number of districts for the whole collection area is determined based on the number of working days in one waste collection cycle: for example if waste is collected on every weekday from Monday to Friday, the number of districts will be equal to 5 or 10 for weekly or fortnightly collection respectively. The number of RCVs required for the whole collection is calculated from Equation 4.15.

$$nveh = \frac{noh}{ncd \times maxhd} \qquad (4.15)$$

Where:
nveh = number of RCVs required (no.) and is rounded up to the nearest integer

ncd = number of collection districts (no.)

4.2.2.6 Completion of round calculations

This completes the determination of round size, number of rounds per day, number of loads per day and number of vehicles required based on a single-compartment vehicle or one compartment in a multi-compartment vehicle. In the case of two or multi-compartment vehicles, the calculations are then repeated to find the limiting set of conditions, corresponding to the minimum round size.

In principle there are two possible options for completing the whole collection. In the first, for (*ncd*-1) days the maximum amount of waste is collected, based on the limiting values for *maxhd* and *nveh*; then any remaining waste is collected on the final collection day. This can be referred to as the Flat-out option, as the crews work 'flat out' until the last day then finish once the job is complete. In the second, it is assumed that equal quantities of waste are collected on each working day so that the average number of households served is given by Equation 4.16. This is referred to as the Averaged option. In the current version of the model, the Averaged option is assumed.

$$avhd = \frac{noh}{ncd \times nveh} \qquad (4.16)$$

Where:
avhd = average households visited per day (HH day^{-1}) and is rounded up to the nearest integer.

4.2.3 Determination of energy consumption

Values for RCV fuel consumption reported in the literature range very widely, and the equations presented in the European Environment Agency EMEP Emission Inventory Guidebook (European Environment Agency, 2009b) were therefore used to estimate the fuel consumption. Fuel consumption mainly depends on distance travelled and the average laden percentage of the RCV on a weight basis. These two parameters are calculated as shown below.

4.2.3.1 Laden percentage of RCV

The determination of laden percentage is essential for calculating energy consumption. It is also an important parameter with respect to performance of the collection system, since it reflects both the amount of spare capacity available to deal with day-to-day variations in load, and the degree to which the RCV is correctly sized: a RCV that is much larger than necessary represents a waste of energy and resources.

Equation 4.17 gives the average weight of waste per load: a similar calculation is performed for vehicles carrying other waste types or combinations of waste types (RM and RW).

$$avWT_i = \frac{1000 \times WT_i \times DA \times avhd}{nld} = \frac{TWT_i}{nld} \quad (4.17)$$

Where:
$avWT_i$ = average weight of a load of waste type *i*, corresponding to *BW*, *RM* and *RW*

The laden percentage in the return (i.e. loaded) stage of the transportation phase is given by Equation 4.18. In the collection phase, the RCV load increases gradually after each pick-up of waste from a participating household. The average laden percentage during collection is therefore assumed to be half the load in the return stage of the transportation phase, as shown in Equation 4.19.

$$x_{\text{tran}} = \frac{100 \times (BW + RM + RW)}{RCV_{Load}} \quad (4.18)$$

$$x_{\text{col}} = 0.5 \times x_{\text{tran}} \quad (4.19)$$

Where:
x_{tran} = Laden percentage in return stage of the transportation phase (%)
x_{col} = Laden percentage in collection phase (%)

4.2.3.2 Travelling distances

For each vehicle type the total distance travelled in the collection phase is given by Equation 4.20. The total transportation distance is calculated using Equation 4.21, which includes a component for intermediate unloading when the collection round is constrained by RCV capacity, as shown in Equation 4.22. The total distance for the whole collection in a city is given by Equation 4.23.

$$d_{col} = d_{\text{HH}} \times noh \quad (4.20)$$

$$d_{tran} = 2 \times d_{int} + ncd \times nveh \times (d_{d2c} + d_{c2us} + d_{us2d}) \quad (4.21)$$

$$d_{int} = (nld - 1) \times ncd \times nveh \times d_{us} \quad (4.22)$$

$$d_{total} = d_{col} + d_{\text{tran}} \quad (4.23)$$

Where:
d_{col} = total distance travelled in collection area (km $collection^{-1}$)
d_{tran} = total distance involved in transportation phase (km $collection^{-1}$)
d_{d2c} = distance between depot and collection area (km $collection^{-1}$) ([1] in Figure 4.4)
d_{c2us} = distance between collection area and unloading site (km $collection^{-1}$) ([4] in Figure 4.4)
d_{us2d} = distance between unloading site and depot (km $collection^{-1}$) ([5] in Figure 4.4)
d_{int} = total distance in intermediate trips to unloading site (km $collection^{-1}$)

d_{us} = distance to unloading site from part way around the collection (km collection^{-1}) ([3] in Figure 4.4)

d_{total} = total travelled distance in collection and transportation phases (km collection^{-1})

4.2.3.3 Energy consumption

The equations in the EEA/EMEP Emission Inventory Guidebook (European Environment Agency, 2009b) for calculation of fuel consumption by heavy duty vehicles (HDV) take into consideration gross vehicle weight and engine type, laden percentage and road gradient. A RCV is classified as a rigid vehicle, and the range from ≤ 7.5 tonnes to ≥32 tonnes gross weight is divided into eight categories: ≤ 7.5-tonne, >7.5-12-tonne, >12-14-tonne, >14-20-tonne, >20-26-tonne, >26-28-tonne, >28-32-tonne and >32-tonne.

In this model, there are two patterns of fuel consumption: in transportation and collection. In the transportation phase the fuel consumption equations can be applied directly, as the fuel efficiency in a RCV during transportation is equivalent to that of a HDV. In the collection phase a factor is introduced to account for the extra fuel consumption involved in collection activities due to the 'go and stop' driving pattern and to uplifting of the bins (Nguyen and Wilson, 2010). Until field data could be collected, the calculated fuel consumption in the collection phase was multiplied by a default factor of 1.35, based on Willis (2010).

In order to provide a means of estimating the fuel consumption at different laden percentages for each category of RCV, second order polynomial curves were fitted to the calculated fuel consumption values at 0%, 50% and 100% laden to derive a set of equations for the collection and transportation phases. For this purpose an average road gradient of zero was assumed, as the RCV returns to the same point at the end of the journey, and the assumption of zero gradients is more conservative than assuming equal positive and negative gradients for two halves of the distance (Personal communication, A. C. Lock, 2014). Literature values for the speeds in city, suburb and village during collection and transport are shown in Table 4.5. Table 4.6 shows examples of the derived equations, based on average speeds of 10 and 50 km hour^{-1} in the collection and transportation phases, respectively.

Table 4.5 Speed of collection and transport in densely populated area, city, suburb and village

	Speed (km hour^{-1})		
	Collection	**Transport**	**References**
Densely populated area	9	50	Zamorano et al. (2009)
City	20	40	Sonesson (2000)
Suburb	30	40	Sonesson (2000)
In village	23	50	Angelelli and Speranza (2002)

Table 4.6 Example of equations used to predict fuel consumption based on laden percentage for different RCV categories [a]

RCV	Equation for fuel consumption in $g^{-1}km$
Collection phase	
<=7.5t	$y_{\mathrm{col}} = -0.0014x_{\mathrm{col}}^2 + 0.2809x_{\mathrm{col}} + 218.61$
>7.5-12t	$y_{\mathrm{col}} = 0.00004x_{\mathrm{col}}^2 + 0.494x_{\mathrm{col}} + 366.98$
>12-14t	$y_{\mathrm{col}} = -0.0002x_{\mathrm{col}}^2 + 0.6382x_{\mathrm{col}} + 408.34$
>14-20t	$y_{\mathrm{col}} = -0.0072x_{\mathrm{col}}^2 + 1.1406x_{\mathrm{col}} + 546.09$
>20-26t	$y_{\mathrm{col}} = 0.0006x_{\mathrm{col}}^2 + 1.0279x_{\mathrm{col}} + 614.7$
>26-28t	$y_{\mathrm{col}} = 0.001x_{\mathrm{col}}^2 + 1.0808x_{\mathrm{col}} + 622.99$
>28-32t	$y_{\mathrm{col}} = 0.0013x_{\mathrm{col}}^2 + 1.4886x_{\mathrm{col}} + 635.01$
>32t	$y_{\mathrm{col}} = 0.0018x_{\mathrm{col}}^2 + 1.6085x_{\mathrm{col}} + 676.71$
Transportation phase	
<=7.5t	$y_{\mathrm{tran}} = 0.0001x_{\mathrm{tran}}^2 + 0.1447x_{\mathrm{tran}} + 83.442$
>7.5-12t	$y_{\mathrm{tran}} = 0.00001x_{\mathrm{tran}}^2 + 0.3173x_{\mathrm{tran}} + 118.94$
>12-14t	$y_{\mathrm{tran}} = 0.00007x_{\mathrm{tran}}^2 + 0.3866x_{\mathrm{tran}} + 125.73$
>14-20t	$y_{\mathrm{tran}} = 0.0002x_{\mathrm{tran}}^2 + 0.4533x_{\mathrm{tran}} + 152.59$
>20-26t	$y_{\mathrm{tran}} = 0.0003x_{\mathrm{tran}}^2 + 0.783x_{\mathrm{tran}} + 179.89$
>26-28t	$y_{\mathrm{tran}} = 0.0001x_{\mathrm{tran}}^2 + 0.8606x_{\mathrm{tran}} + 191.09$
>28-32t	$y_{\mathrm{tran}} = 0.0003x_{\mathrm{tran}}^2 + 1.0798x_{\mathrm{tran}} + 214.44$
>32t	$y_{\mathrm{tran}} = 0.00009x_{\mathrm{tran}}^2 + 1.2452x_{\mathrm{tran}} + 204.24$

[a] based on zero average road gradient, and average speeds in collection and transportation phases of 10 and 50 km $hour^{-1}$, respectively

The RCVs were assumed to run on diesel with a density of 834.7 kg m^{-3} (Defra, 2010a). Equation 4.38 is used to calculate the total fuel consumption.

$$FC_{Total} = \frac{y_{tran.0}(d_{d2c} + d_{iu} + d_{us2d}) + y_{tran}(d_{iu} + d_{c2us}) + y_{col}d_{col}}{834.7} \qquad (4.24)$$

Where:

FC_{Total} = total fuel consumption per collection (L $collection^{-1}$)

$y_{tran.0}$ = fuel consumption in transportation phase when the RCV is empty (g km^{-1})

y_{tran}= fuel consumption in transportation phase when the RCV is loaded (g km^{-1})

y_{col}= fuel consumption in collection phase (g km^{-1})

4.2.4 Time efficiency

The amount of time required to carry out the collection is not directly related to fuel consumption in the collection activity. It is potentially a valuable indicator for assessment of the performance of a collection scheme, however, as staff time is a key component in operating costs. The model can be used to estimate the time spent per tonne of waste collected and the total time required for waste collection in a city. The actual time spent in one collection day is calculated using Equation 4.25 or 4.26 depending on whether the collection is limited by time or vehicle capacity.

Time constraint:

$$t_{act.work} = \frac{t_{d2c} + t_{c2us} + t_{unload} + t_{break} + t_{traffic} + t_{crew} + t_{filling} + \frac{tph \times avhd}{60}}{60} \qquad (4.25)$$

Vehicle constraint:

$$t_{act.work} = \frac{t_{d2c} + t_{c2us} + t_{unload} + t_{break} + t_{traffic} + t_{crew} + t_{filling} + \frac{tph \times avhd}{60} + (nld - 1) \times tiu}{60} \qquad (4.26)$$

Where:
$t_{act.work}$ = Actual working hours per round (hour round^{-1})

The total time for the collection from the whole city is given by Equation 4.27.

$$t_{total} = t_{act\ work} \times nveh \times ncd \qquad (4.27)$$

Where:
t_{total} = Total time required for whole collection (hour collection^{-1})

4.3 Model assumptions

In the model, a number of assumptions are made to facilitate the calculation of energy consumption in the collection and transportation phases. These include:

- Collection method: the model assumes that the distance travelled by the RCV in the collection area in a specific round is equal to the number of households in that round multiplied by a representative 'average' distance between them. In reality, RCVs may stop every 4-6 properties and collectors walk to the house and collect waste from both sides at the same time; and the actual distance covered will depend on the road layout, need for U-turns etc.
- The model only considers collection of waste from domestic properties, and ignores commercial ones. In practice, it will be necessary to travel past commercial properties and through areas without households. No specific allowance is made for this 'deadheading' distance (i.e. the distance travelled by the RCV within the collection area but not collecting), and it is assumed to be included within the 'average' value used for distance between properties. The 'average' value therefore does not represent the real physical distance between properties, although it may be related to it and to housing density etc.
- Staff: the number of collection staff required is assumed to be directly proportional to the amount of waste collected. In practice it is also necessary to consider the vehicle cab size (i.e. number of seats available) when deciding the number of collection staff.

- Emptying and idling: the emptying of waste containers into RCVs or slave bins is done manually. The energy consumed in manual unloading is neglected, but the uplifting of a bin or slave bin to RCV is considered: the energy required for operating the hydraulic system is included as an additional fuel consumption factor in the collection stage which can be modified based on availability of data.
- Time: the effects of traffic congestion and queuing time at the unloading site are not explicitly included.
- Fuel consumption: additional fuel consumed in warming up the engine, traffic congestion and stopping at traffic lights is assumed to be included in the overall values used for fuel consumption.

4.4 Conclusion

The kerbside collection model uses a mechanistic approach to estimate the fuel consumption per collection for a given collection area. The purpose of setting up this model was to allow exploration of the effect of collection parameters on the performance of the scheme in terms of energy and other parameters and therefore has the potential to act as a valuable scoping tool for the preliminary design and benchmarking of collection schemes, as well as a tool for research use.

Chapter 5: DATA COLLECTION AND MODEL VALIDATION

In this chapter, the work on data collection in different study sites and on model validation is presented. The selected study sites are described in Selection 5.1, followed by data collection and route analysis in Section 5.2. Section 5.3 lists the methods used to validate the model at different sites. Results of the model validation and discussion on model formulation and validation are presented in Sections 5.4 and 5.5 respectively. Finally, the findings are summarised in Section 5.6.

5.1 Description of the study sites

The six UK sites selected for validation of the model were Flintshire County Council, Broadland District Council, the London Borough of Lambeth, the London Borough of Bromley, the Royal Borough of Kingston upon Thames and the London Borough of Hackney. The collection schemes operating in these local authorities during the study period and the current trends in recycling rates are described in Sections 5.1.1-5.1.6. Details of the schemes are summarised in Table 5.7.

5.1.1 Flintshire County Council (Flintshire)

Flintshire is a county in the north-east of Wales that includes both urban and rural districts. Food waste is collected from 24,148 households every week (Flintshire County Council, 2014). The households are provided with a small kitchen caddy to store the food waste and a larger green lockable bin is placed at the kerbside for collection (Gredmaier, 2011). The recycling rate in Flintshire increased from 43% in 2009/10 to 55% in 2013/14. Recycling rates and the breakdown between dry and organic recycling are shown in Table 5.1.

Table 5.1 Recycling rates and breakdown of dry and organic recycling in Flintshire (Statswales, 2015a, Statswales, 2015b)

	2009/10	2010/11	2011/12	2012/13	2013/14
Overall recycling rate (%)	43	47	48	55	55
Organic recycling rate (%)	14	17	21	22	22
Dry recycling rate (%)	31	29	28	33	33

Flintshire County Council uses five Isuzu Farid RCVs in 20 collection rounds. The vehicles are single-compartment with a gross weight of 7.5-tonne, a payload of 3.2 tonnes and a volumetric capacity of 5 m^3. The vehicles are dispatched from Alltami depot (53°11'18.3"N, 3°05'16.8"W) to the collection area. Some of the collection rounds in rural areas serve two or more towns in a working day: this involves a certain distance travelling from town to town. At the time of the study the collected food waste was unloaded at a waste transfer station (53°10'36.3"N, 3°03'49.9"W) in Buckley and delivered to the South Shropshire anaerobic digestion plant in Ludlow by a bulk haulage lorry (VALORGAS, 2012b). The locations of Alltami depot and the waste transfer station are shown in Figure 5.1. The bins and collection vehicle used in Flintshire are shown in Figure 5.2.

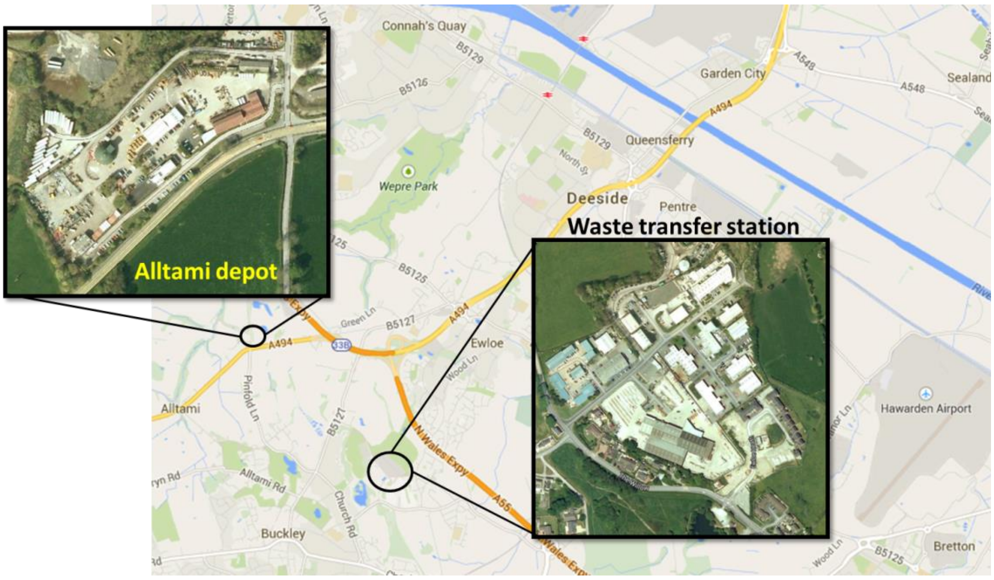


Figure 5.1 Locations and aerial views of Alltami depot and waste transfer station in Buckley

(a) (b)

Figure 5.2 Container and vehicle used in Flintshire (a) Food waste caddy (circled in yellow), (b) Single-compartment vehicle for food waste collection round. Photo credit: L. Gredmaier

5.1.2 Broadland District Council (Broadland)

At the time of the study, Broadland District Council collected refuse and recyclables every alternate week (Broadland District Council, 2013). In addition, source separated domestic food waste is collected from 10,276 households every week. Grey and green 240-litre wheeled bins are provided to collect recyclable and residual waste, while a 21-litre lockable green bin is used for food waste. The overall and dry recycling rates in Broadland have decreased since 2011 while the organic recycling rates remained constant; details of recycling rates and the breakdown between dry and organic recycling are shown in Table 5.2.

Table 5.2 Recycling rates and breakdown of dry and organic recycling in Broadland (Defra, 2015)

	2009/10	2010/11	2011/12	2012/13	2013/14
Overall recycling rate (%)	48	50	49	45	44
Organic recycling rate (%)	18	22	22	22	22
Dry recycling rate (%)	30	28	27	24	23

Two Mercedes-Benz Ateco 918 single-compartment RCVs with a 5.5-tonne payload serve the ten food waste collection rounds in Broadland District Council. Each round begins at Brookside depot (52°42'03.0"N, 1°18'40.1"E) in Flettenham and travels to the collection area. The RCV takes the collected food waste to a composting site (52°50'49.3"N, 1°08'20.1"E) in Edgefield and then returns to the depot. The locations of the depot and composting site are shown in Figure 5.3. Figure 5.4 shows the bins and collection vehicle used for the food waste collection round in Broadland.

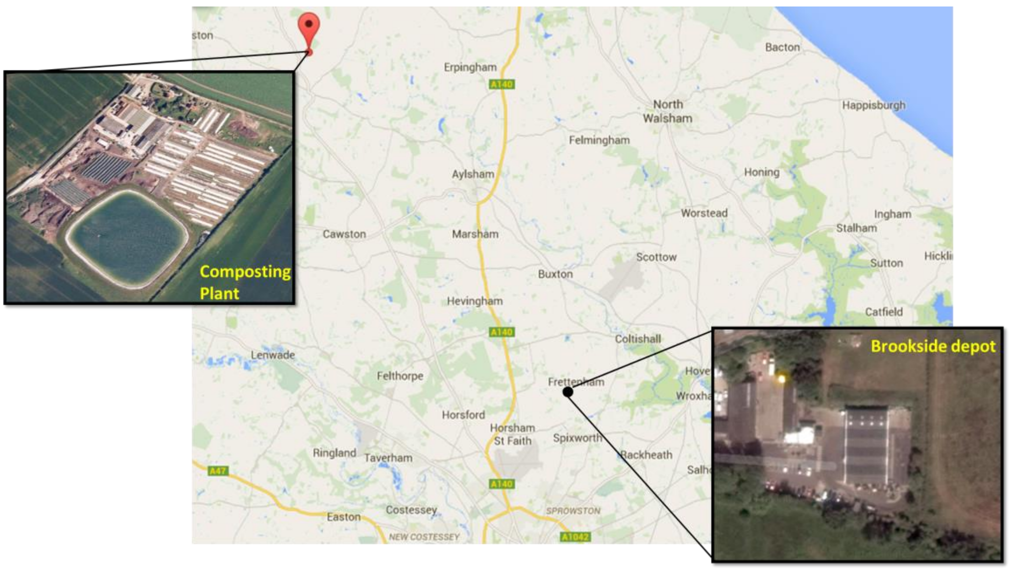


Figure 5.3 Locations and aerial views of Brookside depot and composting plant in Edgefield

(a) (b)

Figure 5.4 Container and vehicle used in Broadland (a) Food waste container (circled in yellow), (b) Single-compartment vehicle for food waste collection round. Photo credit: L. Gredmaier

5.1.3 London Borough of Lambeth (Lambeth)

Lambeth is the third largest borough in inner London and has the fifth highest population density in the UK (Lambeth Council, 2013). It has a mix of suburban, high density business and residential areas. There are approximately 130,000 households in Lambeth, about 8% of which receive kerbside food waste collection every week. Before June 2013, food waste was collected from estates or block of flats and kerbside household properties. The food waste collection was re-organised in June 2013, after which only kerbside household properties were provided with a food waste collection service. Since October 2013, the service has been changed to collect co-mingled food waste and garden waste. A leaflet about food waste collection can be downloaded from Lambeth Council (2014). Recycling rates and the breakdown of dry and organic recycling are shown in Table 5.3: the overall recycling rate decreased from 28% in 2011/12 to 21% in 2013/14 and the organic recycling rate reached a maximum of 4% in the past five years.

Table 5.3 Recycling rates and breakdown of dry and organic recycling in Lambeth (Defra, 2015)

	2009/10	2010/11	2011/12	2012/13	2013/14
Overall recycling rate (%)	27	28	28	23	21
Organic recycling rate (%)	3	4	3	2	3
Dry recycling rate (%)	24	25	25	21	18

During the study period, one single-compartment collection vehicle with 10.7-tonne payload was used to collect food waste every day from Monday to Friday in Lambeth. The vehicle was dispatched from the depot in Brixton (51°27'34.6"N, 0°06'16.8"W), travelled to the collection area and unloaded the collected food waste at a composting plant in Mitcham (51°23'30.6"N, 0°10'00.4"W) before returning to the depot. The locations of depot and composting plant are shown in Figure 5.5.

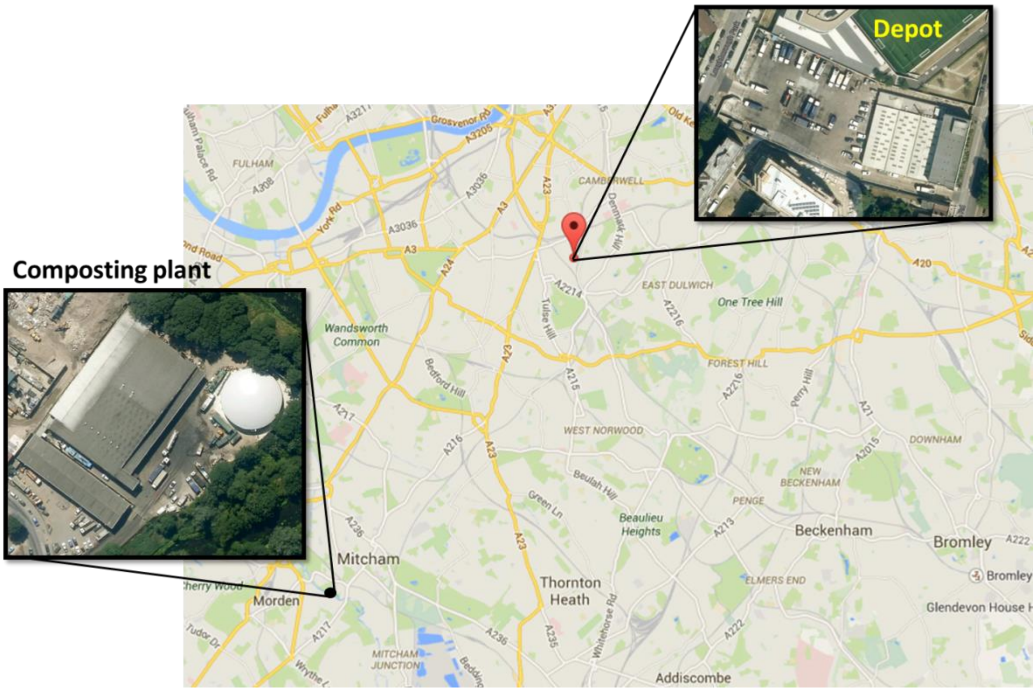


Figure 5.5 Locations and aerial views of depot in Brixton and compositing plant in Mitcham

5.1.4 London Borough of Bromley (Bromley)

Bromley is located in south London. It is the largest borough by area with a population of 309,400 residents (Census, 2012). The population density is highest in the western and northern part of Bromley, while the southern area is countryside and green-belt area. According to information provided by Veolia, about 135,200 households received a food waste collection service in 2013, of which 116,200 were kerbside properties and 19,000 were flats. The overall recycling rate increased from 40% in 2009/10 to 50% in 2011/12 and remained stable in 2013/14, while the organic recycling rate stabilised at 20 % from 2011/12 onward and dry recycling rates were close to 30% for the past five years (see Table 5.4).

Table 5.4 Recycling rates and breakdown of dry and organic recycling in Bromley (Defra, 2015)

	2009/10	2010/11	2011/12	2012/13	2013/14
Overall recycling rate (%)	40	44	50	49	50
Organic recycling rate (%)	12	15	20	20	20
Dry recycling rate (%)	28	30	30	29	29

At the time of the study, source segregated food waste and paper are separately collected in flats and kerbside properties once a week by rear loading split-body collection vehicles, details of food waste collection could refer to London Borough of Bromley (2014). To serve all properties, there are 17 Mercedes-Benz Econic Bluetec-5 collection vehicles, 15 for urban collections, one for countryside and one for flats. They are 5 working days a week, i.e. the number of collection districts (*ncd*) is 5. Figure 5.6 shows the different food waste bins and the two-compartment collection vehicle used for organic collection round in Bromley.

(a)

(b)

(c)

Figure 5.6 Container and vehicle used in Bromley (a) Food waste container for kerbside collection, (b) Food waste communal bin used in estates and flats, (c) Two-compartment vehicle to collect food waste and paper

Sixteen vehicles are dispatched from the depot in Bromley (51°23'55.5"N, 0°02'06.7"E) and one vehicle from Beckenham (51°24'17.4"N, 0°02'52.0"W). During the collection, food waste is loaded into the small compartment while paper is placed in the large compartment. When one of the compartments is full, waste is unloaded at the reuse and recycling centre in Bromley. After that, the vehicle returns to the collection area and finishes the rest of the collection. Once the whole collection is completed, vehicles travel to the recycling centre in Bromley for unloading and then return to their depots. The locations of facilities and their aerial views are shown in Figure 5.7.

Figure 5.7 Locations and aerial views of depots in Bromley and Beckenham and of the waste transfer station in Bromley

5.1.5 The Royal Borough of Kingston upon Thames (Kingston)

Kingston upon Thames is located in southwest London. The council provides weekly kerbside collection for source segregated food waste with dry recyclable materials for about 60,500 households in street-level properties (Kingston Council, 2014). This means about 92% of the households in Kingston receive a food waste recycling service (Office for National Statistics, 2011a). The overall recycling, organic and dry recycling rates have remained fairly stable at around 47%, 17% and 30% respectively since 2009/10, as shown in Table 5.5.

Table 5.5 Recycling rates and breakdown of dry and organic recycling in Kingston (Defra, 2015)

	2009/10	2010/11	2011/12	2012/13	2013/14
Overall recycling rate (%)	46	47	47	46	46
Organic recycling rate (%)	16	17	17	17	16
Dry recycling rate (%)	30	30	29	30	30

The participating households are provided with three types of containers: a 23-litre lockable caddy for food waste, a nylon bag for cardboard and a 55-litre box for dry recyclables. The dry recyclables include paper, cans, plastics, glass and textiles and are collected and sorted at the kerbside. Stillage collection vehicles with 10 compartments are used to collect food waste and the sorted recyclable materials, which are manually loaded into the corresponding compartments: details of the compartment arrangement are given in Section 5.2.4. Figure 5.8

shows the lockable food waste container at the kerb and the multi-compartmental (stillage) vehicle used in Kingston for kerbside-sorted recyclables and food waste collection.

(a) (b)

Figure 5.8 Container and vehicle used in Kingston (a) Food waste container, (b) Stillage vehicle for kerbside-sorted collection

Since November 2012, nineteen IVECO 50E18 EEV collection vehicles have been assigned to collect source separated food waste and dry recyclable materials every day, from Monday to Friday. Vehicles are parked at the depot in Kingston (51°24'12.9"N, 0°17'26.6"W). The household reuse and recycling centre, also functioned as transfer station is next to the depot. The collection vehicle needs to travel between the collection area and recycling centre for unloading 2 to 3 times a day before the whole collection is completed. The locations of the depot and transfer station are shown in Figure 5.9.

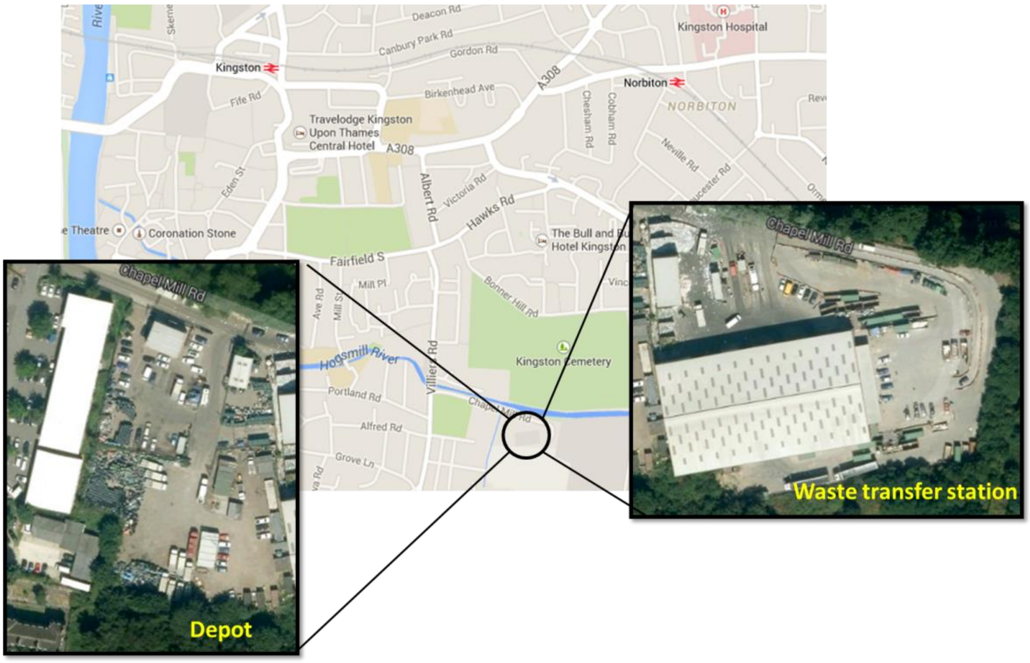


Figure 5.9 Locations and aerial views of depot and transfer station in Kingston

5.1.6 London Borough of Hackney (Hackney)

The London Borough of Hackney is located in north-east London. It is the third most densely populated borough in the UK, with about 246,300 inhabitants (Census, 2013). In total, there are about 104,300 household in Hackney, of which 78% live in flats, maisonettes or apartments, while about 21% live in houses (including detached, semi-detached and terraced) or bungalows (Office for National Statistics, 2012). As the majority of the population lives in flats, a centralised collection system is used to collect source separated household food waste rather than kerbside collection (Hackney Council, 2014). The overall recyclable rate remained at around 25% from 2009/10 to 2013/14 and the organic recycling rate around 6%, as shown in Table 5.6.

Table 5.6 Recycling rates and breakdown of dry and organic recycling in Hackney (Defra, 2015)

	2009/10	2010/11	2011/12	2012/13	2013/14
Overall recycling rate (%)	24	25	24	24	25
Organic recycling rate (%)	6	5	5	5	6
Dry recycling rate (%)	18	20	19	19	20

Before the council expanded the centralised food waste collection in December 2013, there were two single-compartment Leyland DAF LF collection vehicles collecting source segregated food waste once a week from the participating estates. The vehicles set off from the depot in Homerton (51°33'28.9"N, 0°02'22.9"W), pick up and empty the 240-litre wheeled bins in the estates. Food waste is transported to London Waste Eco Park in Edmonton (51°37'01.7"N, 0°02'34.0"W) for unloading, and then the vehicles return to the depot in Homerton. The locations of the depot and the ECO Park are shown in Figure 5.10. The food waste communal bin used in the estates and the vehicle used in Hackney for food waste collection from flats are shown in Figure 5.11.

Figure 5.10 Locations and aerial views of depot in Homerton and London Waste Eco Park in Edmonton

(a) (b)

Figure 5.11 Container and vehicle used in Hackney (a) Food waste communal bin using in estate, (b) Single-compartment vehicle for food waste collection in flat rounds.

Table 5.7 Summary of collection schemes at the selected study sites

	Flintshire	**Broadland**	**Lambeth**	**Bromley**	**Kingston**	**Hackney**
Number of households served	24148	10276	10152	116247	60591	49452
Number of collection vehicle(s)	4	2	1	17	19	2
Total of number of collection rounds	20	10	5	85	95	10
Number of collection day(s) per week	5	5	5	5	5	5
Size of collection crew (included driver)	2	3	3	3	3	2
Type of collection vehicle	Single-compartment	Single-compartment	Single-compartment	30:70 split-bodied	Stillage	Single-compartment
Gross weight (tonne)	7.5	9.5	24	26	15	12
Payload of RCV (tonne)	3.2	5.5	10.7	10	7.76	4
Total volume capacity of vehicle (m^3)	5	5	17	17.6	18.06	7.39
Individual compartment size (m^3)						
First	5	5	17	5.9	1.54	7.39
Second	--	--	--	11.7	1.54	--
Third	--	--	--	--	1.54	--
Fourth	--	--	--	--	1.99	--
Fifth	--	--	--	--	5.74	--
Sixth	--	--	--	--	5.74	--

5.2 Data collection and route analysis

Data collection work commenced in April 2011 and finished in December 2013. Permission for data collection had to be obtained from both the waste management contractor and the relevant local authority, and the work carried out on dates agreed with them: as noted in Chapter 3, this was sometimes a lengthy process. The duration of the observation period (i.e. the period for which quantitative data such as tonnage of waste collected was available from the operator), and of the period spent on site recording primary data on the collection schemes at each of the six study sites, varied from site to site due to data and staff time availability. Details are given in each of the following sections.

5.2.1 Flintshire and Broadland

Flintshire and Broadland are classified as Type I study sites. The observation period for tonnage of food waste collected, total fuel consumption and number of households served in Flintshire was from 1 April 2010 and 31 March 2011, and in Broadland from 19 April 2010 to 3 April 2011. One collection round on 14 April 2011 in Flintshire and one on 6 July 2011 in Broadland was selected for detailed recording of route data using a GPS datalogger. The data obtained from analysis of the sampled collection routes in Flintshire and Broadland are presented in Table 5.8, and were used as the input values for model validation.

Table 5.8 Analysis of collection routes in Flintshire and Broadland

	Flintshire	**Broadland**
Amount of food waste per set-out bin (kg HH^{-1} $week^{-1}$)	2.48	1.65
Time spent in collection (hour):		
- Stopping	1.75	2.65
- Travelling	1.51	0.81
Collector time per household	15.2	17.7
Speed (km $hour^{-1}$):		
- in collection	9.62	14.70
- in transportation	39.53	48.80
Average distance (km):		
- from depot to collection area	8.64	7. 78
- between households (m)	26.46	40.55
- collection area to plant	-	26.71
- collection area to bulking site	10.66	-
- between villages	3.19	-
- Plant/bulking site to depot	3.2	25.1

5.2.2 Lambeth

Another field study for the Type I site was conducted in Lambeth. The observation period was from 1 - 5 July 2013, which was also the period spent in on-site recording of the food waste collection rounds. The characteristics of all collection rounds are analysed and summarised in Table 5.9.

Table 5.9 Analysis of collection routes in Lambeth

	01 July 2013	**02 July 2013**	**03 July 2013**	**04 July 2013**	**05 July 2013**
Number of collection points	1557	1631	2777	2822	1365
Amount of food waste collected from set out HH ($kgHH^{-1}day^{-1}$)	0.12	0.25	0.12	0.11	0.13
Distance between collection point (m)	3.60	3.85	4.65	4.87	5.88
Time per collection point (s)	5.36	4.56	4.69	5.14	4.26
Time (hour:min:sec):					
Depot to first collection point:	00:09:00	00:21:00	00:11:00	00:15:00	00:04:00
In collection area:	02:18:59	02:03:59	03:36:58	04:01:58	01:36:59
Transit:	--	--	00:09:00	00:05:00	--
Intermediate trip to plant:	--	--	--	00:34:00	--
Intermediate trip to collection area:	--	--	--	00:19:00	--
Last collection point to composting plant:	00:39:00	00:41:00	00:13:00	00:23:00	01:02:00
At composting plant:	00:05:00	00:09:00	00:07:00	00:10:00	00:06:00
From composting plant to depot:	00:58:00	00:42:59	00:32:00	00:40:00	01:18:28
Total:	4:09:59	3:57:58	4:48:58	6:27:58	4:07:27
Distance (km):					
Depot to first collection point:	3.44	4.91	4.05	4.57	1.01
In collection area:	5.60	6.28	12.91	13.73	8.03
Transit:	--	--	1.93	1.59	--
Intermediate trip to plant:	--	--	--	9.57	--
Last collection point to composting plant:	--	--	--	8.74	--
At composting plant:	10.10	9.57	5.47	8.77	15.88
From composting plant to depot:	13.66	12.63	11.62	11.65	19.28
Total:	32.80	33.39	35.98	58.62	44.20
Average speeds ($kmhour^{-1}$):					
In transportation	21.46	16.42	19.06	17.44	19.94
In collection area	9.38	8.67	9.21	8.61	8.92

5.2.3 Bromley

Bromley is classified as a Type II study site, as a two-compartment collection vehicle is used for the co-collection of food waste and recyclable materials. The observation period for tonnages of waste and fuel log data was from 1 January to 31 December 2012. Two site visits to the depot in Bromley were conducted. The first site visit took place on 20 March 2012 to gather general information on the collection scheme, while the second visit was to follow the collection crews for logging the collection routes from 28 January to 1 February 2013. One collection round was tracked per day, giving a total of five collection rounds recorded during the study period. The collection routes recorded on 28 January and 1 February were for kerbside organic waste (food waste and paper) collections in the urban area. The organic waste collection rounds for kerbside properties in the countryside and for flats in the urban area were observed on 29 January and 31 January respectively. The route recorded on 30 January was for the dry recyclable collection in flats and kerbside properties. The data collected on 30 January was not used for model validation but was used in another study. The analysis of the collection routes is summarised in Table 5.10.

Table 5.10 Analysis of collection routes in Bromley

	28 Jan 2013	**29 Jan 2013**	**30 Jan 2013**	**31 Jan 2013**	**1 Feb 2013**
Number of collection points	1118	833	1219	179	800
Amount of waste collected from collection point ($kgHH^{-1}day^{-1}$)	1.36	1.05	1.21	7.66	1.03
Distance between collection points (m)	8.93	14.42	9.35	75.25	7.72
Time per collection point (s)	9.49	12.52	12.32	59.79	10.43
Time (hour:min:sec):					
Depot to first collection point:	00:12:00	00:15:52	00:27:44	00:09:01	00:18:28
In collection area:	02:56:55	02:53:56	04:10:20	02:58:23	01:55:25
Transit:	--	--	--	--	00:16:34
Last collection point to plant:	00:08:42	00:12:22	00:16:47	00:15:27	00:17:26
Total:	3:17:37	3:22:10	4:54:51	3:22:51	2:47:53
Distance (km):					
Depot to first collection point:	4.30	7.03	8.80	2.77	8.04
In collection area:	9.98	16.90	11.40	13.47	5.32
Transit:	--	--	--	--	2.55
Last collection point to Plant:	4.20	27.27	6.40	6.06	6.07
Total:	18.48	51.20	26.60	22.30	21.98
Average speeds (km hour^{-1}):					
In transportation	24.58	25.66	27.51	21.55	22.28
In collection area	6.89	12.56	5.27	7.95	10.64

5.2.4 Kingston

Kingston uses a kerbside-sorted collection system to collect household food waste and dry recyclable materials, making it a Type III study site. The observation period for tonnage data was from 1 November 2012 to 30 April 2013. The waste depot was visited between 29 April 2013 and 1 May 2013, for three days in total, to record the tracking data. In addition to the tracking record, the composition of recyclable materials and the sizes of each compartment were determined. In the 6 months of the observation period (from November 2012 and April 2013), 8548.12 tonnes of food waste and recyclables materials were sent to other waste sorting facilities. The details of the quantity, composition and assumed waste density of each recyclable material and food waste are presented in Table 5.11. As the quantity of textiles (0.06%) collected from households was trivial, it was neglected in subsequent calculations: this was done by removing the weight of textiles from total weight of kerbside household waste collected, without altering the percentages for each waste component (i.e. accepting that the total was not 100%).

Table 5.11 Quantity of recyclable material and food waste collected in Kingston

	Quantity of waste collected (tonnes)	**% in weight**	**Assumed waste density [a] (kg m^{-3})**
Food waste	2229.48	26.08	527
Mixed cans	247.78	2.90	60
Mixed glass	1767.34	20.68	456
Soft mixed paper	1841.88	21.55	330
Cardboard	1785.02	20.88	112
Mixed plastic bottle	621.38	7.27	26

[a] FromWRAP (2010), see Table 4.4

The configuration of the stillage vehicle used in Kingston is shown in Figure 5.12. There are 10 compartments of 4 different sizes. Details of the dimensions and sizes of compartment A-F are presented in Table 5.12. Compartment A is for tins and cans. Compartments B-D are identical in size and collect food waste, glass and paper respectively. Compartments E and F are the same size and collect plastics and cardboard. Compartment G is a 240-litre wheeled bin which is placed in the vehicle to collect textiles. The area within the dotted line is the accessible area for the crew to sort waste.

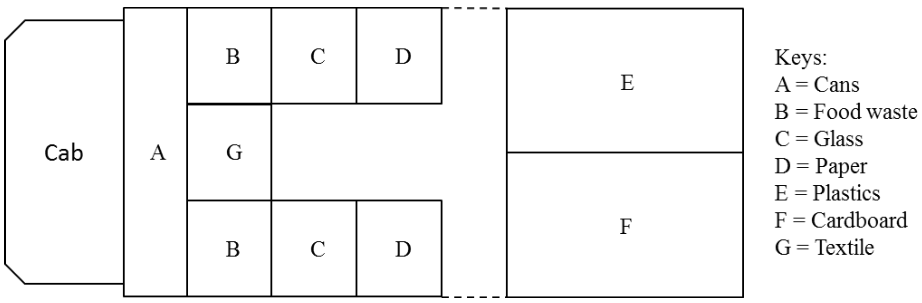


Figure 5.12 Configuration of compartments in stillage vehicle

Table 5.12 Dimensions and volumes of the compartments

	Compartment A	**Compartment B-D**	**Compartment E and F**
Height (cm)	197	160	177
Width (cm)	240	80	120
Depth (cm)	42	60	270
Volume (m^3)	1.99	0.77	5.74

Due to the limited time available, only one urban collection round was selected for route tracking in the three days of the study. The characteristics of the selected collection routes are analysed and shown in Table 5.13.

Table 5.13 Analysis of collection routes in Kingston

	29 Apr 2013	30 Apr 2013	01 Apr 2013
Number of collection points	601	609	523
Amount of waste collected from collection point ($kgHH^{-1}day^{-1}$)	1.35	1.02	1.12
Distance between collection points (m)	8.98	12.81	7.16
Time per collection point (s)	24.10	21.11	27.50
Time (hour:min:sec):			
Depot to first collection point:	00:17:00	00:15:27	00:15:00
In collection area:	02:31:00	02:30:43	02:30:00
Intermediate trip to unloading site:	00:09:52	00:20:00	00:09:00
At unloading site:	01:09:00	00:10:29	00:13:00
Intermediate trip to collection area:	00:16:00	00:17:00	00:04:00
In collection area:	03:08:00	02:53:00	02:14:00
Last collection point to unloading site:	00:12:00	00:19:00	00:03:00
Total:	07:42:52	06:45:39	05:28:00
Distance (km):			
Depot to first collection point:	3.07	8.58	1.90
In collection area:	2.24	2.27	1.58
Intermediate trip to unloading site:	2.93	9.92	2.04
Intermediate trip to collection area:	2.60	8.10	1.69
In collection area:	3.15	5.52	2.16
Last collection point to unloading site:	2.50	8.04	1.24
Total:	16.49	42.43	10.61
Average speeds (km $hour^{-1}$):			
In transportation	18.17	29.67	15.80
In collection area	7.54	6.58	4.67

5.2.5 Hackney

The collection model was originally designed for the assessment of kerbside collection. In order to test whether the model could be applied to a centralised collection system, data was gathered from Hackney. Hackney uses a centralised system to collect food waste from flats, and is classified as Type IV site in this study. The observation period for tonnage of food waste collected and the period of site recording was the same. The first visit was arranged on 11-15 November 2013 in order to collect the tracking data for one set of food waste collection rounds (Monday to Friday). As the field data obtained on the first day of the visit was incomplete, due to an error in the initial fuel reading on the dashboard, the site was revisited on 9 December 2013 to collect the tracking data for the Monday round. The analysis of the collection routes is shown in Table 5.14.

Table 5.14 Analysis of collection routes in Hackney

	9 Dec 2013	**12 Nov 2013**	**13 Nov 2013**	**14 Nov 2013**	**15 Nov 2013**
Number of collection points	122	68	104	95	83
Amount of waste collected from collection point (kg $HH^{-1}day^{-1}$)	3.61	5.76	3.46	2.74	5.78
Distance between collection points (m)	213.56	597.50	303.07	322.11	460.51
Time per collection point (s)	1.82	2.64	1.62	1.48	2.05
Time (hour:min:sec):					
Depot to first collection point:	00:08:58	00:06:57	00:02:27	00:15:44	00:09:23
In collection area:	05:45:27	05:18:02	04:59:50	04:10:13	05:09:06
Last collection point to unloading site:	00:21:03	00:28:51	00:26:43	00:28:43	00:34:10
At unloading site:	00:12:34	00:15:23	00:20:41	00:18:50	00:19:04
Unloading site to depot:	00:20:25	00:30:15	00:28:14	00:27:32	00:30:12
Total:	6:48:27	6:39:28	6:17:55	5:41:02	6:41:55
Distance (km):					
Depot to first collection point:	2.57	1.95	0.77	4.68	1.83
In collection area:	26.05	40.63	31.52	21.83	38.22
Last collection point to unloading site:	11.06	11.83	12.65	20.38	20.61
Unloading site to depot:	11.81	11.9	11.74	11.83	11.83
Total:	51.48	66.31	56.68	58.72	72.49
Average speeds (km $hour^{-1}$):					
In transportation	27.93	18.92	22.40	30.60	24.64
In collection area	12.22	15.62	13.11	10.42	15.69

5.3 Model validation

The kerbside collection model described in Section 4.2 was validated by comparing several output parameters, including the number of collection rounds and energy used in collection, with the data gathered from the real collection schemes at the six study sites. Due to variations in data availability, no single standard method was used to validate the model in each case. In general, all collection routes except Flintshire, Broadland and Bromley were validated individually. All input values used in validation and model outputs are reported according to the type of study site. Full details of the input used in validation of each sites are shown in Appendix A.

5.3.1 Flintshire and Broadland

As only one collection route was recorded, the distance between the collection area and depot or unloading site logged for that collection round is not fully representative of all collection rounds. As a result, the collection round sheets were used to obtain the geo-location of the first and the last collection points for each round. Based on the geo-location data for the depot, unloading site and/or composting plant, the distance from the depot to the first collection point, the last collection point to the unloading site or composting plant and the composting plant to the depot were estimated using Google Maps (https://www.google.co.uk/maps). The average distance for each transportation stage and the distance between collection points (households) were found prior to validating the model.

The distance in each transportation stage was found by averaging the distance of each stage estimated from Google Maps. To calculate the average distance between collection points, the total distance in the transportation and collection stages had to be calculated. The total distance in the transportation stage was calculated by summing the distance in this stage for all collection rounds. The total distance in the collection stage was found by subtracting the total distance in transportation from the total travelling distance for all collection rounds; an estimate of the average distance between collection points (households) could then be found by dividing the total distance in the collection stage by the total number of collection points.

5.3.2 Bromley

Model validation for a co-collection system is relatively data-hungry compared to single collections of household waste. Combined with the inconsistencies in record keeping and the lack of some pieces of information, this increased the complexity of the validation process. As a result, some relevant parameters had to be back-calculated from other information and some assumptions were made in order to estimate the data required as input for the model. The missing data included:

- The individual quantities of co-collected food waste and paper
- Daily fuel consumption
- The number of collection points for flats

The weight of co-collected food waste and paper is always recorded on the weighbridge as a single value. To find the individual quantities of food waste and paper by weight, records of the tonnages of food waste and of each recyclable waste sent to the corresponding treatment or sorting plant in 2012 were used to estimate the mix ratio of the waste collected. The percentage of each waste was taken as the proportion of food waste or paper bulked at the unloading site and sent to the corresponding treatment facilities out of the total tonnage of organic waste collected. It was found that food waste made up 41% of the total weight of organic waste collected, while 59% was paper: this mix ratio was then assumed to apply to every compartmentalised collection vehicle.

In practice, the waste collection team's routine record-keeping procedure means that fuel usage is only recorded every two to four days when the vehicle is fuelled up. It was also possible for the vehicles to change from any given round to any other from day to day; therefore, it was difficult to know how much of the recorded fuel consumption was for collection in flats and in houses, respectively. It was also impossible to trace back the monthly fuel consumption of each collection round based on the information provided. In this case, the overall yearly fuel consumption records of all collection vehicles were used for comparison with the calculated fuel consumption value.

Two sets of data are required to calculate fuel consumption in the model. The first dataset represented the urban kerbside collection round. Data obtained from tracking, such as speed and time per collection point in the organic waste (food waste and paper) collection rounds in urban and countryside areas, was averaged to represent the value of all urban kerbside collection rounds. The tracking data taken from the food waste collection rounds for flats was used as the second dataset to validate the flats collection round. Both datasets were used separately to calculate the number of collection rounds, vehicles needed and fuel consumption per week. The annual fuel consumption was obtained by multiplying the weekly fuel consumption in all collection rounds by the number of collection weeks in 2012.

The contractor operating the collection round for flats did not know the total number of households served, but the Council was able to provide this information. In order to estimate the number of collection points, it is necessary to know the number of households sharing a communal food waste bin, but this information was not available. In blocks of flats in Tower Hamlets the average number of households sharing one communal food waste bin was 15.3. As the housing types were similar it was decided to apply this value in Bromley, giving an estimated 752 collection points to be visited for the whole collection in estates or flats.

5.3.3 Lambeth, Kingston and Hackney

The data on fuel consumption, distance and tonnage for each tracked collection route was collected without problems, and hence the method described in Section 3.4.2 was used for data analysis on each route. To validate the model, the first step was to check whether it could predict the correct limiting factor (time, weight or volume). After this, the time per household was calculated so that the number of collection rounds and RCVs required could be estimated. Finally, the model was run using the extra fuel consumption factor of 1.35, and the predicted value for fuel consumption was compared with field data (i.e. observed value).

The next part of the validation work involved combining all tracked collection rounds in the selected study site. The number of collection points was used as input for the total number of household visited, and the average values for the remaining input data such as quantities of collected waste, speed, distance and time per collection point were used to run the model. The output values were compared with the observed values and the extra fuel consumption factor in the collection stage was also calibrated. This was done by assuming the fuel consumption of RCVs in transportation is similar to that of a heavy duty vehicle, and calculating the total fuel consumption in transportation stage using the equations in Table 4.6. The net fuel usage in the collection stage was then calculated by subtracting the total fuel consumption in the transportation stage from the measured total fuel consumption. To calculate the factor for extra fuel consumption in collection, the laden percentage, speed and the total distance in collection were input and the factor was found by adjusting it until the calculated value for fuel consumption in collection was the same as the actual value obtained from the field data.

5.4 Results

In this section, the results of the model validation are reported in terms of the limiting factor, number of collection rounds and collection vehicles, laden percentage and total travelling distance. In addition, fuel consumption, specific fuel consumption and fuel efficiency before and after calibration are also reported in order to show the effect of changes in the extra fuel consumption factor.

5.4.1 Type I study site: Flintshire, Broadland and Lambeth

This part of the validation work showed how well the kerbside collection model performs for modelling single additional collections. The predicted values from modelling and the observed values from field data for Flintshire, Broadland and Lambeth are presented in Tables 5.15, 5.16 and 5.17 respectively. The results show that the model could predict the correct limiting factor, number of routes and number of vehicles required in all situations. The laden percentage was reasonably well predicted in most of the collection routes. The difference between predicted and observed values ranged from -0.2% to 4.7%. Part of the variation between observed and predicted values is likely to be due to errors and deficiencies in the data records held by the organisations providing the collection service. This lack of reliable and detailed data in suitable formats further reinforces the potential value of models of this type: since most places have little or no data, a model calibrated with validated data from somewhere else is a considerable step forward in terms of providing a prediction / scoping tool.

Fuel consumption was underestimated in all cases when the extra fuel consumption factor of 1.35 was used in the calculation. The results calculated by the model for Flintshire and Broadland were 48% and 6% less than the observed values, respectively. For Lambeth, the predicted value was on average about 30% less than the observed value. The single largest difference in fuel consumption was observed on the route tracked on Day 4, where the predicted value was 42% less than the observed value. Fuel consumption was recalculated after the extra fuel consumption factor was calibrated. Generally, the predicted value was less than 1% different from the observed value in all situations except for the route on Day 4 in Lambeth. On that route it was 14% less than the observed value, and also caused the overall prediction of fuel consumption in Lambeth to be slightly less than the observed value. The reasons for this type variation are discussed in more detail in Section 5.5.3. In this calibration exercise, the extra fuel consumption factors in the collection stages were found to be 3.03 in Flintshire, 1.51 in Broadland and 2.1-3.25 in Lambeth. The difference in the extra fuel consumption factors for Broadland and Flintshire may be due to different operating practices. Slave bins were frequently used in the Broadland collection rounds studied, reducing the amount of 'stop-and-go' driving required. In addition, the engine was sometimes turned off during the collection period, and therefore the idling time was reduced. Both of these features could contribute to the smaller correction factor for Broadland. As mentioned in Section 2.5.1 and 2.5.2, the driving pattern and the vehicle operation can also have a significant effect on fuel consumption. These may explain why three of the five correction factors for Lambeth were very close to the median (2.64), while the other two were respectively high (on Day 1) and low (on Day 3).

Table 5.15 Comparison of predicted and observed values from model and field data in Flintshire

	Observed	**Predicted**	**% Difference**
Limiting factor	Time	Time	--
Number of routes	20	20	0
Number of vehicles required	4	4	0
Total distance travelled (km)	4035	4069.92	0.87
Laden percentage (%)	52	54.01	3.87
% Difference when factor = 1.35			
Fuel consumption (L)	1580.71	810.04	-48.75
Fuel per tonne collected (L $tonne^{-1}$)	10.68	5.47	-48.78
Distance per litre diesel (km L^{-1})	2.55	5.02	96.86
% difference after the factor is calibrated = 3.03			
Fuel consumption (L)	1580.71	1581.80	0.07
Fuel per tonne collected (L $tonne^{-1}$)	10.68	10.67	-0.09
Distance per litre diesel (km L^{-1})	2.55	2.57	0.78

Table 5.16 Comparison of predicted and observed values from model and field data in Broadland

	Observed	Predicted	% Difference
Limiting factor	Time	Time	--
Number of routes	10	10	0
Number of vehicles required	2	2	0
Total distance travelled (km)	897	897.03	0
Laden percentage (%)	31.45	31.39	-0.19
% Difference when factor = 1.35			
Fuel consumption (L)	211.90	198.83	-6.17
Fuel per tonne collected (L $tonne^{-1}$)	16.84	15.84	-5.94
Distance per litre diesel (km L^{-1})	4.21	4.51	7.13
% Difference after calibration of factor = 1.51			
Fuel consumption (L)	211.90	211.93	0.01
Fuel per tonne collected (L $tonne^{-1}$)	16.84	16.88	0.24
Distance per litre diesel (km L^{-1})	4.21	4.23	0.48

Table 5.17 Comparison of predicted and observed values from model and field data in Lambeth

	Day 1	Day 2	Day 3	Day 4	Day 5	Overall
Observed value						
Limiting factor	Time	Time	Time	Time	Time	Time
Number of routes	1	1	1	1	1	5
Number of vehicles required	1	1	1	1	1	1
Total distance travelled (km)	32.8	33.39	35.98	58.62	44.2	204.99
Laden percentage (%)	5.51	11.78	9.72	9.26	5.33	7.39
Predicted value						
Limiting factor	Time	Time	Time	Time	Time	Time
Number of routes	1	1	1	1	1	5
Number of vehicles required	1	1	1	1	1	1
Total distance travelled (km)	32.80	33.39	35.98	40.31	44.20	186.95
Laden percentage (%)	5.51	11.78	9.72	9.25	5.33	8.71
% Difference in general						
Number of routes	0	0	0	0	0	0
Number of collection vehicles	0	0	0	0	0	0
Total distance travelled (km)	0	0	0	-31.2	0	-8.8
Laden percentage (%)	0	0	0	-0.1	0	4.7
Observed value						
Fuel consumption (L)	20.00	21.00	24.50	38.00	26.00	129.50
Fuel per tonne collected (L $tonne^{-1}$)	33.90	16.70	23.60	38.40	45.60	31.60
Distance per litre diesel (km L^{-1})	1.64	1.69	1.47	1.54	1.70	1.60
When factor = 1.35						
Fuel consumption (L)	13.98	16.45	18.87	21.87	19.79	91.23
Fuel per tonne collected (L $tonne^{-1}$)	23.64	13.06	18.14	22.09	34.72	19.58
Distance per litre diesel (km L^{-1})	2.35	2.03	1.91	1.84	2.23	2.05
After the factor is calibrated						
Factor after calibration	3.25	2.56	2.10	2.64	2.67	2.64
Fuel consumption (L)	20.00	20.99	24.46	32.49	26.0	126.28
Fuel per tonne collected (L $tonne^{-1}$)	33.90	16.66	23.52	32.82	45.61	27.10
Distance per litre diesel (km L^{-1})	1.64	1.59	1.47	1.24	1.70	1.48
% Difference when factor = 1.35						
Fuel consumption (L)	-30.1	-21.7	-23.0	-42.4	-23.9	-29.6
Fuel per tonne collected (L $tonne^{-1}$)	-30.3	-21.8	-23.1	-42.4	-23.9	-38.1
Distance per litre diesel (km L^{-1})	43.3	20.1	29.9	19.7	31.4	28.9
% Difference after calibration of factor						
Fuel consumption (L)	0	0	-0.2	-14.5	0	-2.5
Fuel per tonne collected (L $tonne^{-1}$)	0	-0.1	-0.3	-14.5	0	-14.3
Distance per litre diesel (km L^{-1})	0	0	0	-19.4	0	-7.5

5.4.2 Type II study site: Bromley

The results of model validation using field data collected from Bromley are presented in Table 5.18, which shows the performance of the kerbside collection model for co-collection of two different types of waste by two-compartment RCVs. The model could accurately predict the limiting factor and the number of vehicles required. In this section, the number of loads is reported rather than the number of routes, where the number of loads means the number of times vehicles travel to an unloading site for unloading activities in a month. The results show that the model predicted 85 loads per month while 90 loads were observed, or about 6% more than the predicted value. Because of the lower predicted number of loads, the total predicated travelling distance was 11% less than the field data. For the laden percentage, the difference between predicted and observed values ranged from -15.7% to 4.5%. On the other hand, the fuel consumption predicted by the model was 57% less than the observed value before calibration. After calibration, the extra fuel consumption factor was found to be 3.5. Using this calibrated factor, the fuel usage was still 7% less than observed value. Using this model to predict fuel consumption for a co-collection system is slightly less accurate than for separate collection, as the added complexity of co-collection means more real data is required to complete the modelling, or a more extensive suite of reference values is needed linked to a set of factors that explain when to apply them. It is likely that the correction factor of 3.5 is comparatively higher than in Type I study sites because the gross weight of vehicle is much higher; also more energy may be used in lifting bins, as two types of waste are collected at the same time.

Table 5.18 Comparison of predicted and observed values from model and field data in Bromley

	Observed	**Predicted**	**% Difference**
Limiting factor	Time	Time	--
Number of loads per month	90	85	-5.56
Number of vehicles required	17	17	0
Total distance travelled (km)	2550.61	2264.55	-11.22
Laden percentage in house collection round (%)	55.40	57.91	4.50
Laden percentage in flat collection round (%)	68.63	57.87	-15.7
% Difference when factor = 1.35			
Fuel consumption (L)	3101.94	1333.84	-57
Fuel per tonne collected (L $tonne^{-1}$)	6.21	2.71	-57
Distance per litre diesel (km L^{-1})	0.82	1.7	107.31
% Difference after calibration of factor = 3.5			
Fuel consumption (L)	3101.94	2872.04	-7.41
Fuel per tonne collected (L $tonne^{-1}$)	6.21	5.83	-6.12
Distance per litre diesel (km L^{-1})	0.82	0.79	-3.66

5.4.3 Type III study site: Kingston

The field data from Kingston was used to compare values for the kerbside-sorted method of collection for source segregated food waste and dry recyclables in a multi-compartment vehicle with those calculated by the kerbside collection model: the results are presented in Table 5.19.

The model is capable of predicting the limiting factor and number of loads in all cases. Regarding the number of vehicles required, the estimated values for a single route showed good agreement but the overall total was twice the observed value. Because of this, the estimated average laden percentage in the overall prediction was halved: the reasons for this are discussed in detail in section 5.5.3. For the fuel consumption, in most cases the estimated value was less than the field data by 11-32% when using the factor of 1.35 for extra fuel consumption in the collection process. Only the collection route tracked in Day 2 was exceptional, with the observed fuel consumption 10% higher than the estimated value. After calibration, the extra fuel consumption factor in collection was found to range from 1.06-2.52. The correction factor is lower than Lambeth (2.1-3.25) and Bromley (3.5) due to the smaller vehicle size and greater manual effort in loading.

Table 5.19 Comparison of predicted and observed values from model and field data in Kingston

	Day 1	Day 2	Day 3	Overall
Observed value				
Limiting factor	Volume	Volume	Volume	Volume
Number of loads	2	2	2	3
Number of vehicles required	1	1	1	1
Total distance travelled (km)	16.50	42.53	10.61	105.42
Laden percentage (%)	26.15	20.09	18.93	21.72
Predicted value				
Limiting factor	Volume	Volume	Volume	Volume
Number of loads	2	2	2	6
Number of vehicles required	1	1	1	2
Total distance travelled (km)	16.50	42.53	10.61	69.63
Laden percentage (%)	26.15	20.09	18.93	10.87
% Difference				
Number of loads	0	0	0	100
Number of collection vehicles	0	0	0	100
Total distance travelled (km)	0	0	0	51.40
Laden percentage (%)	0	0	0	49.95
Observed value				
Fuel consumption (L)	11.7	13.7	9.0	34.4
Fuel per tonne collected (L $tonne^{-1}$)	2.88	4.39	3.06	3.45
Distance per litre diesel (km L^{-1})	1.41	3.10	1.18	2.02
When factor = 1.35				
Fuel consumption (L)	8.01	15.13	6.22	30.73
Fuel per tonne collected (L $tonne^{-1}$)	1.97	4.85	2.12	3.04
Distance per litre diesel (km L^{-1})	2.06	2.81	1.71	2.27
After the factor is calibrated				
Factor after calibration	2.52	1.06	2.37	1.69
Fuel consumption (L)	11.70	13.72	9.01	34.42
Fuel per tonne collected (L $tonne^{-1}$)	2.88	4.40	3.07	3.40
Distance per litre diesel (km L^{-1})	1.41	3.10	1.18	2.02
% Difference when factor = 1.35				
Fuel consumption (L)	-31.54	10.28	-30.89	-10.67
Fuel per tonne collected (L $tonne^{-1}$)	-31.60	10.48	-30.72	-11.88
Distance per litre diesel (km L^{-1})	46.07	-9.35	45.05	12.15
% Difference after calibration of factor				
Fuel consumption (L)	0	0	0.11	0.06
Fuel per tonne collected (L $tonne^{-1}$)	0	0.23	0.33	-1.45
Distance per litre diesel (km L^{-1})	0	0	0.09	-0.2

5.4.4 Type IV study site: Hackney

The results in Table 5.20 show the performance of the kerbside collection model when used for centralised collection by a single-compartment vehicle. The model is capable of predicting the limiting factor, number of routes, and number of collection vehicles, travelling distance and the laden percentage of vehicle in all single routes. The number of vehicles required in the collection was overestimated, however, with the prediction that two vehicles are needed rather than one. As a result, the average laden percentage of vehicle estimated by the model was halved and the total travelling distance was doubled in the overall prediction. The reasons for these deviations are discussed in detail in section 5.5.3. Regarding the fuel consumption, the predicted value was about 12-42% less than the observed value when using the extra fuel consumption factor of 1.35. After calibration the extra fuel consumption factor ranged from 1.6 to 2.75. Although the gross weight of the vehicle in Hackney (12 tonnes) is slightly smaller than the one in Kingston (15 tonnes), the correction factor is similar to Kingston (1.60-2.52) probably because a bin-lift system was also used in Hackney.

Table 5.20 Comparison of predicted and observed values from model and field data in Hackney

	Day 1	Day 2	Day 3	Day 4	Day 5	Overall
Observed value						
Limiting factor	Time	Time	Time	Time	Time	Time
Number of routes	1	1	1	1	1	5
Number of vehicles required	1	1	1	1	1	1
Total distance travelled (km)	51.48	66.31	56.68	58.721	72.49	305.69
Laden percentage (%)	31.43	28.00	25.72	18.57	34.29	28.98
Predicted value						
Limiting factor	Time	Time	Time	Time	Time	Time
Number of routes	1	1	1	1	1	5
Number of vehicles required	1	1	1	1	1	2
Total distance travelled (km)	51.49	66.31	56.68	58.72	72.49	453.15
Laden percentage (%)	31.43	28.00	25.71	18.57	34.29	14.64
% Difference in general						
Number of routes	0	0	0	0	0	0
Number of collection vehicles	0	0	0	0	0	100
Total distance travelled (km)	0	0	0	0	0	48.2
Laden percentage (%)	0	0	0	0	0	-49.5
Observed value						
Fuel consumption (L)	22.0	23.0	30.0	21.0	26.0	122.0
Fuel per tonne collected (L $tonne^{-1}$)	10.0	11.7	16.7	16.2	10.8	13.1
Distance per litre diesel (km L^{-1})	2.3	2.9	1.9	2.9	2.8	2.5
When factor = 1.35						
Fuel consumption (L)	15.3	20.3	17.5	16.1	20.5	118.2[a]
Fuel per tonne collected (L $tonne^{-1}$)	9.1	10.4	9.7	12.3	8.4	11.5 [a]
Distance per litre diesel (km L^{-1})	2.6	3.3	3.2	3.7	3.5	3.8 [a]
After the factor is calibrated						
Factor after calibration	2.21	1.60	2.75	2.05	1.9	2.05
Fuel consumption (L)	22.0	22.9	30.2	21.0	26.0	121.8[b]
Fuel per tonne collected (L $tonne^{-1}$)	10.0	11.7	16.8	16.1	10.7	12.0[b]
Distance per litre diesel (km L^{-1})	2.3	2.9	1.9	2.8	2.8	2.51[b]
% Difference when factor = 1.35						
Fuel consumption (L)	-30.4	-11.8	-41.5	-23.4	-21.1	-3.2
Fuel per tonne collected (L $tonne^{-1}$)	-8.6	-11.7	-41.5	-24.0	-22.0	-12.0
Distance per litre diesel (km L^{-1})	9.4	13.5	71.0	26.8	26.6	53.6
% Difference after calibration of factor						
Fuel consumption (L)	0.1	-0.3	0.6	0.1	0	-0.2
Fuel per tonne collected (L $tonne^{-1}$)	0.1	-0.3	0.6	-0.6	-1.2	-8.4
Distance per litre diesel (km L^{-1})	-0.1	0.4	-0.7	-3.4	-0.1	0.4

[a] The value was calculated by using the number of vehicles predicted from the model.
[b] The value was calculated by assuming one collection vehicle was used to collect food waste communal bin.

5.5 Discussion

5.5.1 The collection model

The approach used to estimate the fuel consumption in this model represents an advance on Sonesson's model (2000) in several respects. The total number of collection rounds is estimated in Sonesson's model (Sonesson, 2000) without considering the feasibility of combining several collection rounds into one working day when the collection activity depends on vehicle capacity. Hence, total travelling may be over-estimated due to unnecessary trips between the collection area and treatment facilities, especially when a long transport distance to a transfer station is involved. On the other hand, some of the fuel consumption studies such as those of Tanskanen and Kaila (2001) and Sonesson (2000) may give misleading results for fuel consumption, as their calculations did not consider how fuel consumption is affected by the size of the vehicle or by travelling speeds. The work of De Feo and Malvano (2012) showed that vehicle size affects fuel consumption in kerbside waste collection systems, with larger vehicles consuming more fuel in both the collection and transportation stages. Unfortunately, a wide range of specific fuel consumption values can be found in the literature, ranging from 3 to 9 L $tonne^{-1}$ (Tanskanen and Kaila, 2001, Eisted et al., 2009, Di Maria and Micale, 2013). This makes it difficult to select a realistic value for the assessment of fuel consumption assessment in waste collection. In the current work, this issue was addressed by using the European Environment Agency EMEP Emission Inventory Guidebook to calculate RCV fuel consumption. This provides a more systematic way to determine the fuel consumption according to the speed in different stages of the collection, the average laden percentage, the total travelling distance and the size of vehicle; although as the Guidebook was primarily designed for estimating fuel consumption in heavy duty vehicles, a correction factor had to be taken from literature or field data to allow for the 'stop-and-go' mode of travel, as well as the energy used in the bin lift system and in compacting the waste during the collection stage.

In comparison with Sonesson's model (Sonesson, 2000), the current model requires slightly more input data on the collection area . The additional parameters include the average speed in the collection and transportation stages, a representative average distance between properties and the time spent for bin-lifting per stop; these are often difficult to obtain due to lack of available data and/or considerations of commercial confidentiality on the part of the waste collection service contractor. As a result, it is suggested that sensitivity analysis is conducted in order to find which parameters have the greatest effect on fuel consumption and other outputs within the ranges tested, so that greater attention can be given to establishing reliable values for these. New refuse collection vehicles now often come with a pre-installed GPS device or 'black box', however, and it may therefore soon become somewhat easier for the waste management contractor to obtain data such as the average speed, time taken per route and distance driven. It remains to be seen, however, how soon this data will be made available for research purposes, without a specifically funded programme to collect it.

5.5.2 Limitations in the data collection method

The data collection method applied in this research has limitations, especially in the determination of time per collection point and of fuel consumption in different stages. Firstly, the kerbside collection model assumes the refuse collector visits properties one after another during the collection activity. In reality this is not always true, mainly because some collection crews still work under the 'job and finish' system, which means the collector starts at a fixed time and finishes once the round is completed. From conversations with the collection crew (Personal communication, Veolia staff, 2013), this system may affect how the waste is collected. For example, when a single waste material is collected in a densely populated residential area, the driver may drop the first collector at the first collection area and then drop the second collector in another area which is several streets apart. The first collector brings the bins to the kerbside (for centralised collection) or from the setting-out households to the end of the street (for kerbside collection), to be ready for when the vehicle passes. Therefore, two collectors can work in parallel. This practice is common in kerbside food waste collection (Personal communication, Veolia staff, 2013). The time spent to pick up waste can be obtained from GPS data, but the GPS data will show the driving pattern for one pattern in one area but not in another as the collection activities overlap at some points. This is not easy to generalise from one set of data, and illustrates that even the use of GPS data may give an incorrect estimate of the number of collection points that could be visited per day. An alternative approach to estimating the pick-up time for a bin is therefore manual recording of the time spent from leaving the cab to collect the bin and return to the cab, using a manual stopwatch (see Table 3.2).

The method used to log the amount of diesel fuel added to the collection vehicles was adapted from Nguyen and Wilson (2010). This can provide the total fuel consumption over a period, but does not give the real-time fuel consumption readings which would allow accurate measurement of fuel use in the collection and transportation phases. Gupta et al. (2008) explored several possible methods for measuring the instantaneous fuel consumption of vehicles, such as fuel flow rate monitoring and fuel injector monitoring. The equipment needs to be installed and calibrated before use, however, meaning it cannot readily be moved between vehicles. The installation cost of the sensor for fuel rate monitoring is high, while fuel injector monitoring is restricted by the engine type. Another type of portable data logger has been successfully used to measure the instantaneous fuel consumption, speed and GPS position etc (Auterra, 2011). This portable device must be plugged into the vehicle data port to log the collection route, however, and was not approved for use in the current study for reasons of commercial confidentiality. The approach of assuming that fuel use by an RCV in the transportation stage is similar to that of a HDV at normal travelling speeds (Nguyen and Wilson, 2010), and then back-calculating from the total fuel consumption to obtain the fuel use in collection, was thus the only feasible option in the current work.

5.5.3 Model validation: Prediction of collection rounds

Generally speaking, the model could accurately predict the limiting factor, number of vehicles and number of rounds in single collection, co-collection and kerbside sorted collection systems. Nevertheless, some differences were still seen between predicted and observed values in number of loads, laden percentage, distance travelled and fuel consumption. This section mainly focuses on explanations for the differences observed in the first part of the model calculations, while the differences in fuel consumption are discussed in the next section.

For the collection round on Day 4 in Lambeth, the track report showed that the RCV finished the collection in the first collection area before the vehicle was fully loaded, travelled to the treatment plant for unloading, and then took up the collection again in the next part of the area. The model predicted that the RCV had enough capacity to collect all the waste from both collection areas before heading to the treatment plant, thus saving one return journey between the collection area and unloading site. This could explain the 31% reduction in total travelling distance for the route in Day 4, with a 15% reduction in diesel fuel. This case provides an interesting indication of how use of the model could potentially allow optimisation of the collection system through benchmarking against the expected performance; although of course in practice this specific result is based on a single day's data and there may be day-to-day fluctuations in the amount of waste collected which make an intermediate trip essential on some days. In future, additional information in the form of on-board weight monitoring data could allow crews to respond more flexibly in such cases.

In Bromley, the number of loads predicted by the model was less than that observed. In normal circumstances, the required number of loads per day is 17 if each RCV is to finish the collection without exceeding the vehicle capacity. According to the data provided by Veolia, however, the average number of loads was 18 loads per day. This implies that at least one collection round needs an extra load before the collection can be completed. The error in calculating the number of loads from the field data was because the sample size was limited: the number of collection rounds that could be followed was restricted by the time available for the field survey, and thus did not fully reflect the average situation. Although increasing the sample size may improve this, time spent in tracking and route analysis needs to be well balanced. On the other hand, despite the fact that some data, such as number of households per estate, was missing and the use of values from Tower Hamlet was required to complete the rest of calculation, the model managed to predict the right number of collection rounds in estates. In practice, adoption of automated data collection coupled with the growing use of modelling techniques is expected to mean that better and more representative datasets are available in future.

For the validation using the data from Kingston, the model could accurately predict the limiting factor between time and vehicle capacity, in addition to determining which compartment filled up first. By observation it was found that the compartments collecting either plastics or cardboard usually filled up first, and the limiting factor predicted by the model is in line with the observed one. The dependence of the modelling outcomes on correctly identifying the first compartment to fill is a potential weakness, however, as the very wide range of bulk densities reported in the literature for different type of wastes makes it difficult to select realistic values in each case. Poor choices could affect the calculated round size, number of rounds and number of vehicles because these are all dependent on the bulk density and thus the filling order of the compartments. This is what happened in calculation of the number of vehicles required when using the data from Kingston and Hackney.

The model estimate of the number of vehicles required was double the observed values in Kingston and Hackney; this error came from calculation of the average round size based on the volume capacity of the compartment. For Kingston, the average round size according to time was found to be 578 households per round, and 572 households per round based on the compartment volume. For Hackney, the average round size based on time was found to be 95 collection points per round, and 91 collection points per round based on vehicle volume. The difference between the round size in time and volume capacities was 6 households or 1% of the total in Hackney and 4 collection points or 4% of the total in Hackney. In other words, if a small difference in the critical waste density meant that the vehicle could collect waste from the remaining households or collection points, the number of vehicles required would be reduced from 2 to 1. In practice, during food waste collection the collectors may decide to visit the rest of the households or central collection points before returning to the unloading site because the amount of food waste generated per collection point is usually small and the waste is compact. This decision is made taking into account how the collection points are distributed across the collection area and whether a large quantity of waste is expected in the remaining household or communal bins. The collection crew is thus carrying out its own optimisation based on experience. On the other hand, this version of the model assumed equal quantities of waste are collected on each working day rather than using the ‘Flat-out’ option. As a result, the laden percentage of vehicle is halved and the number of vehicles required is doubled when the model estimates that two RCVs are required.

5.5.4 Model validation: Fuel consumption

The correction factor of 1.35 used by Willis (2010) for the extra fuel consumed in the collection stage led to underestimation of the fuel consumption in this study, except in the collection round tracked in Day 2 in Kingston. With a correction factor of 1.35, the fuel use predicted by the model for this particular route was 11% more than the observed value. This case is an exception, however, and one potential explanation may be that the tank was not completely re-filled after the collection finished, causing an error in the fuel record.

This research provided a new set of correction factors for calculation of the fuel consumption in the collection stage. An attempt was made to relate the correction factor to the size of vehicle, but a very weak correlation was found ($R^2 = 0.288$, $n = 21$, $p = 0.012$). This was probably due both to the small sample size, and the presence of many other factors such as different driving pattern and operation of vehicle, some of which are discussed above (see Section 5.4). It was noted, however, that the correction factor was 3.5 for a 26-tonne RCV while for a 12-tonne RCV it ranged from 1.6 to 2.75. Although these are only preliminary values due to the limited amount of data, they help to fill a major gap in current knowledge and suggest a way forward for future work. The correction factors found in this study are applied to the theoretical study of different collection schemes in Chapter 6, 7, 8 and 9.

5.6 Conclusion

In this chapter, parts of the kerbside collection model were validated using data from field studies. Although the model does not consider the specific geographical features of the collection area in a detailed spatial and topographical way, the robustness of the prediction of limiting factor, number of vehicles required and number of loads/rounds for most of the collection systems has been proved. In addition, it has been shown that a factor of 1.35 for extra fuel consumption in the collection stage is not always applicable. The correction factors for extra fuel consumption in the collection stage were found to range from 1.06 to 3.5 and appear to depend on several factors such as the gross weight of vehicle, driving pattern, operation of vehicle and the loading method for bins. To conclude, although the model has some limitations, it could provide reasonably good estimates of the fuel consumption of different size of vehicle and of other collection parameters without excessive demands in terms of data inputs.

Chapter 6: MODELLING KERBSIDE SOURCE SEGREGATED FOOD WASTE COLLECTION: SINGLE ADDITIONAL COLLECTION

In this chapter, the kerbside collection model is used to estimate the fuel consumption, total time spent, total travelling distance and the number of vehicles required in kerbside source segregated food waste collection as an additional collection service. Section 6.1 gives the general background and the aim of this theoretical study. Section 6.2 explains and justifies the choice of model inputs and describes the scenarios used. Section 6.3 shows the model outputs from different scenarios, and the results of sensitivity analysis is given in Section 6.4. A discussion on various output parameters and their sensitivity is presented in Section 6.5, and the findings are summarised in Section 6.6.

6.1 Introduction

The objective of the work described in this chapter is to apply the deterministic mathematical kerbside collection model developed in the current research to estimate fuel consumption and other parameters in a theoretical example of a typical single additional collection scheme for source separated food waste under various conditions. The specific sub-objectives were as follows:

- Investigate the difference in fuel consumption in relation to set-out rate and type of RCV.
- Investigate the utilisation of the RCV and its energy performance in specific circumstances.
- Suggest optimum choice(s) of RCV for different situations.
- Conduct a sensitivity analysis in order to determine which factors have a major effect on energy consumption in the source segregated food waste collection.
- Recommend possible approaches for reducing the energy consumption in collection.

6.2 Methodology

6.2.1 Food waste collection rates

The average amount of food waste collected from setting-out households in the WRAP trial collection schemes was 3.2 kg week^{-1}, equivalent to 0.457 kg day^{-1} (WRAP, 2009a), while the range was typically around 2.5 to 4.0 kg week^{-1} (2009b). These values were adopted for modelling and sensitivity analysis, respectively, in the current study.

6.2.2 Collection vehicles

As this case study concerns the 'additional' type of food waste collection, in practice only single-compartment RCVs are likely to be used. Scenarios were therefore set up for six different sizes of single-compartment RCVs ranging from 3.5 to 26-tonne. The specifications for each type of RCV came from the model's database and were based on WRATE life cycle assessment tool (Environment Agency, 2012a) and the Farid UK Ltd collection vehicle manufacturing company (FARID, 2012b). Details of the selected RCVs are presented in Table 6.1.

Table 6.1 Specification of single-compartment vehicles used in hypothetical study

Code	Refuse collection vehicle	GVW[a] (tonnes)	Payload (tonnes)	Volume (m^3)
3.5t Single	FARID Mini-micro	3.5	0.715	5.5
7.5t Single	FARID MicroL	7.5	3.58	5
12t Single	FARID PN10	12	3.74	10
15t Single	FARID PN13	15	5.9	13
18t Single	FARID PN15	18	7.75	15
26t Single	WRATE 6x4 RCV Fleet	26	12.84	24.5

[a] GVW = Gross weight vehicle

6.2.3 Scenarios

The study considered a hypothetical set of 25,000 households, with a food waste collection service provided by a single additional RCV as described in Section 3.5.3. It was assumed that the RCV is dispatched from the depot to the designated collection area and unloads the waste on a site at or adjacent to the depot, for processing or for bulking and further transport. When the collection activity is completed, the RCV returns to the depot for parking and maintenance. In this study, two collection frequencies (weekly and fortnightly) and ten different set-out rates were considered in order to illustrate the variation in total fuel consumption and other parameters. The scenarios are listed in Table 6.2.

Table 6.2 Scenarios for source separated food waste collection

Scenario	Description
C1-W1	Weekly source segregated collection of food waste by 3.5-tonne RCV
C1-W2	Weekly source segregated collection of food waste by 7.5-tonne RCV
C1-W3	Weekly source segregated collection of food waste by 12-tonne RCV
C1-W4	Weekly source segregated collection of food waste by 15-tonne RCV
C1-W5	Weekly source segregated collection of food waste by 18-tonne RCV
C1-W6	Weekly source segregated collection of food waste by 26-tonne RCV
C1-F1	Fortnightly source segregated collection of food waste by 3.5-tonne RCV
C1-F2	Fortnightly source segregated collection of food waste by 7.5-tonne RCV
C1-F3	Fortnightly source segregated collection of food waste by 12-tonne RCV
C1-F4	Fortnightly source segregated collection of food waste by 15-tonne RCV
C1-F5	Fortnightly source segregated collection of food waste by 18-tonne RCV
C1-F6	Fortnightly source segregated collection of food waste by 26-tonne RCV

6.2.4 Collection parameters

The parameters used in modelling kerbside source segregated food waste collection are shown in Table 6.3, with their associated values. The working hours are the total length of a working day, including time for non-productive activities such as breaks. A value of 6 hours was used assuming the collection crew works from 7am until 1pm which was in line with practice in the UK at the time of collecting field data. The time for intermediate unloading is the time to unload when more than one load is deposited per day; while the time at the unloading site is the time for final unloading at the end of the round, when vehicle queuing times may be longer. The bin pick-up time is defined as described in Table 4.3, and its value varies depending on the way the bin is picked up, and the distance between the bin and the vehicle. Values based on the data collected in the fieldwork were adopted, and the bin pick-up time was taken as 21.6 seconds, with a range of 8.46-27.5 seconds for use in sensitivity analysis.

In general, the travelling distance between collection points reflects the type of collection area e.g. densely populated, semi-rural or countryside. In this case study, the distance between collection points was taken as 15 m with a range of 3.6-29.5 m based on the data collected from the study sites. It was assumed that two collectors were available to pick up food waste containers from the kerbside and load them manually into the vehicle. The bulk density of food waste was taken as 470 kg m^{-3} as reported by WRAP (2009a), with a range of 400-600 kg m^{-3}. The correction factor for extra fuel consumption depends on the size of the RCV: factors obtained by calibration from the field data were used in this study, and are shown in Table 6.3.

Table 6.3 Input values for modelling kerbside collection in a hypothetical city of 25,000 households

Parameter	Value	Units
General information:		
Number of households	25000	no. of HH
Amount of food waste generated	0.457	kg HH^{-1} day^{-1}
Number of collectors	2	no. of collectors
Density of food waste	470	kg m^{-3}
Time:		
Working hours	6	hours
Break	30	mins
Traffic congestion	0	mins
Pick up crews	5	mins
Fuel filling	10	mins
Depot to first collection point	15	mins
Last collection point to depot	15	mins
At unloading site	30	mins
To intermediate unload when full	15	mins
For intermediate unloading	15	mins
Pick-up time for food waste bin	21.6	s HH^{-1}
Distance:		
From depot to first collection point	6.25	km
From last collection to unloading site	6.25	km
Between collection points	15.0	m
To intermediate unload when full	6.25	km
Fuel consumption:		
Speed in transportation	25.0	km hr^{-1}
Speed in collection	10.0	km hr^{-1}
Factor for extra fuel consumption in collection:		
3.5-tonne to 9.5tonne RCV	1.51	
12-tonne to 15-tonne RCV	2.02	
26-tonne RCV	2.86	

6.2.5 Sensitivity analysis

In view of the wide range of reported values for some model input parameters, sensitivity was carried out using Monte Carlo simulation. The aim of the sensitivity analysis and the selection of probability distributions are as discussed in Section 3.6. The seven parameters given ranged values were: food waste generation rate, food waste density, pick-up time for food waste bin, speeds in collection and transportation, correction factor for extra fuel consumption in collection, and the distance between collection points (households). Data collected from the field study sites were used to provide the input ranges for all parameters except for the amount of food waste generated and the density of food waste. Details for each input parameter are given in Table 6.4.

Table 6.4 Minimum, maximum and static values of each input parameters

Parameter	Min	Static	Max	Distribution
Amount of food waste generated (kg HH^{-1} wk^{-1})	2.5	3.2	4	Uniform
Density of food waste (kg m^{-3})	400	470	600	Uniform
Pick-up time for food waste bin (s)	8.46	21.6[a]	27.5	Uniform
Distance between collection points (m)	3.6	15[b]	29.5	Uniform
Speed in transportation (km hr^{-1})	15.8	25[c]	48.8	Uniform
Speed in collection (km hr^{-1})	6	10[c]	14.7	Uniform
Correction factor for extra fuel consumption:				
3.5-tonne to 9.5-tonne RCV	1.51	1.51[c]	3.04	Uniform
12-tonne to 15-tonne RCV	1.06	2.02[c]	2.75	Uniform
26-tonne RCV	2.1	2.86[c]	3.5	Uniform

[a] WRAP (2009a); [b] Knipe (2007); [c] Average values of the field data

6.3 Results

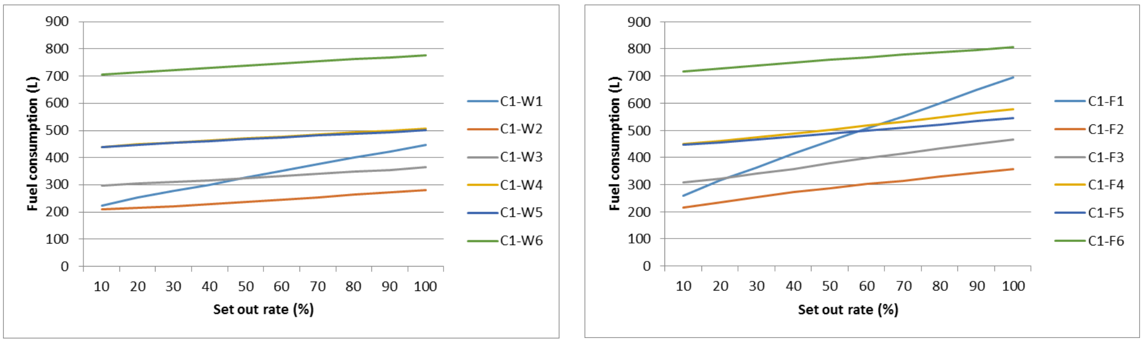
In this part of the research, the total fuel consumption was considered to be the most significant output. The average laden percentage of the RCV, the number of RCVs required, the total time required to complete the whole collection and total distance travelled are also reported. All these outputs are potential criteria for selection of the optimal collection scheme.

6.3.1 Fuel consumption in collection and transportation phases

The amount of fuel consumed in collecting and transporting food waste in each set of conditions is shown in Table 6.5 and Figure 6.1. Fuel consumption increased with increasing set-out rates. From Figure 6.1, it can be seen that the 7.5-tonne RCV (scenario C1-W2) had the lowest fuel consumption at all set-out rates while the 26-tonne RCV consumed most in both weekly and fortnightly collections. Fuel consumption by the 3.5-tonne RCVs (scenarios C1-W1 and C1-F1) changes dramatically with an increase in set-out rates at both collection frequencies, but at a much faster rate in fortnightly collection than in weekly. In weekly collection, the 3.5-tonne RCVs consume less fuel than 12-tonne RCVs at set-out rates of 50% or below. In fortnightly collection, the fuel consumption for 3.5-tonne RCVs is even higher than for 12-tonne and 15-tonne RCVs at set-out rates of between 20-60% and 70% or more, respectively. This result contradicts the views expressed by Holiwast (2006), who considered that a small collection vehicle for single additional collection of food waste is the most appropriate in all circumstances. Interestingly, there is not much difference in fuel consumption when food waste is collected by 26-tonne RCVs every week or every two weeks. Reasons for these differences are discussed in Section 6.5.1 below.

Table 6.5 Fuel consumption in collection and transportation of food waste (litres)

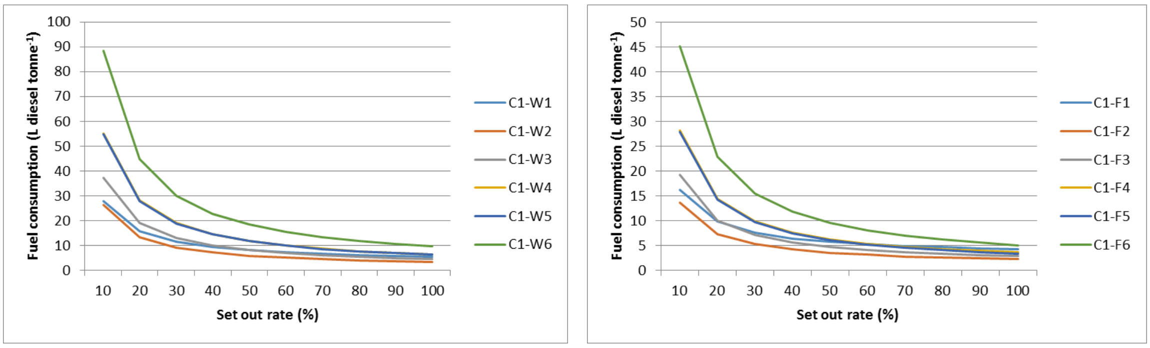
	Set-out rate (%)									
Scenario	10	20	30	40	50	60	70	80	90	100
C1-W1	223.8	252.4	277.8	301.1	326.3	351.0	376.1	400.4	423.5	446.1
C1-W2	208.9	214.7	221.4	228.8	237.0	245.9	254.5	263.7	272.2	281.4
C1-W3	296.9	304.2	310.8	317.5	324.8	332.2	340.2	348.0	355.6	363.9
C1-W4	439.5	448.4	456.3	463.7	470.5	478.3	485.7	492.3	499.5	506.5
C1-W5	439.2	446.9	454.7	461.8	468.4	474.8	481.5	488.0	494.5	500.8
C1-W6	705.9	714.7	722.7	731.1	738.7	746.4	754.1	761.8	769.2	776.0
C1-F1	259.6	315.6	362.1	413.4	461.2	507.1	551.7	599.9	648.1	694.4
C1-F2	216.5	233.4	252.9	271.4	285.3	301.5	314.2	329.6	342.6	356.2
C1-F3	307.5	320.6	340.0	358.3	377.9	397.3	414.6	432.6	449.9	466.3
C1-F4	449.7	461.1	473.0	489.1	502.6	516.5	532.6	548.1	563.8	578.4
C1-F5	446.2	455.6	465.0	476.6	488.2	499.7	509.1	521.7	535.1	546.3
C1-F6	717.8	727.7	738.5	749.3	759.6	769.3	778.3	787.8	796.6	806.1



(a) (b)

Figure 6.1 Fuel consumption of food waste collection with different set-out rates and RCVs, (a) weekly (b) fortnightly

The specific fuel consumption in litres of diesel per tonne of food waste collected is shown in Figure 6.2. As expected, specific fuel consumption decreased with increasing set-out rate in weekly and fortnightly collections. Large differences in specific fuel consumption were found between the collection vehicles at low set-out rates. At set-out rates higher than 50% the specific fuel consumption for the small RCVs was similar, but increased with increasing gross vehicle weight. There was little difference between the fuel consumption for 15 and 18-tonne RCVs at all set-out rates and collection frequencies. Compared with the other RCVs, the specific fuel consumption of a 3.5-tonne RCV shows relatively little difference at the highest set-out rates. The 3.5-tonne RCV consumes more diesel per tonne than 12-tonne RCVs at set-out rates of 60% or more in weekly collection. The difference is much more distinct in fortnightly collection, where 3.5-tonne RCVs have the second highest fuel consumption at set-out rates above 70%. The results of modelling showed that the lowest fuel consumption was 2.2-13.4 L per tonne of food waste collected, while the highest was 22.9-44.7 L per tonne of food waste collected at set-out rates of 20% to 60%, with the differences caused by vehicle type and collection frequency.



(a) (b)

Figure 6.2 Fuel consumption in collecting one tonne of food waste with different set-out rates and RCVs, (a) Weekly (b) fortnightly

In order to allow comparison of weekly and fortnightly collections, the energy consumption over a two-week collection period was calculated and is shown in Figure 6.3. The solid lines represent consumption in weekly collection while dotted lines represent fortnightly collection. Not surprisingly, fortnightly collection consumed less diesel than weekly in most cases. The exceptions occurred in weekly collection with the 3.5-tonne, 7.5-tonne and 12-tonne RCVs. The 7.5-tonne RCVs consume less diesel than fortnightly collection by 3.5-tonne RCVs at set-out rates of 50% or above, 18-tonne RCVs at set-out rates of 50% or below, and 15-tonne and 26-tonne RCVs in all situations. Weekly collection with 12-tonne RCVs shows better performance in fuel consumption than fortnightly collection by 26-tonne RCVs at all set-out rates. At set-out rates of 80% or more, fortnightly collection with 26-tonne RCVs uses less diesel than weekly collection with 3.5-tonne RCVs.

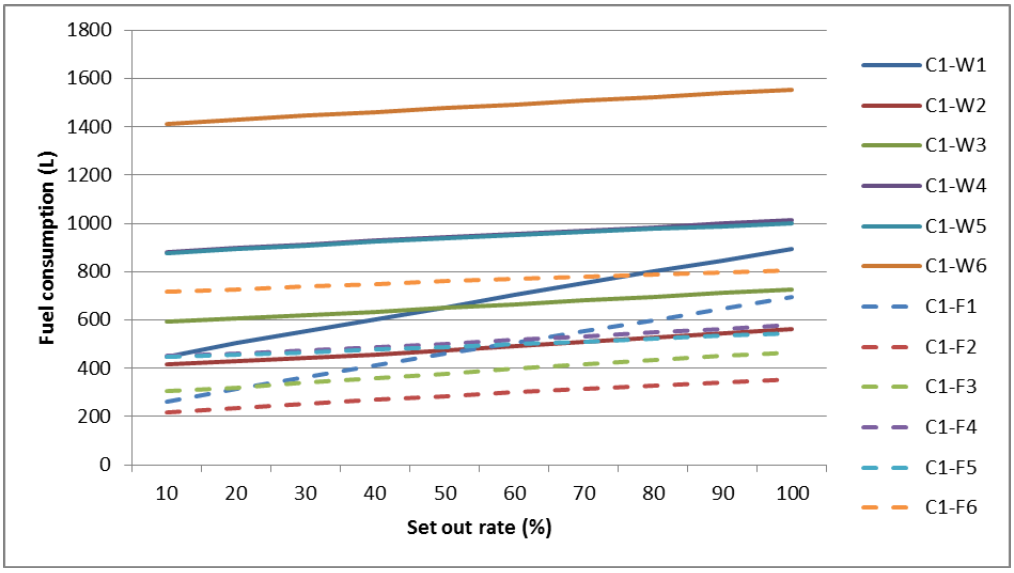


Figure 6.3 Comparison of total fuel consumption in weekly and fortnightly food waste collection

6.3.2 Total time spent in collection and transportation of food waste

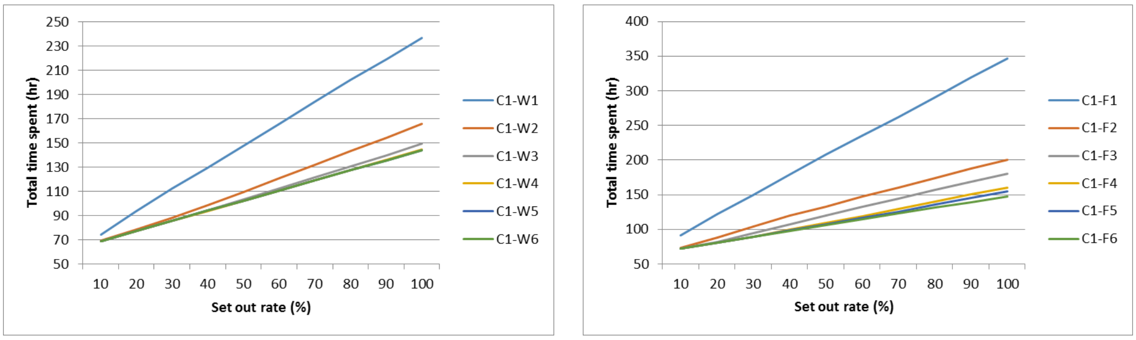
Results for collection time are shown in Table 6.6 and Figure 6.4. As expected, the time spent in collection and transport increased with increasing set-out rates. The 3.5-tonne RCVs had the worst performance in both weekly and fortnightly collection. There was little difference in time spent for collection with 15-tonne, 18-tonne and 26-tonne RCVs at all set-out rates in weekly collections. In fortnightly collections, at set-out rates below 60% the differences between the three large RCVs were relatively small. On the other hand, the time required in weekly collection is approximately double that for fortnightly collections for most vehicle types except the 3.5-tonne RCV: details are shown in Table 6.7.

Table 6.6 Total time to collect food waste in hypothetical area of 25,000 households (hours)

	Set-out rate (%)									
Scenario	10	20	30	40	50	60	70	80	90	100
C1-W1	74.4	93.8	112.1	129.3	147.6	165.6	184.0	201.8	219.2	236.3
C1-W2	69.4	78.5	88.4	98.7	109.4	120.6	131.7	143.1	154.2	165.6
C1-W3	68.9	77.5	85.8	94.3	103.3	112.3	121.4	130.7	139.9	149.3
C1-W4	68.7	77.2	85.5	93.8	101.9	110.5	119.0	127.3	135.8	144.2
C1-W5	68.8	77.1	85.7	94.0	102.3	110.5	118.9	127.3	135.7	144.0
C1-W6	69.0	77.4	85.6	94.0	102.3	110.6	118.9	127.4	135.7	143.9
C1-F1	91.3	122.5	150.1	179.7	207.9	235.1	262.1	290.7	319.3	346.8
C1-F2	73.8	88.4	104.5	119.9	133.1	147.6	160.3	174.6	187.5	200.9
C1-F3	72.8	82.4	95.0	106.9	119.8	132.6	144.2	156.7	168.7	180.3
C1-F4	72.6	80.9	89.7	100.1	109.5	119.1	129.8	140.1	150.6	160.6
C1-F5	72.4	80.6	89.0	98.3	107.7	116.9	125.5	135.4	145.4	154.6
C1-F6	72.4	80.4	88.9	97.5	106.1	114.5	122.8	131.3	139.5	148.0

Table 6.7 Time ratio of weekly/fortnightly collection for different RCVs

	Set-out rate (%)									
	10	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
3.5-tonne	0.81	0.77	0.75	0.72	0.71	0.70	0.70	0.69	0.69	0.68
7.5-tonne	0.94	0.89	0.85	0.82	0.82	0.82	0.82	0.82	0.82	0.82
12-tonne	0.95	0.94	0.90	0.88	0.86	0.85	0.84	0.83	0.83	0.83
15-tonne	0.95	0.95	0.95	0.94	0.93	0.93	0.92	0.91	0.90	0.90
18-tonne	0.95	0.96	0.96	0.96	0.95	0.95	0.95	0.94	0.93	0.93
26-tonne	0.95	0.96	0.96	0.96	0.96	0.97	0.97	0.97	0.97	0.97



(a) (b)

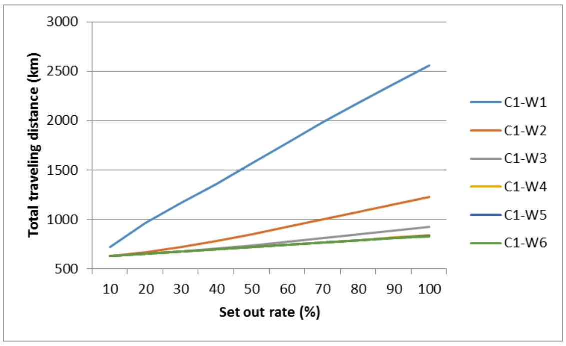
Figure 6.4 Total times spent in food waste collection with different set-out rates and RCVs, (a) weekly (b) fortnightly

6.3.3 Total travelling distance in collection and transportation

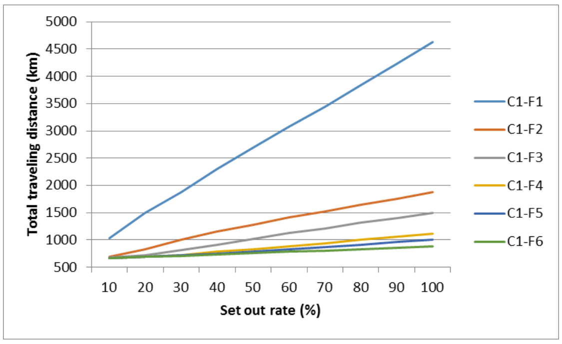
Total travelling distance in collection and transportation for the food waste collection is shown in Table 6.8 and Figure 6.5. The pattern in Figure 6.5 is similar to that in Figure 6.4 for time spent in collection. The 3.5-tonne RCV showed a sharp increase in distance travelled with set-out rate in both weekly and fortnightly collection. A similar but less pronounced trend can be seen for the 7.5-tonne RCV, particularly in weekly collection. Larger RCVs showed little increase in distance travelled with set-out rate.

Table 6.8 Total travelling distance in collection and transportation in a hypothetical area of 25,000 households (km)

	Set-out rate (%)									
Scenario	10	20	30	40	50	60	70	80	90	100
C1-W1	724.1	962.6	1169.2	1358.1	1568.7	1773.4	1981.7	2182.5	2371.9	2557.5
C1-W2	630.5	668.3	718.2	778.2	846.1	922.0	996.5	1075.2	1148.1	1227.2
C1-W3	628.8	654.6	678.3	705.0	737.7	771.4	809.7	848.2	885.5	928.4
C1-W4	627.4	652.2	674.9	696.6	716.9	743.0	768.1	790.1	815.8	840.1
C1-W5	628.0	650.2	675.1	698.1	720.0	740.8	764.8	787.1	810.6	833.4
C1-W6	629.5	651.8	672.7	696.7	717.7	739.8	762.8	785.9	808.3	828.3
C1-F1	1030.1	1495.2	1873.6	2300.9	2697.7	3076.1	3440.8	3839.2	4238.3	4623.5
C1-F2	695.8	833.5	1000.2	1160.3	1276.1	1414.4	1520.4	1651.4	1760.9	1874.7
C1-F3	673.8	723.2	818.4	910.8	1018.1	1124.5	1216.5	1313.0	1405.3	1491.7
C1-F4	669.2	693.3	726.4	782.3	826.8	877.2	939.8	999.2	1061.3	1118.2
C1-F5	668.3	690.0	714.6	752.6	792.2	831.6	863.1	912.3	964.3	1007.1
C1-F6	668.1	685.7	709.8	735.9	761.4	785.4	807.3	832.4	854.8	880.7



(a)



(b)

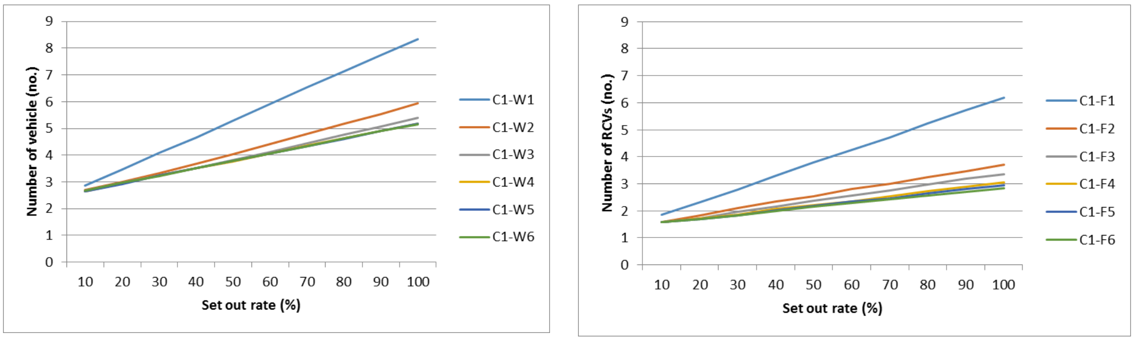
Figure 6.5 Total travelling distances in food waste collection with different set-out rates and RCVs, (a) weekly (b) fortnightly

6.3.4 Total number of RCVs required

The number of vehicles required for the weekly and fortnightly food waste collection is shown in Table 6.9 and Figure 6.6. The total number of RCVs required increased with increasing set-out rates and decreased with increasing gross weight of vehicles in weekly and fortnightly collection. There was no difference between the number of medium and large RCVs (12-tonne to 26-tonne) required for weekly food waste collection (scenarios C1-W3 to C1-W6) at all set out rates. Scenarios C1-F5 and C1-F6 also used the same number of RCVs at all set-out rates. Weekly food waste collection required 1 to 2 RCVs more than fortnightly collection.

Table 6.9 Total number of RCVs required for food waste collection in a hypothetical area of 25,000 households

	Set-out rate (%)									
Scenario	10	20	30	40	50	60	70	80	90	100
C1-W1	3	3	4	5	5	6	7	7	8	8
C1-W2	3	3	3	4	4	4	5	5	6	6
C1-W3	3	3	3	4	4	4	4	5	5	5
C1-W4	3	3	3	4	4	4	4	5	5	5
C1-W5	3	3	3	4	4	4	4	5	5	5
C1-W6	3	3	3	4	4	4	4	5	5	5
C1-F1	2	2	3	3	4	4	5	5	6	6
C1-F2	2	2	2	2	3	3	3	3	3	4
C1-F3	2	2	2	2	2	3	3	3	3	3
C1-F4	2	2	2	2	2	2	3	3	3	3
C1-F5	2	2	2	2	2	2	2	3	3	3
C1-F6	2	2	2	2	2	2	2	3	3	3



(a) (b)

Figure 6.6 Total number of vehicles required for the food waste collection, (a) Weekly, (b) Fortnightly

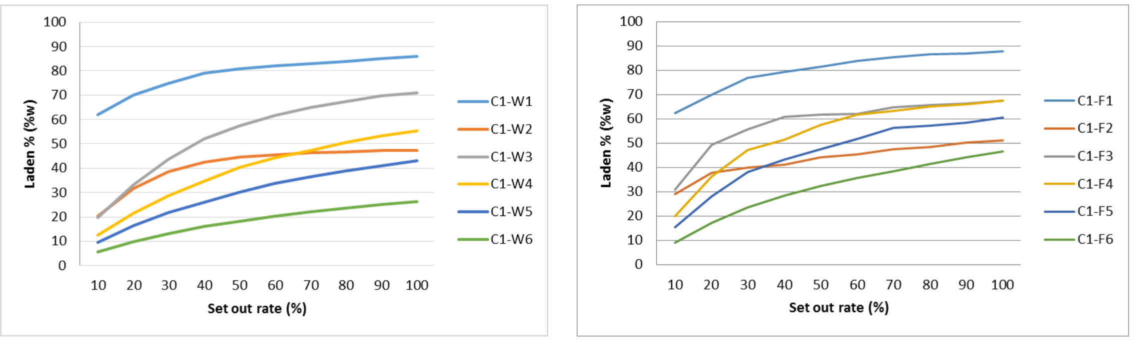
6.3.5 Capacity utilisation of food waste collection vehicles

Utilisation of RCV capacity in terms of weight and volume varied with different vehicle sizes and set-out rates. Results for laden percentage of vehicle in terms of weight are shown in Table 6.10 and Figure 6.7, while Table 6.11 and Figure 6.8 show the laden percentage of vehicles in volume terms. In general, vehicles had better utilisation of capacity at the high set-out rates.

In weekly collection, there was a rapid increase in the laden percentage at low set-out rates (< 40%) which continued to rise more gently until the set-out rate reached 100% (Figure 6.7a); however, the laden percentage for the 7.5-tonne and 12-tonne RCVs flattens out at high set-out rates. The laden percentage of the 7.5-tonne RCV is lower than the 12-tonne RCVs in all situations; below the 15-tonne RCVs at set-out rate of 70% or more. Fortnightly collection has a similar pattern to weekly collection. Most of the vehicles were carrying less than half the maximum payload at all set-out rates, except for the 3.5-tonne RCV at all set-out rates and 12-tonne RCV at set-out rates of 40% or more. Figure 6.7b also shows the laden percentage of the 7.5-tonne RCV flattens out at set-out rates of 50% or more.

Table 6.10 Laden percentages in weight for RCV in transportation stage (%)

	Set-out rate (%)									
Scenario	10	20	30	40	50	60	70	80	90	100
C1-W1	62	70	75	79	81	82	83	84	85	86
C1-W2	20	32	39	42	45	45	46	47	47	47
C1-W3	20	33	44	52	57	62	65	67	70	71
C1-W4	13	21	29	35	40	44	47	51	53	55
C1-W5	10	16	22	26	30	34	37	39	41	43
C1-W6	6	10	13	16	18	20	22	24	25	26
C1-F1	62	70	77	79	81	84	85	86	87	88
C1-F2	29	38	40	41	44	45	48	49	50	51
C1-F3	31	49	56	61	62	62	65	66	66	68
C1-F4	20	36	47	52	58	62	63	65	66	67
C1-F5	15	28	38	43	48	52	56	57	58	61
C1-F6	9	17	24	28	32	36	39	41	44	47



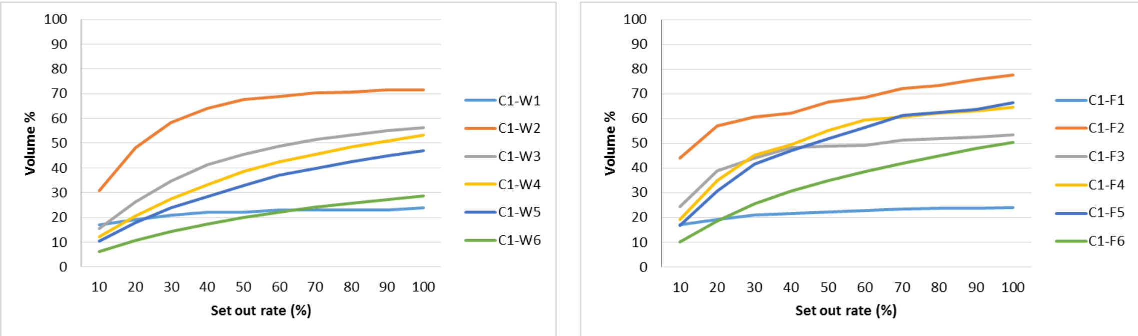
(a) (b)

Figure 6.7 Variation in laden percentage by weight of different RCV in weekly collection (in transportation), (a) Weekly, (b) Fortnightly

For the laden percentage in volume capacity of the vehicle, the 7.5-tonne RCV has the highest utilisation in both collection frequencies. The trends with set-out rate showed a similar pattern to those for the laden percentage by weight. The utilisation of RCV capacity of 3.5-tonne RCV, however, remained low (17-24%) at all set-out rates in weekly and fortnightly collection, and even lower than the 26-tonne RCV at set-out rate of 80% or more in fortnightly collection. For fortnightly collection, the 26-tonne RCV did not reach more than 30% capacity at any set-out rate, while in the 12 to 18-tonne range the vehicles were around 60% capacity at all set-out rates.

Table 6.11 Laden percentages in volume of collection vehicle in transportation stage (%)

	Set-out rate (%)									
Scenario	10	20	30	40	50	60	70	80	90	100
C1-W1	17	19	21	22	22	23	23	23	23	24
C1-W2	31	48	58	64	68	69	70	71	72	72
C1-W3	16	26	35	41	45	49	51	53	55	56
C1-W4	12	21	27	33	39	42	45	49	51	53
C1-W5	10	18	24	29	33	37	40	42	45	47
C1-W6	6	11	14	17	20	22	24	26	27	29
C1-F1	17	19	21	22	22	23	23	24	24	24
C1-F2	44	57	61	62	67	69	72	73	76	78
C1-F3	24	39	44	48	49	49	51	52	52	53
C1-F4	19	35	45	49	55	59	61	62	63	65
C1-F5	17	31	42	47	52	57	61	63	64	66
C1-F6	10	19	26	31	35	39	42	45	48	51



(a) (b)

Figure 6.8 Variation in laden percentage by volume of different RCVs in fortnightly collection (in transportation), (a) Weekly, (b) Fortnightly

6.3.6 Selection of the most suitable collection options in different situations

In this part of the work the primary focus was on fuel use in collection, but a number of other output parameters may be important when selecting the most appropriate collection options. The best combinations of food waste collection options for fuel consumption, total time spent, total travelling distance and number of vehicles required at different set-out rates are shown in Table 6.12. The results showed that where fortnightly food waste collection is an acceptable option, this gives the best performance in all situations. When fuel consumption is the main concern, the 7.5-tonne RCV has advantages at all set-out rates. When time spent, travelling distance and number of vehicles are taken into consideration, the fortnightly segregated collection of food waste by 26-tonne RCV (scenario C1-F6) would be the best system to adopt for this hypothetical typical location.

Table 6.12 Summary of selection of best scenarios at different set-out rates

	Output parameter			
Set-out rate (%)	Fuel consumption	Time spent	Travelling distance	Number of vehicle
10	C1-F2	C1-F6	C1-F6	C1-F2/F3/F4/F5/F6
20	C1-F2	C1-F6	C1-F6	C1-F2/F2/F4/F5/F6
30	C1-F2	C1-F6	C1-F6	C1-F2/F2/F4/F5/F6
40	C1-F2	C1-F6	C1-F6	C1-F2/F2/F4/F5/F6
50	C1-F2	C1-F6	C1-F6	C1-F2/F2/F4/F5/F6
60	C1-F2	C1-F6	C1-F6	C1-F2/F2/F4/F5/F6
70	C1-F2	C1-F6	C1-F6	C1-F2/F2/F4/F5/F6
80	C1-F2	C1-F6	C1-F6	C1-F2/F2/F4/F5/F6
90	C1-F2	C1-F6	C1-F6	C1-F2/F2/F4/F5/F6
100	C1-F2	C1-F6	C1-F6	C1-F3/F4/F5/F6

6.4 Sensitivity Analysis

6.4.1 Fuel consumption

The effects of the two most critical parameters for fuel consumption are summarised in Table 6.13. Generally speaking, the distance between properties was the parameter which most affected the fuel consumption in all scenarios, with regression coefficients ranging from 0.76 to 0.90. The second biggest influence on fuel consumption in all scenarios except for the weekly and fortnightly collection of food waste by 26-tonne RCV (scenarios C1-W6 and C1-F6), is the correction factor for extra fuel consumption in collection: in this case the regression coefficient ranged from 0.33 to 0.47. In scenarios C1-W6 and C1-F6, the speed in collection had a significant negative effect on the fuel consumption at all set-out rates, with a regression coefficient of -0.32 to -0.30.

Table 6.13 Summary of regression coefficients from sensitivity analysis for fuel consumption at set-out rates from 10-100%

		Set-out rate (%)									
Scenario	Parameter	10	20	30	40	50	60	70	80	90	100
C1-W1	Distance between properties	0.90	0.89	0.88	0.85	0.85	0.83	0.82	0.80	0.79	0.76
	Factor on extra fuel consumption	0.39	0.37	0.37	0.36	0.36	0.34	0.33	0.35	0.37	0.41
C1-W2	Distance between properties	0.90	0.89	0.89	0.88	0.88	0.87	0.87	0.87	0.87	0.87
	Factor on extra fuel consumption	0.36	0.37	0.37	0.39	0.39	0.39	0.39	0.39	0.37	0.37
C1-W3	Distance between properties	0.83	0.83	0.83	0.83	0.82	0.82	0.82	0.81	0.81	0.81
	Factor on extra fuel consumption	0.44	0.44	0.44	0.45	0.45	0.46	0.46	0.46	0.47	0.47
C1-W4	Distance between properties	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81
	Factor on extra fuel consumption	0.42	0.42	0.42	0.42	0.43	0.43	0.43	0.43	0.43	0.43
C1-W5	Distance between properties	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
	Factor on extra fuel consumption	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.44	0.44	0.44
C1-W6	Distance between properties	0.88	0.88	0.88	0.88	0.89	0.89	0.89	0.89	0.89	0.89
	Speed in collection	-0.32	-0.32	-0.32	-0.31	-0.31	-0.31	-0.31	-0.31	-0.31	-0.31
C1-F1	Distance between properties	0.87	0.87	0.85	0.85	0.84	0.83	0.81	0.79	0.78	0.76
	Factor on extra fuel consumption	0.38	0.37	0.36	0.36	0.37	0.35	0.35	0.35	0.38	0.41
C1-F2	Distance between properties	0.90	0.89	0.89	0.89	0.88	0.88	0.88	0.88	0.87	0.86
	Factor on extra fuel consumption	0.36	0.37	0.38	0.39	0.39	0.39	0.39	0.39	0.39	0.38
C1-F3	Distance between properties	0.83	0.83	0.83	0.82	0.82	0.82	0.82	0.81	0.81	0.81
	Factor on extra fuel consumption	0.42	0.43	0.43	0.43	0.44	0.44	0.45	0.45	0.45	0.45
C1-F4	Distance between properties	0.82	0.82	0.83	0.82	0.83	0.83	0.83	0.82	0.82	0.82
	Factor on extra fuel consumption	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.46	0.46	0.46
C1-F5	Distance between properties	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84
	Factor on extra fuel consumption	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43
C1-F6	Distance between properties	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88
	Speed in collection	-0.31	-0.31	-0.30	-0.30	-0.30	-0.30	-0.30	-0.30	-0.30	-0.30

6.4.2 Total time spent

The three parameters which have the greatest impact on total time spent are summarised in Table 6.14a and 6.14b, for weekly and fortnightly food waste collection respectively. The distance between properties has the biggest influence on the total time spent in collection activities in all scenarios, with a regression coefficient ranging from 0.58-0.86. When the set-out rate is 50% or less, the speed in collection is the second most important parameter that affects the time spent in all scenarios. When the set-out rate is 60% or above, the time spent in picking up the bin becomes the second most influential parameter. The regression coefficients for speed in collection and time spent in bin pick-up ranged from -0.33 to -0.5 and 0.07 to 0.63, respectively.

6.4.3 Total distance travelled

Table 6.15 summarises the two most critical input parameters that affect the total distance travelled. The distance between properties is the most critical and the speed in transportation is the second most critical parameter influencing the total distance travelled in all scenarios, except when:

- Food waste is collected every week by 3.5 tonne RCV (scenario C1-W1) at a set-out rate of 30% or more.
- Food waste is collected every two weeks by 3.5 tonne RCV (scenario C1-F1) at a set-out rate of 60% or more

In scenarios C1-W1 and C1-F1, the amount of food waste collected in each property becomes the second most important parameter to affect the total distance travelled. Regarding the regression coefficients, the values for distance between properties and speed in transportation are 0.32-0.96 and 0.23-0.84 respectively.

Table 6.14a Summary of regression coefficients from sensitivity analysis for total time spent for weekly collection at set-out rates from 10-100%

		Set-out rate (%)									
Scenario	Parameter	10	20	30	40	50	60	70	80	90	100
C1-W1	Distance between properties	0.83	0.83	0.78	0.75	0.74	0.72	0.68	0.65	0.62	0.59
	Speed in collection	-0.50	-0.46	-0.48	-0.45	-0.41	-0.38	-0.37	-0.35	-0.35	-0.34
	Time to collect bin	0.10	0.18	0.24	0.32	0.37	0.41	0.47	0.51	0.54	0.58
C1-W2	Distance between properties	0.84	0.82	0.81	0.78	0.75	0.73	0.71	0.70	0.67	0.65
	Speed in collection	-0.47	-0.47	-0.47	-0.47	-0.45	-0.44	-0.40	-0.37	-0.35	-0.34
	Time to collect bin	0.07	0.15	0.22	0.30	0.39	0.44	0.51	0.54	0.59	0.63
C1-W3	Distance between properties	0.82	0.82	0.80	0.79	0.76	0.74	0.72	0.69	0.67	0.64
	Speed in collection	-0.47	-0.47	-0.46	-0.46	-0.45	-0.44	-0.43	-0.41	-0.40	-0.38
	Time to collect bin	0.09	0.16	0.24	0.31	0.38	0.44	0.49	0.54	0.58	0.63
C1-W4	Distance between properties	0.82	0.81	0.80	0.78	0.76	0.74	0.71	0.69	0.66	0.63
	Speed in collection	-0.47	-0.47	-0.45	-0.45	-0.44	-0.42	-0.40	-0.39	-0.38	-0.36
	Time to collect bin	0.09	0.17	0.24	0.31	0.39	0.45	0.50	0.55	0.59	0.63
C1-W5	Distance between properties	0.84	0.83	0.81	0.80	0.78	0.75	0.73	0.70	0.67	0.65
	Speed in collection	-0.47	-0.47	-0.46	-0.45	-0.44	-0.43	-0.41	-0.40	-0.38	-0.37
	Time to collect bin	0.09	0.17	0.25	0.32	0.39	0.45	0.50	0.56	0.61	0.64
C1-W6	Distance between properties	0.84	0.83	0.81	0.80	0.77	0.75	0.73	0.70	0.67	0.65
	Speed in collection	-0.48	-0.47	-0.46	-0.45	-0.44	-0.43	-0.41	-0.40	-0.39	-0.37
	Time to collect bin	0.08	0.16	0.23	0.30	0.37	0.44	0.49	0.55	0.59	0.63

Table 5.14b Summary of regression coefficients from sensitivity analysis for total time spent for fortnightly collection at set-out rates from 10-100%

		Set-out rate (%)									
Scenario	Parameter	10	20	30	40	50	60	70	80	90	100
C1-F1	Distance between properties	0.80	0.82	0.76	0.74	0.73	0.70	0.67	0.64	0.62	0.58
	Speed in collection	-0.48	-0.45	-0.47	-0.43	-0.40	-0.38	-0.36	-0.37	-0.36	-0.35
	Time to collect bin	0.10	0.16	0.23	0.31	0.35	0.42	0.47	0.49	0.52	0.57
C1-F2	Distance between properties	0.81	0.79	0.77	0.74	0.72	0.70	0.68	0.64	0.61	0.61
	Speed in collection	-0.47	-0.46	-0.46	-0.44	-0.43	-0.39	-0.38	-0.35	-0.34	-0.33
	Time to collect bin	0.07	0.14	0.21	0.29	0.35	0.41	0.46	0.52	0.57	0.58
C1-F3	Distance between properties	0.84	0.83	0.82	0.79	0.77	0.74	0.71	0.69	0.66	0.64
	Speed in collection	-0.47	-0.47	-0.46	-0.45	-0.44	-0.43	-0.42	-0.40	-0.37	-0.36
	Time to collect bin	0.08	0.17	0.23	0.31	0.37	0.43	0.49	0.53	0.57	0.61
C1-F4	Distance between properties	0.85	0.84	0.83	0.80	0.78	0.76	0.73	0.70	0.67	0.64
	Speed in collection	-0.47	-0.47	-0.46	-0.46	-0.44	-0.42	-0.41	-0.40	-0.38	-0.37
	Time to collect bin	0.08	0.17	0.24	0.32	0.39	0.45	0.50	0.55	0.60	0.64
C1-F5	Distance between properties	0.86	0.84	0.82	0.80	0.78	0.76	0.73	0.70	0.67	0.64
	Speed in collection	-0.48	-0.47	-0.46	-0.45	-0.44	-0.42	-0.41	-0.39	-0.37	-0.36
	Time to collect bin	0.09	0.18	0.25	0.33	0.40	0.45	0.51	0.56	0.60	0.64
C1-F6	Distance between properties	0.83	0.82	0.81	0.80	0.78	0.75	0.73	0.70	0.67	0.65
	Speed in collection	-0.47	-0.47	-0.46	-0.45	-0.44	-0.43	-0.41	-0.40	-0.38	-0.36
	Time to collect bin	0.08	0.17	0.24	0.32	0.38	0.45	0.51	0.56	0.61	0.64

Table 6.15 Summary of regression coefficients from sensitivity analysis for total distance travelled at set-out rates from 10-100%

Scenario	Parameter	Set-out rate (%)									
		10	20	30	40	50	60	70	80	90	100
C1-W1	Distance between properties	0.80	0.70	0.60	0.48	0.42	0.40	0.37	0.34	0.32	0.29[a]
	Speed in transportation	0.42	0.52	0.63	0.71	0.76	0.76	0.78	0.80	0.80	0.82
C1-W2	Distance between properties	0.95	0.91	0.87	0.79	0.70	0.62	0.59	0.59	0.60	0.62
	Speed in transportation	0.23	0.30	0.38	0.46	0.53	0.57	0.57	0.56	0.54	0.54
C1-W3	Distance between properties	0.94	0.93	0.92	0.91	0.88	0.85	0.80	0.76	0.72	0.69
	Speed in transportation	0.23	0.26	0.29	0.32	0.36	0.40	0.45	0.48	0.51	0.54
C1-W4	Distance between properties	0.94	0.93	0.92	0.91	0.90	0.89	0.88	0.86	0.85	0.83
	Speed in transportation	0.24	0.26	0.28	0.30	0.32	0.35	0.36	0.39	0.41	0.43
C1-W5	Distance between properties	0.95	0.95	0.94	0.93	0.92	0.91	0.90	0.88	0.87	0.86
	Speed in transportation	0.23	0.26	0.28	0.30	0.32	0.34	0.36	0.39	0.40	0.41
C1-W6	Distance between properties	0.96	0.96	0.95	0.94	0.93	0.93	0.92	0.90	0.89	0.88
	Speed in transportation	0.24	0.26	0.28	0.31	0.33	0.34	0.37	0.39	0.40	0.42
C1-F1	Distance between properties	0.81	0.72	0.66	0.72	0.77	0.40	0.37	0.34	0.32	0.29[a]
	Speed in transportation	0.44	0.55	0.61	0.49	0.43	0.78	0.80	0.81	0.83	0.84
C1-F2	Distance between properties	0.96	0.93	0.89	0.81	0.73	0.67	0.62	0.61	0.64	0.66
	Speed in transportation	0.23	0.30	0.36	0.46	0.54	0.55	0.57	0.52	0.52	0.49
C1-F3	Distance between properties	0.96	0.95	0.94	0.93	0.91	0.87	0.82	0.77	0.72	0.68
	Speed in transportation	0.24	0.27	0.30	0.33	0.36	0.41	0.47	0.52	0.54	0.57
C1-F4	Distance between properties	0.96	0.95	0.94	0.93	0.93	0.91	0.90	0.88	0.86	0.85
	Speed in transportation	0.24	0.27	0.29	0.32	0.33	0.36	0.39	0.41	0.43	0.45
C1-F5	Distance between properties	0.95	0.94	0.93	0.92	0.91	0.90	0.88	0.87	0.85	0.84
	Speed in transportation	0.23	0.26	0.29	0.30	0.32	0.34	0.36	0.38	0.40	0.41
C1-F6	Distance between properties	0.94	0.93	0.93	0.92	0.91	0.90	0.88	0.87	0.86	0.85
	Speed in transportation	0.24	0.26	0.28	0.31	0.32	0.34	0.37	0.38	0.40	0.41

[a] Distance between properties is ranked the third biggest influence on total time spent at 100% set-out. The second biggest influence parameter is amount of food waste collected in each property (R = 0.31)

6.5 Discussion

6.5.1 Fuel consumption

The current study showed that the 7.5-tonne RCV has the best performance in fuel consumption in all scenarios; however, the 3.5-tonne RCVs does not give good performance, especially in fortnightly collection at high set-out rates (see Figure 6.1b). Compared with the other scenarios, the 3.5-tonne RCVs show a rapid rate of increase in fuel consumption with set-out rates in both weekly and fortnightly food waste collection (C1-W1 and C1-F1), as indicated by the steep slopes in Figure 6.1. This can be explained by the extra journeys to and from the unloading sites which are needed because of the smaller capacity of the vehicle. This result suggests that the 3.5-tonne RCV could be a suitable choice in terms of fuel consumption for a local authority trialling a scheme, in the initial period when set-out rates are low, especially if this type of vehicle is already available; but as public participation and scheme coverage increases it is advisable to switch to a larger vehicle.

Figure 6.2 showed that the fuel consumption per tonne of food waste collected by 15-tonne and 18-tonne RCVs is similar: This reflects the fact that these vehicles are classified in the same category of gross weight according to the European Environment Agency EMEP Emission Inventory Guidebook (2010), although the laden percentage of the collection vehicle differs slightly in the collection rounds.

The comparison between fuel consumption in weekly and fortnightly collection is useful, as it indicates whether fortnightly collection always has the best performance. The results could help to support a decision on which collection system to select when other practical issues are at stake. Weekly food waste collection is the option favoured by local authorities in the UK, mainly for reasons of public acceptability (WRAP, 2008c). In most cases, fortnightly collection uses less fuel; however, there is some overlap at certain set-out rates (See Figure 6.3). To balance acceptability and fuel consumption, the use of a 7.5-tonne or 12-tonne RCV in weekly collection at all set-out rates could be considered, rather than sending a vehicle of gross weight 15 tonnes or more to collect food waste every fortnight. On the other hand, the climate in different regions will influence this decision: in Scandinavia in winter, for example, collection frequencies could be reduced to every two weeks. In this case, fortnightly collection by 7.5-tonne RCVs (scenario C1-F2) would be a preferred option.

Using the methane gas production value reported by Banks et al. (2011), it can be shown that fuel consumption in weekly and fortnightly food waste collection at set-out rates of 10-100%

represents 3.6-26.4% and 2.3-13.7% of the maximum energy potentially available from food waste as raw methane; or 9.5-70.1% and 6.0-36.6% of the reported net energy yield as electricity after allowing for the parasitic demand of the AD plant. Simple comparisons of this type must be treated with care, as they compare primary and secondary energy sources within different system boundaries; but the modelling results can provide a basis for determining whether separate food waste collection is effective in energy terms (VALORGAS, 2013b).

6.5.2 Utilisation of collection vehicle and distance travelled

Although laden percentage is not a key parameter in assessing the performance of a collection system, it provides an indication of resource utilisation. Laden percentage is generally presented in terms of weight because the quantity of waste collected per vehicle is measured by weighbridge at the transfer station; calculation of the fuel consumption by the formulas in (European Environment Agency, 2009b) is also based on weight. In fact, however, the payload may not always be the constraint for all vehicles in all cases. For the 7.5-tonne RCV, volume was the determining factor. For example, the laden percentage in weight at set-out rates of 50-100% was about 45% for this vehicle, but in volume terms it was approximately 70% full. When selecting the optimal condition based on the utilisation of capacity, both volume and payload should be taken in account, and in this respect the current model has advantages over those of Sonesson (2000) and Di Maria and Micale (2013). In this study, the maximum utilisation of vehicle capacity reached about 90% in weight and 70% in volume. A high percentage utilisation of capacity is good if embodied energy and resources are being considered, since it implies no materials have been wasted in the construction of the collection vehicle. On the other hand, there are likely to be day-to-day and seasonal variations in loads for collection. No specific information is available in the literature on the typical optimum amount of spare capacity, and further analysis would be required to determine this, confirming once again the importance of better data availability. It is assumed, however, that 100% utilisation is not ideal and is suggested that a minimum of 5-10% spare capacity is necessary to give some day-to-day operational flexibility: this was achieved in all of the scenarios considered.

The trends and patterns in the graphs of laden percentage by weight shown in Figure 6.7 can be explained by reference to the effect of set-out rates. A steep slope is observed at low set-out rates (<40%) simply because only a small quantity of food waste is collected, which does not reach the limit of the vehicle capacity. The slope flattens out and becomes level at high set-out rates. The compartment is never 100% full, however: the highest value is 88% in the 3.5-tonne RCV. This is because the model assumes the average number of households is served on each working day rather than adopting the ‘Flat-out’ approach described in section 4.2.2.6; therefore the laden percentage of the vehicle is averaged across the collection period. If the Flat-out option is adopted to calculate the number of household served per day, the maximum utilisation of collection vehicles may reach 100%. This means that other methods may have to be adopted to deal with variations in demand, such as that used in Kingston where the team supervisor drives a spare empty vehicle to the collection area and exchanges it for the full RCV. The supervisor then takes the full vehicle for unloading and the crew continue their jobs with the empty RCV (Personal Communication, Veolia staff, 2013).

As noted in Chapter 4, laden percentage had relatively little effect on fuel consumption: the main factor was distance travelled. To reduce fuel consumption, the first step is thus to reduce the total travelling distance, and one way to achieve this in real situations is by route optimisation (Golden et al., 2002). Route planning and route optimisation software such as JOpt Tour Planner, RouteSmart and FleetRoute™ is already used to minimise the driving distance in refuse collection services by the re-allocation of collection routes and re-scheduling of collection sequences (Ford, 1999, DNAevolutions, 2009, FleetRoute, 2011); and it has been suggested that total travelling mileages could be reduced by up to 10%, saving 12% of the cost of fuel in household waste collection (Ordnance Survey, 2007). In practice, however, many collection crews prefer to decide the collection order based on their own experience and habits (Ford, 1999), taking into account factors such as congestion, accessibility, safety, time and effort (e.g. at steep gradients the preferred direction of travel is chosen so that loaders take full bins downhill and bring empty ones up) (Personal Communication, Veolia staff, 2013).

Fuel consumption in the transportation stage to the treatment facility was not modelled in this study or those in subsequent chapters: the volume of food waste is relatively small and it cannot be stored for long, so it is reasonable to assume that it is unloaded at or adjacent to the depot for bulking and transport. In general, however, longer driving distances have an adverse impact on the environment, and optimisation of the location of treatment facilities would reduce fuel consumption.

Apart from minimising the total travelling distance, better utilisation of the capacity of vehicles could potentially reduce the number of separate collections operated and thereby the fuel consumption. Figure 6.7 and 6.8 show that the 26-tonne RCV has the worst capacity utilisation in weight and volume in weekly collection. To improve resource utilisation, multi-compartment collection vehicles with two or three compartments or stillage vehicles could be introduced for the co-collection of source-separated food waste and recyclable or residual waste. The total travelling distance is expected to be reduced by the co-collection of source separated household waste, if the compartments are designed in the right ratio and the workload is balanced; and this topic is explored further in the following chapters. On the other hand, household and commercial wastes are usually collected separately in the UK, but the overall distance travelled also could be reduced by joint collection of both wastes at the same time (McLeod et al., 2011). Furthermore, in UK waste collection it is common practice to have only one shift per working day. Collection activity begins as early as 6 am and the task is normally finished before 2 pm (McLeod et al., 2011, Dudley, 2012). Although this minimises the disturbance to business the resources are not fully utilised, especially for large collection vehicles which have the capacity to continue collecting all day. In this case, increasing the number of shifts may be effective. The first collection crew could hand over the task to a second crew in the collection area and the collection activity could continue until the RCV is full; or the RCV could return briefly to the depot for exchange of crews with only a relatively small addition to the distance travelled. Collection in shifts could further reduce the time spent and the mileage travelled to the unloading site, thus maximising the productivity and reducing the total fuel consumption.

6.5.3 Total time and number of collection vehicle required

The time for collection of source segregated food waste per completed collection and the number of RCVs required are discussed together in this section, as these parameters give an indication of the relative costs of labour and the capital cost of the collection system. The time spent in collecting food waste is related to the number of full loads delivered per day, which explains the variations in total time spent for different sizes of RCVs. The time required for the weekly collection of food waste by vehicles with a gross weight of 15 tonnes or above is the same, because the number of full loads per working area is the same and the vehicle travels to the unloading site only once per day. In contrast, the 3.5-tonne RCV required the longest time to complete the whole collection as the number of full loads is approximately 3 times greater than for the larger vehicles.

With respect to the number of RCVs required, the fleet size is larger when smaller vehicles such as 3.5-tonne and 7.5-tonne RCVs are used for the food waste collection. Considering the total time spent and the RCV fleet size, the larger RCVs such as 15-tonne, 18-tonne and 26-tonne vehicles could be the most sensible collection system to use at all collection frequencies and set-out rates.

6.5.4 The most suitable food waste collection schemes

In this study, the main focus was the fuel consumption in source segregated food waste collection, while total time spent, total distance travelled and number of vehicles required were regarded as less important. Therefore, the discussion on selection of the most suitable collection schemes emphasised fuel consumption rather than other parameters. The results in Table 6.12 indicate that for this case study of a hypothetical city of 25,000 households, the 7.5-tonne RCV is the preferred vehicle for use in a single additional collection mode under all scenarios and at all set-out rates if fuel consumption is considered, while the 26-tonne RCVs is the best one for the rest of the output parameters. As large vehicles may not function well in narrow streets or congested spaces, however, in some cases they may be a non-preferred option even when their use could save time and travelling distance or reduce fleet size. If fuel consumption is the only factor in selection of the best collection system, fortnightly collection is definitely the best frequency. If the study is widened to consider collection of the whole waste stream with downstream materials recovery, however, fortnightly collection may not always be the right choice for a number of reasons, including the fact that lower set-out rates for food waste are predicted. Further research is needed to clarify the influence of a wide range of external factors on scheme performance; and better understanding of these may suggest a broader range of scenarios to model. The approach used here, however, appears to offer useful insights into collection schemes and increased understanding of the implications of different options in terms of energy and resource use.

6.5.5 Sensitivity analysis

The purpose of the sensitivity analysis was to determine which inputs have the greatest influence on the outputs, so that particular attention can be paid to these when selecting values to run the model. In this study, the distance between properties always made the biggest contribution to uncertainty in fuel consumption, total time spent and total distance travelled. It is clear that an increase in the distance will increase these three output parameters. The factor of distance between properties mainly represents the overall density of housing in a particular area, and further work would be useful to identify the best means of selecting a suitable value. In the validation studies in the current work, the parameter was set by dividing the total distance travelled in collection area by the number of properties served, but this is only possible when the round already exists, and the approach is thus not applicable in hypothetical or initial scoping studies. Further research is therefore needed to elucidate how best to relate this parameter to easily-obtainable data on collection areas. This result from the sensitivity analysis implies that areas with a high housing density, such as city centres and urban areas, will typically use less fuel in waste collection, while rural areas will use more as the properties are more scattered. This is supported by the data presented in VALORGAS (2013a): the population density in Flintshire was 3.48 person ha^{-1} (Conwy County Borough Council, 2013) which is higher than in Broadland (2.2 person ha^{-1}) (Norwich City Council, 2012), while Flintshire has lower fuel consumption per tonne of food waste collected (10.9 L $tonne^{-1}$) than Broadland (12.94 L $tonne^{-1}$). The result shows the limitations inherent in making simplistic fuel-used-per-tonne-collected comparisons between different locations and scheme types, and illustrates the potential value of a simple modelling tool in which the performance of different scenarios can be compared while all other characteristics of the location are kept constant.

The second most important parameters affecting the fuel consumption were the correction factor for extra fuel consumption in collection, and the speed in collection. As the regression coefficients of the correction factor (R=0.33-0.47) and speed in collection (R=-0.3) are considerably smaller than that for the distance between properties (R=0.76-0.9), however, the results showed that errors in these parameters are less critical for estimation of the fuel consumption.

Regarding the second most critical factors influencing the total time spent, the speed in collection has a greater effect at low set-out rates (≤50%) while the time spent in picking up the bins has most influence at high set-out rates (>50%). This is not surprising, because fewer bins have to be picked up at low set-out rates, thus speed in collection overrides the effect of the bin pick-up time. Relatively little data is available in the literature on the actual time required to pick up bins, with Tchobanoglous et al. (1993) and Eunomia (2007b) being the main sources of information. The field data collected at different sites in this research has provided more information on this topic. On the other hand, finding average speeds in collection and transportation is likely to become easier in future now that an increasing number of vehicles have tracking systems installed that can provide these data.

6.6 Conclusions from modelling of single additional food waste collections

A kerbside collection of source separated food waste in a hypothetical city of 25,000 households was modelled for weekly and fortnightly collection intervals using the model described in chapter 4. The model was run with six different sizes of single-compartment collection vehicles at set-out rates from 10-100%. The results showed that:

- For the hypothetical medium-sized town considered, the single additional food waste collection consumed 6.0-70.1% of the recoverable energy in the food waste.
- The 7.5-tonne RCV performs best in term of fuel consumption at all set-out rates for weekly and fortnightly collection, while the 3.5-tonne RCV has the worst performance. However, the 3.5-tonne RCV had the highest utilisation of compartments in all situations.

- In terms of total travelling distance and time spent, fortnightly collection of food waste by 26-tonne single-compartment vehicle is the best (scenario C1-F6) in all set-out rates.
- Fortnightly collection of food waste by all vehicle types except the 3.5-tonne RCV (scenario C1-F6) uses the minimum number of vehicles at set-out rates 90% or below. When all food waste is captured, using RCVs of gross weight 12 tonnes or above required the smallest number of vehicles.
- The distance between properties is the most influential factor on fuel consumption, total time spent and total distance travelled. Other parameters have less effect on the outputs, including the correction factor for extra fuel consumption in collection, speed in collection and transportation. More detailed study of this parameter and of rapid ways to assign a suitable value to it in scoping and hypothetical studies would therefore be valuable as a means of improving the accuracy of model predictions.
- Reductions in total travelling distance could potentially be achieved by introducing multi-compartment collection vehicles for the co-collection of food waste and other household waste, or by joint collection of domestic and household waste, route optimisation and location optimisation of treatment facilities.

The next stage of the work thus goes on to study energy consumption and resource use in collection of the whole household waste stream with different allocations of waste types and compartments in two-compartment and stillage vehicles.

Chapter 7: MODELLING KERBSIDE SOURCE SEGREGATED FOOD WASTE COLLECTION: SEPARATE COLLECTION AND CO-COLLECTION

In this chapter, the kerbside collection model is used to estimate the fuel consumption, total time spent, total travelling distance and the number of vehicles required in the kerbside collection of household waste as a whole: source segregated food waste, co-mingled recyclable waste and residual waste. Section 7.1 gives the general background and the research questions that are addressed. Section 7.2 is the methodology section that describes the composition of kerbside household waste, the scenarios and the data inputs used, and lists the various model inputs considered in sensitivity analysis. Section 7.3 reports the results of modelling the effect of capture rates for food waste and recyclables on fuel consumed per tonne of residual waste collected, and identifies the best and the worst scenarios as well as comparing the performance in terms of fuel consumption, total distance travelled, time spent in whole collection and the number of vehicles required. Last but not least, the best collection vehicles and the allocation of waste types and compartments are also considered. Section 7.4 reports the result of sensitivity analysis on output parameters. Section 7.5 discusses the implications of the results and the limitations of this study. Finally, the findings of this study are summarised in Section 7.6.

7.1 Introduction

The increasingly widespread adoption of source-separated household waste collections is driving local authorities to think of introducing different types of collection vehicles in order to maximise collection efficiency and reduce operating costs. When the degree of source separation increases, multi-compartment collection vehicles become more attractive. Currently, the two-compartment collection vehicle is gaining in popularity amongst local authorities that collect three separate waste fractions. Only limited information, however, is available to support local authorities in their choice of RCV and collection scheme. Vehicles are usually selected based on the experience of other users, through word-of-mouth or from the manufacturers' promotional materials. According to the literature, only a limited amount of research has been carried out on collection by multi-compartment vehicles. Most studies have looked at goods delivery by compartmentalised vehicles, and similar studies on waste collection are rare (Mendoza et al, 2009; Derigs et al, 2011). It is important, however, to establish the difference in fuel consumption when using traditional and compartmentalised vehicles in order to provide an insight into better options for fleet management and resource allocation.

In addition, the results of the study in chapter 6 on the use of single-compartment collection vehicles for the collection of source-segregated food waste showed that the 18- to 26-tonne collection vehicle is not ideal for food waste collection because of the high fuel consumption and the imbalance between compartment size and working time. This chapter therefore applies the kerbside collection model described in Chapter 4 to look at fuel consumption and other parameters in collection schemes involving two-compartment vehicles. In order to do this it is necessary to look at the whole waste stream, since the vehicles carry both source segregated food waste and residual or recyclable waste. The aims of the modelling are thus:

- To investigate how capture rates affect the total energy required for the whole collection.
- To determine which scenarios have the best and worst performance in total fuel consumption for household waste collection.
- To compare the difference in fuel consumption for the single collection and co-collection of household waste.
- To determine which vehicle types are best at different capture rates.
- To establish the best method of allocation of waste between compartments.
- To estimate the appropriate size of compartment and ratio of compartment based on the proportion of each waste fraction.
- To conduct a sensitivity analysis in order to determine which factors have a major effect on energy consumption in the co-collection of waste.

7.2 Methodology

7.2.1 Composition of kerbside household waste

Household waste composition was based on the results of a detailed survey of local authority collected waste in England (Defra, 2012a) including household residual and recyclable waste collected at the kerbside, at HWRC and in street bins. The Defra survey classified the waste into 20 categories, which for the purposes of this work were combined as follows: Paper and card, Food waste, Garden & other organic waste, Plastics, Glass, Metals, Wood, Textiles, WEEE, and Other. For this study waste composition was re-calculated from the reported data to give kerbside collected material only (i.e. excluding waste collected via bring systems). Total household waste collected from the kerbside, including residual waste, was 17,397,102 tonnes in England in 2010/11. Assuming there were 22,063,368 households in England in 2011 (Office for National Statistics, 2013), each household in England generates on average 788.5 kg per year of kerbside waste, equivalent to 2.16 kg per household per day. The estimated average quantities of food waste, recyclables and residual wastes collected are shown in Table 7.1. In this study, recyclable waste means Paper and card, Plastics, Glass and Metals that are collected co-mingled. Residual waste is a mixture of materials including Wood, Textiles, WEEE, and

Other wastes, and any recyclables and food waste that have not been captured in the recycling bins. The set-out rate for residual waste bins was assumed to be 100%, while Garden & other organic wastes were assumed to be composted or collected separately.

Table 7.1 Composition of kerbside household waste used in modelling

Composition [a]	Proportion [b] (%)
Paper and card	22.15
Food	21.70
Plastics	11.43
Glass	7.13
Metals	3.17
Wood	0.83
Textiles	2.69
WEEE	0.82
Other	11.42

[a] Assuming garden and other organic waste are composted on site or collected separately
[b] Adapted from Defra (2012a)

7.2.2 Options for collection vehicles

Several types of RCV can be specified in the model. The vehicles are categorised into two main types, which are single-compartment and compartmentalised collection vehicles. For the single-compartment vehicles, there are six different sizes ranging from 3.5- to 26-tonne. Compartmentalised vehicles are sub-divided into two categories, which are the front and rear compartmentalised vehicle (Duo body) and the rear split collection vehicle (Twin body). Details of the differences between these vehicles are given in Chapter 2. The specification of each collection vehicle is shown in Table 7.2.

Table 7.2 Specification of collection vehicles used in modelling

					Compartment size	
Code	Refuse collection vehicle	GVW (tonnes)	Payload (tonnes)	Number of compartment(s)	Small (m^3)	Large (m^3)
3.5t	FARID Mini-micro	3.5	0.715	1	5.5	--
7.5t	FARID MicroL	7.5	3.58	1	5	--
12t	FARID PN10	12	3.74	1	10	--
15t	FARID PN13	15	5.90	1	13	--
18t	FARID PN15	18	7.75	1	15	--
26t	WRATE 6x4 RCV Fleet	26	12.842	1	25	--
Duo1	Phoenix 2 Duo - 12W + Combi7	26	11.77	2	5	13.89
Duo2	Phoenix 2 Duo - 12W + Combi9	26	11.57	2	7	13.89
Duo3	Phoenix 2 Duo - 15W + Combi9	26	11.26	2	7	16.45
Twin1	Phoenix TwinPack 50:50 split	26	10.58	2	10	10
Twin2	Phoenix TwinPack15 70:30 split	23	9.28	2	5	10
Twin3	Phoenix TwinPack20 70:30 split	26	10.88	2	6	14

7.2.3 Scenarios

As in the preceding chapter, a hypothetical area of 25,000 households corresponding to a medium-size town was used for the case study. It is assumed that kerbside household waste is collected by a single-compartment or compartmentalised collection vehicle on a weekly or fortnightly basis. Nine scenarios were considered based on some of the combinations of collection frequencies, vehicle types and waste types that occur most commonly in the UK. Each scenario was run with capture rates for food waste and recyclables ranging from 10-100%. The scenarios are shown in Table 7.3. In this study, only weekly collection of source separated food waste was considered as this is widely regarded as the maximum acceptable interval in much of the UK and many other parts of Europe, although practice varies depending on climate and season.

Table 7.3 Nine scenarios for collection systems

Scenario	Description
C1-S1	Weekly separate collections of recyclables, residual and food waste by single-compartment RCV
C1-S2	Alternate fortnightly collection of recyclables and residual waste and weekly collection of food waste by single-compartment RCV
C1-S3	Weekly co-collection of recyclables and residual waste by compartmentalised RCV, weekly collection using single-compartment RCV for food waste
C1-S4	Fortnightly co-collection of recyclables and residual waste by compartmentalised RCV, weekly collection using single-compartment RCV for food waste
C1-S5	Weekly co-collection of recyclables and food waste by compartmentalised RCV, weekly collection using single-compartment RCV for residual waste
C1-S6	Weekly co-collection of recyclables and food waste by compartmentalised RCV, fortnightly collection using single-compartment RCV for residual waste
C1-S7	Weekly co-collection of residual waste and food waste by compartmentalised RCV, weekly collection using single-compartment RCV for recyclables
C1-S8	Weekly co-collection of residual waste and food waste by compartmentalised RCV, fortnightly collection using single-compartment RCV for recyclables
C1-S9	Weekly food waste collection with AWC of residual waste and recyclables by compartmentalised RCV

7.2.4 Model inputs

The values used in modelling the scenarios are shown in Table 7.4. Descriptions of inputs such as working hours, time for intermediate unloading, unloading site and the pick-up time for bins are as given in Chapter 6: for details refer to Section 6.2.4.

All of the input values used in the study of single additional collections were applied in this study; in addition, some further inputs such as bulk density of recyclable and residual waste, pick-up time for recycling or residual waste bins were needed. It was assumed that recyclables and residual waste were collected in wheeled bins. The average pick-up time used for the wheeled bin was 36 seconds per location (Tchobanoglous et al., 1993): this is longer than for a food waste container, as extra time is required to load the waste using a bin lifter. For the size of the crew, it was assumed 2 and 2.5 collectors were available to pick up food waste containers and wheeled bins respectively from households setting them out. The bulk density of co-mingled recyclables was taken as 405 kg m^{-3} as reported by WRAP (2010), and of residual waste as 348 kg m^{-3} (WRAP, 2008f).

Table 7.4 Input values for modelling kerbside collection of household waste in a hypothetical city of 25,000 households

Parameter	Value	Units
General information:		
Number of households	25000	no. of HH
Amount of kerbside household waste generated	2.16	kg HH^{-1} day^{-1}
Number of collectors for food waste collection	2	no. of collectors
Number of collectors for recyclable and residual waste collection	2.5	no. of collectors
Bulk density of waste:		
Food waste	470	kg m^{-3}
Recyclable waste	405	kg m^{-3}
Residual waste	348	kg m^{-3}
Time:		
Working hours	6	hours
Break	30	mins
Traffic congestion	0	mins
Pick up crews	5	mins
Fuel filling	10	mins
Depot to first collection point	15	mins
Last collection point to depot	15	mins
At unloading site	30	mins
To intermediate unload when full	15	mins
For intermediate unloading	15	mins
Pick-up time for food waste bin	21.6	s HH^{-1}
Pick-up time for recycling/ residual waste bin	36	s HH^{-1}
Distance:		
From depot to first collection point	6.25	km
From last collection to unloading site	6.25	km
Between collection points	15	m
To intermediate unload when full	6.25	km
Speed:		
In transportation	25	km hr^{-1}
In collection	10	km hr^{-1}
Factor for extra fuel consumption in collection:		
3.5-tonne to 9.5-tonne RCV	1.51	
12-tonne to 18-tonne RCV	2.02	
26-tonne RCV	2.86	

7.2.5 Sensitivity analysis

Monte Carlo simulation was carried out using the @Risk® software to assess the effect on model output of uncertainty in inputs values. Input values for the model were collected from literature and reports, and probability distributions were applied to 14 inputs. These were the bulk density of different wastes, the number of collectors in different situations, pick-up time for different containers, the average distance between properties, the average speed in collection and transportation and the correction factors for extra fuel consumption for different vehicles.

The probability distribution of each parameter was based on the available data and on an understanding of the inputs. Details are given in Table 7.5.

Data collected from the study sites were used to provide input ranges for all parameters apart from the density of food waste, recyclables and residual waste; the number of collectors; and the pick-up time for recyclables and residual waste. The minimum and maximum value of bulk density of food waste was taken from WRAP (2010), while the most likely value came from WRAP (2009a). The minimum and maximum values of residual waste densities were taken from WastesWork Ltd (2009) and Enviros RIS (2001), respectively. Minimum and maximum values for the density of co-mingled recyclables were as reported by WRAP (2010). The minimum and maximum number of collectors involved in the waste collection was decided according to the waste type and the size of the cab. The maximum number of collectors for the recyclable and residual waste collection was assumed to be 3 because this is the maximum capacity of the cab in addition to the driver, who was not counted as available for collection activities. The minimum and maximum pick-up times for recycling and residual waste bins were taken from Tchobanoglous (2002).

The average values for the fuel consumption, total working time, total travelling distance and the number of vehicles required at different capture rates were used to identify the optimal scenarios for the collection system and the allocation of compartments. Scenarios C1-S1 and C1-S2 were separated into three parts for the sensitivity analysis. Scenarios C1-S1a and C1-S2a represent weekly and fortnight collection of recyclables, while C1-S1b and C1-S2b represent weekly and fortnight collection of residual waste. Scenario C1-S9 was split into two parts to conduct the sensitivity analysis. Scenario C1-S9a represents the AWC of residual waste with food waste, while C1-S9b represents the AWC of recyclables with food waste.

Table 7.5 Minimum, maximum and static values of each input parameter

Parameter	Minimum	Static	Maximum	Distribution
Bulk density:				
- Food waste (kg m^{-3})	400	473[a]	600	Triangle
- Co-mingled recyclable (kg m^{-3})	239	405[a]	758	Triangle
- Residual waste (kg m^{-3})	69	348[a]	418.3	Triangle
Number of collectors:				
- For picking up food waste	1	2	2.5	Uniform
- For picking up recyclable and residual waste	2	2.5	3	Uniform
Pick-up time:				
- For food waste bin	8.46	21.6	27.5	Uniform
- For recycling/residual waste bin	30	36	54	Uniform
Distance between collection points (m)	3.6	15	29.5	Uniform
Speed in transportation (km hr^{-1})	15.8	25	48.8	Uniform
Speed in collection (km hr^{-1})	6	10	14.7	Uniform
Correction factor for extra fuel consumption:				
3.5-tonne to 9.5-tonne RCV	1.51	1.51	3.04	Uniform
12-tonne to 18-tonne RCV	1.06	2.02	2.75	Uniform
26-tonne RCV	2.1	2.86	3.5	Uniform

[a] Represents the most likely value when triangle probability distribution is used.

7.2.6 Comparison of scenarios

The different scenarios were grouped to allow comparison of the difference in fuel consumption with respect to collection frequency, collection method and allocation of waste to the compartments. Scenarios C1-S1, S3, S5 and S7 were compared to find the differences between single collection and the weekly co-collection of kerbside household waste. Scenarios C1-S2, S4 and S9 were considered in parallel to compare alternate weekly collection and fortnightly co-collection of household waste using single-compartment and two-compartment RCVs. Scenarios C1-S6 and C1-S8 were compared to investigate the effect of allocating the different types of waste to different vehicle compartments in fortnightly collection. The same comparison was made for scenarios C1-S3, S5 and S7 for weekly collection.

7.2.7 Reporting units

Litres of diesel per week for the total household waste collection, and litres of diesel per tonne of waste collected were used to report the fuel consumption. The latter unit was mainly used to study the difference in the fuel consumption of the residual waste collection when the capture rates of food waste and recyclables varied.

7.3 Results

7.3.1 Effect of capture rates for food waste and recyclables on fuel consumed per tonne of residual waste collected

Figures 7.1 and 7.2 show the fuel consumption per tonne of residual waste collected in scenarios C1-S1 and C1-S2 at different capture rates for food waste and recyclables. At low capture rates for food waste and recyclables there is a significant amount of residual waste to be collected. In both weekly and fortnightly collection, the fuel consumption per tonne for residual waste increases with an increase in capture rates for food waste and of recyclables, as expected. In Figure 7.1, it can be seen that the fuel consumption per tonne of residual waste collected ranges from 2.37 to 5.7 L tonne^{-1}. In weekly residual waste collection, for recyclables capture rates from 10-60%, changes in the food waste capture rate have little effect on the fuel consumption per tonne of residual waste collected. As the capture rate for recyclables rises above 60%, the fuel consumption per tonne of residual waste also rises, by a factor of up to 1.40 as the food waste capture rate increases. On the other hand, the change in the recyclable capture rate has an even greater effect as more food waste is captured The maximum fuel consumption per tonne of residual waste collected is up to 1.52 times higher than the minimum.

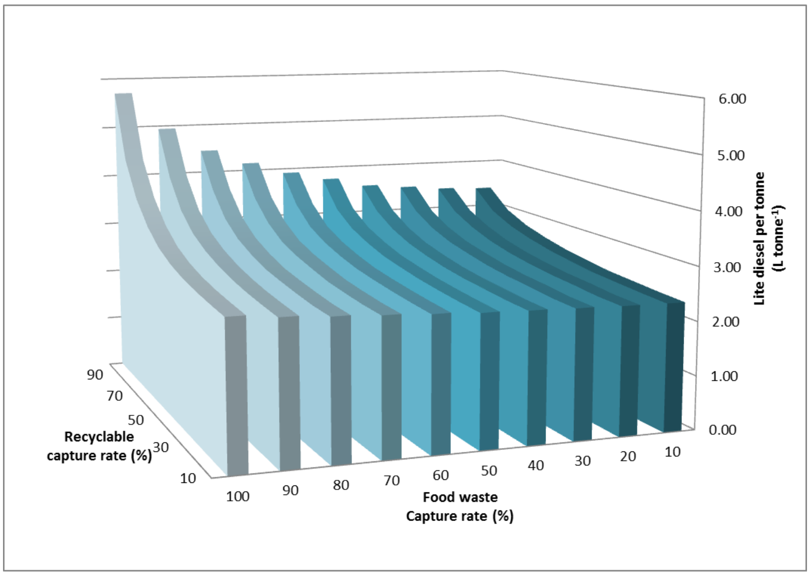


Figure 7.1 Fuel consumption for collection of one tonne of residual waste at different capture rates for food waste and recyclables (Weekly collection)

Figure 7.2 shows the fuel consumption for collection of one tonne of residual waste in fortnightly collection, which ranges from 1.89 to 3.86 L tonne^{-1}. As the food waste capture rate increases, the fuel consumption for residual waste rises by from 1.11 to 1.35 times for recyclable waste capture rates from 10-100%, respectively. When the majority of food waste is captured (capture rate ≥ 70%), from 1.33 to 1.44 times more fuel is used to collect one tonne of residual waste as the capture rate for recyclables rises. Comparing weekly and fortnightly collection of residual waste, the maximum increase in fuel consumption in weekly collection is about 9% higher than in fortnightly collection when both capture rates of food waste increases.

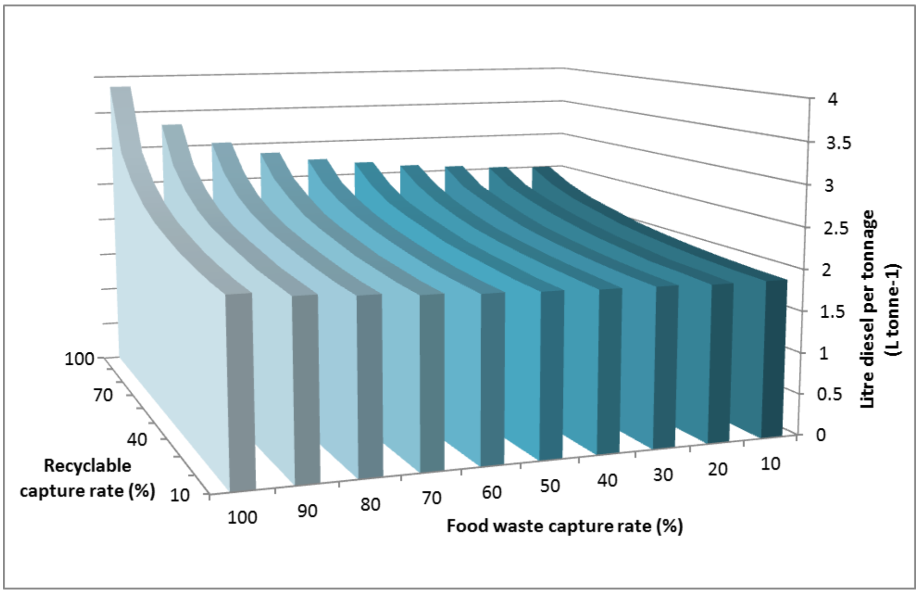


Figure 7.2 Fuel consumption in collection one tonne of residual waste at different capture rate for food waste and recyclables (Fortnightly collection)

7.3.2 Best and worst collection systems

For the purposes of comparison, equal capture rates were assumed for food waste and recyclables in this part of the work.

7.3.2.1 Fuel consumption in collection of the whole household waste stream

Table 7.6 and Figure 7.3 show the fuel consumption for collection of the whole household waste stream in each scenario at capture rates of 10-100% for recyclables and food waste. For scenarios using a single-compartment RCV, the model was run for the whole range of RCVs shown in Table 7.2, and the result shown is for the vehicle giving the lowest fuel consumption in each case. Similarly, for twin-compartment vehicles all permutations of waste stream and compartment were tested, and the result shown is for the combination giving the lowest fuel consumption. In general, the fuel consumption for collecting the whole household waste stream decreases when the capture rates for co-mingled recyclables and for food waste increase, and the reasons for this are explained further in section 7.3.2.2; in some scenarios, however, there is a small increase in fuel consumption at high capture rates. Figure 7.3 shows that alternate fortnightly collection of recyclables and residual waste and weekly collection of food waste by single-compartment RCV (scenario C1-S2) consumed the least fuel at all capture rates. On the other hand, weekly co-collection of recyclables and food waste by compartmentalised RCV with weekly collection using single-compartment RCV for residual waste (scenario C1-S5) consumed the most fuel in most situations. Considering the co-collection of household waste by compartmentalised vehicles, fortnightly co-collection of recyclables and residual waste by compartmentalised RCV and weekly collection using single-compartment RCV for food waste (scenario C1-S4) is better than other scenarios that involved co-collection of household wastes. Weekly food waste collection with AWC of residual waste and recyclables by compartmentalised vehicles (scenario C1-S9) is the second best co-collection system, but it still consumed more fuel than weekly and fortnightly separate collection of recyclable and residual waste with weekly food waste collection by the single-compartment vehicles.

Table 7.6 Summary of fuel consumption for collection of the whole household waste stream under optimal collection options for each scenario (L week^{-1})

	Capture rate (%)									
Scenario	10	20	30	40	50	60	70	80	90	100
C1-S1	1036.9	1038.9	1036.4	1026.2	1007.6	986.6	963.3	951.5	939.4	909.5
C1-S2	803.0	803.5	799.7	794.9	788.3	780.7	767.6	749.2	725.2	705.7
C1-S3	1261.9	1256.9	1245.5	1231.6	1211.7	1193.9	1176.4	1168.3	1174.6	1176.9
C1-S4	910.9	907.8	903.3	891.9	876.1	853.2	826.4	812.5	832.0	797.8
C1-S5	1331.1	1340.4	1345.8	1342.8	1331.7	1316.0	1293.4	1274.6	1246.5	1193.8
C1-S6	1201.5	1212.8	1220.3	1223.9	1220.4	1211.0	1194.3	1169.8	1136.0	1100.2
C1-S7	1266.3	1266.8	1261.2	1253.6	1236.4	1219.5	1211.6	1211.2	1226.3	1245.9
C1-S8	1162.0	1159.0	1150.0	1141.3	1128.4	1118.5	1115.0	1113.8	1122.5	1135.7
C1-S9	1047.9	1052.8	1052.7	1049.1	1040.2	1020.3	995.0	968.2	938.0	928.3

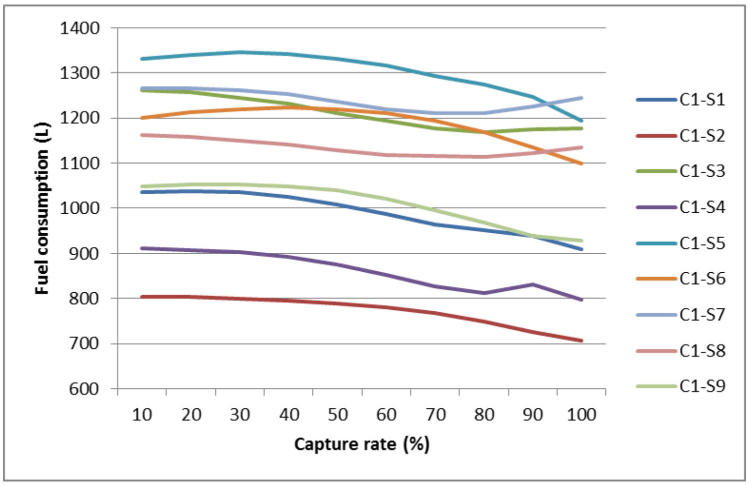


Figure 7.3 Fuel consumption for household waste collection at different capture rates under optimal collection options for each scenario

7.3.2.2 Total travelling distance in collection of the whole household waste stream

The total distance travelled per week in the collection of household waste was examined as an indicator of the lifespan of the collection vehicle with respect to wear-and-tear and maintenance.

Figure 7.4 and Table 7.7 shows the best outcome regarding travelling distance for the whole household waste collection at 10-100% capture rates of recyclables and food waste in each scenario. Basically, three types of trend are seen. For scenarios C1-S1 and C1-S5, an upward trend is observed when the capture rate for recyclables and food waste increase from 10% to 100%. Most of the scenarios showed a small increase in the total travelling distance at low capture rates; the distance travelled then falls at the middle range of capture rates and rises again at high capture rates. Scenario C1-S9 shows another pattern in which the distance travelled is constant at low capture rates and decreases rapidly with an increase in capture rate for recyclables and food waste. Some peaks are observed along the lines. Sudden increases in distance travelled are mainly caused by an increase in the number of collection rounds required.

A distinct difference between the worst and the best scenarios is observed in Figure 7.4. Weekly separate collections of recyclables, residual and food waste by single-compartment RCV (scenario C1-S1) is the worst, and in this scenario the total travelling distance increases significantly with an increase in capture rate for recyclables and food waste. The best collection system was weekly food waste collection with AWC of residual waste and recyclables by compartmentalised vehicles (scenario C1-S9). The total travelling distance for this scenario actually reduced at capture rates of 50% or above. This is explained by considering the two components involved in AWC of residual waste and food waste (week 1) and of recyclable and food waste (week 2). For the co-collection residual waste and food waste there is a significant decrease in the travelling distance with increasing capture rates for these materials: this is because at low capture rates more intermediate unloading of the residual fraction is required. When more food waste and recyclables are diverted from the residual waste stream, the constraint shifts from volume capacity to time spent. When both halves of the AWC are taken into account there is thus a net decrease in total travelling distance for the whole household waste collection. This also explains the reduction in fuel consumption at high capture rates for all AWC scenarios in Fig 7.3.

Table 7.7 Average distance travelled per week in collecting the whole household waste stream at different capture rates under the optimal collection option for each scenario (km week^{-1})

	Capture rate (%)									
Scenario	10	20	30	40	50	60	70	80	90	100
C1-S1	2678.7	2754.7	2823.9	2889.1	2936.9	2974.8	3029.9	3094.9	3169.8	3264.7
C1-S2	2135.9	2188.6	2222.3	2243.3	2245.6	2232.9	2188.2	2138.3	2108.5	2132.6
C1-S3	2424.8	2420.5	2389.6	2352.0	2292.7	2237.8	2182.0	2160.6	2181.9	2181.6
C1-S4	2153.8	2158.9	2157.3	2131.3	2087.6	2012.1	1918.1	1868.2	1931.5	1789.8
C1-S5	2030.0	2075.1	2112.4	2142.9	2154.7	2161.9	2184.3	2214.3	2256.9	2315.4
C1-S6	1810.4	1862.6	1898.1	1919.4	1921.6	1909.5	1865.4	1816.9	1787.5	1806.0
C1-S7	2461.7	2502.3	2520.1	2531.6	2508.2	2475.7	2466.6	2460.0	2492.1	2545.5
C1-S8	2138.5	2148.7	2132.8	2109.4	2049.9	1986.1	1943.7	1900.9	1900.1	1922.8
C1-S9	1796.3	1811.3	1805.5	1788.1	1748.5	1666.1	1563.0	1451.4	1336.2	1302.0

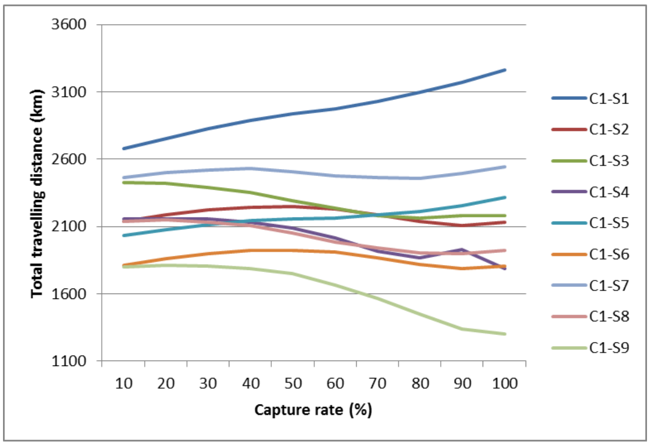


Figure 7.4 Distance travelled in household waste collection at different capture rates under the optimal collection option for each scenario

7.3.2.3 Total time spent in collection of the whole household waste stream

The time for collection of the whole household waste stream per week was investigated as this provides an indicator of the relative costs of labour. The values shown in Figure 7.5 and in Table 7.8 represent the minimum time spent on collection at each capture rate for food waste and recyclables at equal rates. It is apparent that total time spent for collecting the whole household waste stream decreases when the capture rates for co-mingled recyclables and for food waste increase. Two sets of slope gradients can be seen in Figure 7.5: the time spent in collection of the whole household waste stream increases gradually in scenarios C1-S3, C1-S8, C1-S4 and C1-S9, while the other scenarios show a steeper increase when the capture rates increase from 10% to 100%. It is clear that weekly food waste collection with AWC of residual waste and recyclables by compartmentalised vehicles (scenario C1-S9) uses the least time to complete the whole collection at capture rates of 20% or more. Weekly separate collections of recyclables, residual and food waste by single-compartment RCV (scenario C1-S1) has the worst performance with respect to total time per week in all situations except at a capture rate of 10%.

Table 7.8 Time spent per week in collecting the whole household waste stream at different capture rates under the optimal collection option for each scenario (hours week^{-1})

	Capture rate (%)									
	10	20	30	40	50	60	70	80	90	100
C1-S1	412.1	446.9	481.1	515.1	548.6	581.2	614.9	649.1	683.7	719.6
C1-S2	272.4	295.4	316.9	338.0	358.3	377.4	395.0	411.8	429.9	451.2
C1-S3	405.9	414.8	422.3	429.4	435.1	441.1	447.2	455.0	465.6	474.2
C1-S4	275.9	285.3	294.1	301.9	308.7	313.7	317.9	324.5	337.1	338.5
C1-S5	335.5	358.1	380.1	401.8	422.6	443.2	464.6	486.4	508.8	532.1
C1-S6	238.4	261.3	283.4	304.8	325.1	344.4	362.2	379.5	397.8	418.8
C1-S7	421.0	444.4	466.7	488.6	508.7	528.0	548.5	569.7	592.7	616.4
C1-S8	378.4	389.6	399.2	408.4	415.9	422.9	430.9	439.3	449.9	461.2
C1-S9	241.5	252.3	261.9	270.9	278.8	284.5	288.8	292.5	295.7	303.7

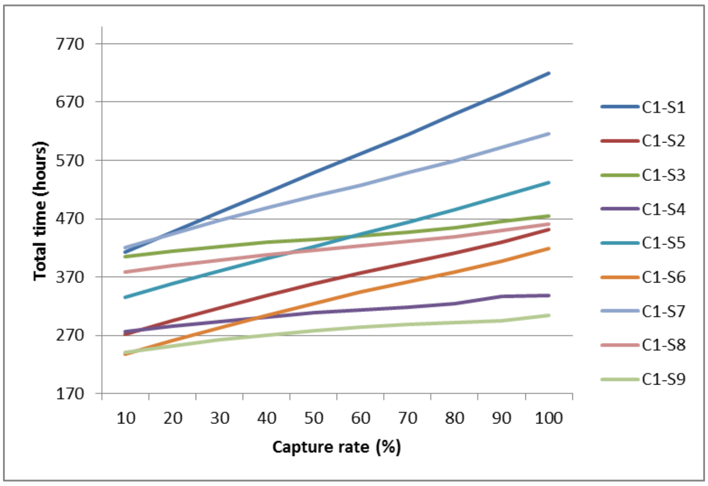


Figure 7.5 Time spent in collection of the whole household waste stream at different capture rates under the optimal collection option for each scenario

7.3.2.4 Total number of vehicles required for collection of the whole household waste stream

The number of collection vehicles required for collection of the whole household waste stream was studied as this provides an indicator of the capital and operating costs of the scenario. The capital cost of the fleet is affected by both the type and number of vehicles required, and this is considered in more detail in Chapter 9. The number of vehicles required is also significant, as these will require parking space, maintenance and road tax. A breakdown of the number of RCVs required for the collection of whole household waste stream at capture rates from 10-100% for recyclables and food waste is presented in Table 7.9. In most of the scenarios, the size of fleet increases at various rates when the capture rates increases. In Figure 7.6, it can be clearly see that weekly co-collection of recyclables and food waste by compartmentalised RCV with single additional fortnightly collection of residual waste (scenario C1-S6) requires the smallest number of RCVs to complete the collection at low capture rates (10-30%), starting at 10 RCVs and going up to 11. At capture rates of 30% or above, the number of vehicles required ranges from 11 to 13 RCVs, and weekly co-collection of recyclables and residual waste by compartmentalised RCV with single additional weekly collection of food waste (scenario C1-S4) is the optimal collection option at these capture rates. The worst results are for scenario C1-S9 at capture rates of 10-50%, and scenario C1-S1 at capture rates of 50-100%, where the number of RCVs required ranges from 18 to a maximum of 27.

Table 7.9 Breakdown and total number of RCVs required for collection of the whole household waste stream at different capture rates under the optimal collection option for each scenario

		Capture rate (%)									
Scenario	Material[a]	10	20	30	40	50	60	70	80	90	100
C1-S1	FW	3	4	4	4	5	5	6	6	6	7
	RM	4	5	5	6	7	8	9	10	11	11
	RW	9	9	9	9	9	9	9	9	9	9
	Total	*16*	*18*	*18*	*19*	*21*	*22*	*24*	*25*	*26*	*27*
C1-S2	FW	3	4	4	4	5	5	6	6	6	7
	RM	2	3	3	4	4	5	5	5	6	6
	RW	6	6	6	6	6	6	5	5	5	5
	Total	*11*	*13*	*13*	*14*	*15*	*16*	*16*	*16*	*17*	*18*
C1-S3	RM/RW	12	12	12	12	12	11	11	11	11	11
	FW	3	4	4	4	5	5	6	6	6	7
	Total	*15*	*16*	*16*	*16*	*17*	*16*	*17*	*17*	*17*	*18*
C1-S4	RM/RW	8	8	7	7	7	7	7	7	7	6
	FW	3	4	4	4	5	5	6	6	6	7
	Total	*11*	*12*	*11*	*11*	*12*	*12*	*13*	*13*	*13*	*13*
C1-S5	RM/FW	4	5	5	6	7	8	8	9	10	11
	RW	9	9	9	9	9	9	9	9	9	9
	Total	*13*	*14*	*14*	*15*	*16*	*17*	*17*	*18*	*19*	*20*
C1-S6	RM/FW	4	5	5	6	7	8	8	9	10	11
	RW	6	6	6	6	6	6	5	5	5	5
	Total	*10*	*11*	*11*	*12*	*13*	*14*	*13*	*14*	*15*	*16*
C1-S7	RW/FW	12	12	12	12	12	11	11	11	11	11
	RM	4	5	5	6	7	8	9	10	11	11
	Total	*16*	*17*	*17*	*18*	*19*	*19*	*20*	*21*	*22*	*22*
C1-S8	RW/FW	12	12	12	12	12	11	11	11	11	11
	RM	2	3	3	4	4	5	5	5	6	6
	Total	*14*	*15*	*15*	*16*	*16*	*16*	*16*	*16*	*17*	*17*
C1-S9	RM/FW	4	5	5	6	7	8	9	9	10	11
	RW/FW	14	14	14	14	14	13	13	12	11	11
	Total	*18*	*19*	*19*	*20*	*21*	*21*	*22*	*21*	*21*	*22*

[a] FW = Food waste; RM = Recyclable materials; RW = Residual waste

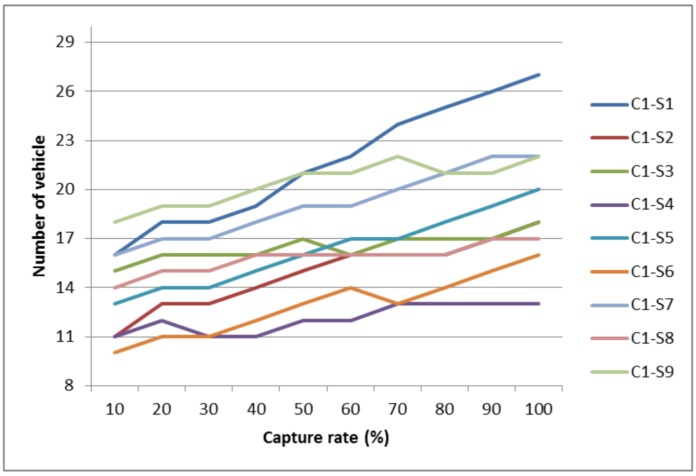


Figure 7.6 Number of RCVs required for collection of the whole household waste stream at different capture rates under the optimal collection option for each scenario

7.3.3 Comparison of optimal scenarios

7.3.3.1 Fuel consumption

The scenarios presented in Table 7.6 were compared with respect to fuel consumption for the whole household waste collection. It is clear that all co-collection options at both different collection frequencies used more fuel than separate collection by single-compartment RCV. Scenario C1-S1 was used as a baseline to determine the difference between the weekly single collection and co-collection, and showed that the extra fuel used by weekly co-collection of household waste ranged from 20.0% to 37.0% (Figure 7.7a). Scenarios C1-S2, S4 and S9 were compared to show the differences between single collection and co-collection once a fortnight using single-compartment and two-compartment RCVs. Scenarios C1-S4 and S9 use respectively 7.7-14.7% and 29.2-32.0% more fuel than scenario C1-S2 at all capture rates (Figure7.7b).

Scenarios C1-S6 and C1-S8 were compared to investigate the effect of allocating wastes to different vehicle compartments in fortnightly collection. Figure 7.7c shows that scenario C1-S6 consumed 1.2-8.3% more fuel than scenario C1-S8 at capture rates of 90% or below. When all food waste and recyclables are captured, about 3% of fuel could be saved by scenario C1-S6. It shows that weekly co-collection of recyclables and food waste by two-compartment RCV with single additional fortnightly collection of residual waste is suitable in most cases. Figure 7.7d shows the fuel used at different capture rates in scenarios C1-S3, S5 and S7 with weekly collection. The best and the worst options respectively are scenario C1-S3 at all capture rates and scenario C1-S7 at high capture rates. The differences between the highest and lowest diesel consumption ranged from 5.5% to 10.2%. The variations in fuel consumption with increasing capture rates are due to changes in the number of vehicles required and the number of intermediate unloads. Although the fuel consumption required to collect e.g. recyclables or food waste in a single-compartment vehicle increases with increasing capture rate, this can be offset by reductions in the fuel required to collect one or more other components of the waste stream, for example by using an optimal size of vehicle, or by a better arrangement of compartments and waste types if the waste is co-collected by two compartment vehicles. This also explains variations in the total distance travelled shown in Figure 7.8.

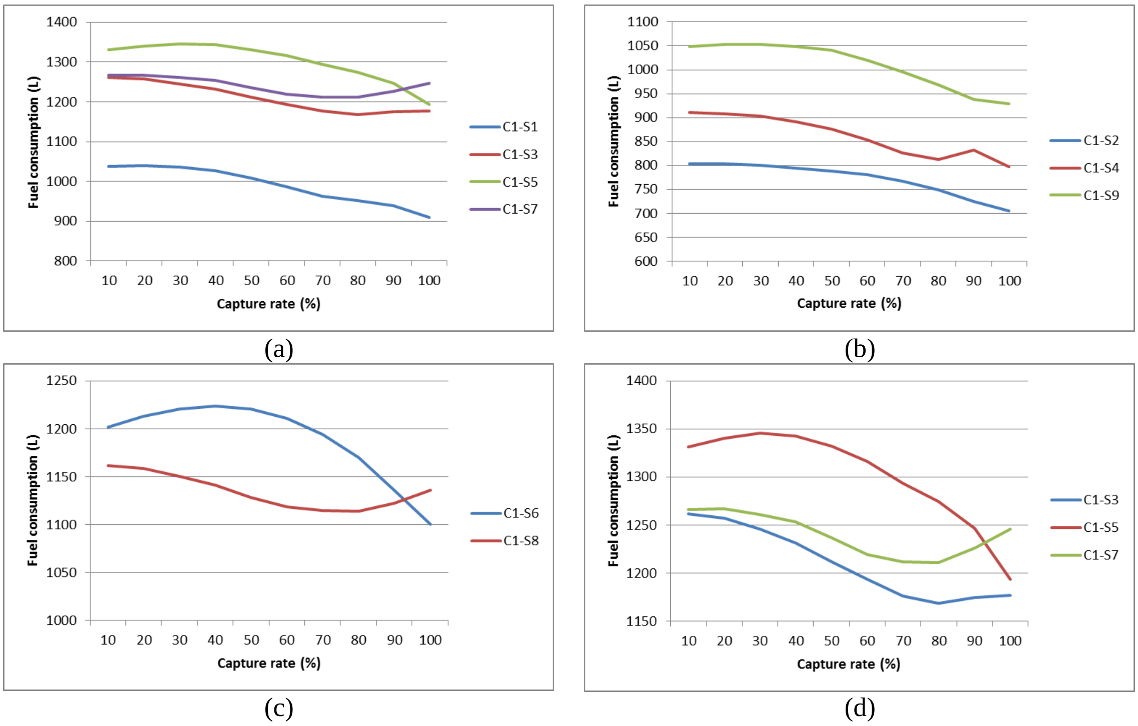


Figure 7.7 Comparison of fuel consumption for collection of the whole household waste stream in single collection and co-collection (a) weekly and (b) fortnightly; effect of permutations of waste type and compartment in weekly co-collection along with (c) fortnightly collection and (d) weeklyly collection

7.3.3.2 Total travelling distance

Weekly and fortnightly single collection of household waste always has the worst performance in total travelling distance. The total travelling distance saved by any weekly and fortnightly co-collection of household waste ranges from 8.1-33.2% and 1.4-38.9% respectively (Figure 7.8a and 7.8b). With the optimal combinations of waste type and compartment, up to 15.3% of the total distance could be saved in weekly co-collection (Figure 7.8c) and up to 16.7% in fortnightly co-collection (Figure 7.8d).

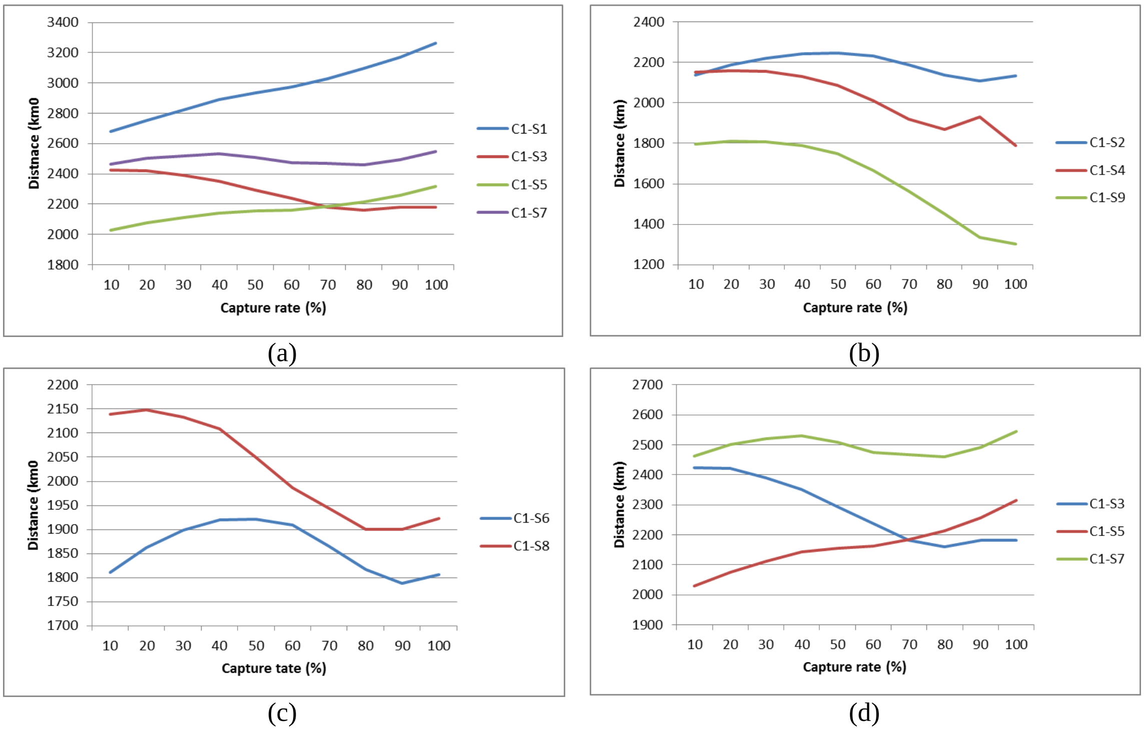


Figure 7.8 Comparison of total travelling distance for collection of the whole household waste stream in single collection and co-collection (a) weekly and (b) fortnightly; effect of permutations of waste type and compartment in weekly co-collection along with (c) fortnightly collection and (d) weekly collection

7.3.3.3 Total time spent in collection and transportation

As with the total travelling distance, weekly and fortnightly co-collection of household waste always gave a reduction in total time spent in collection and transportation, compared to single collection of household waste. The total time spent is up to 34.1% less in weekly co-collection (Figure 7.9a) and 32.7% in fortnightly co-collection (Figure 7.9b). With the optimal permutations of waste type and compartment, the total time saved could be from 10.1-58.7% in weekly co-collection (Figure 7.9c) and up to 23.1% in fortnightly co-collection (Figure 7.9d).

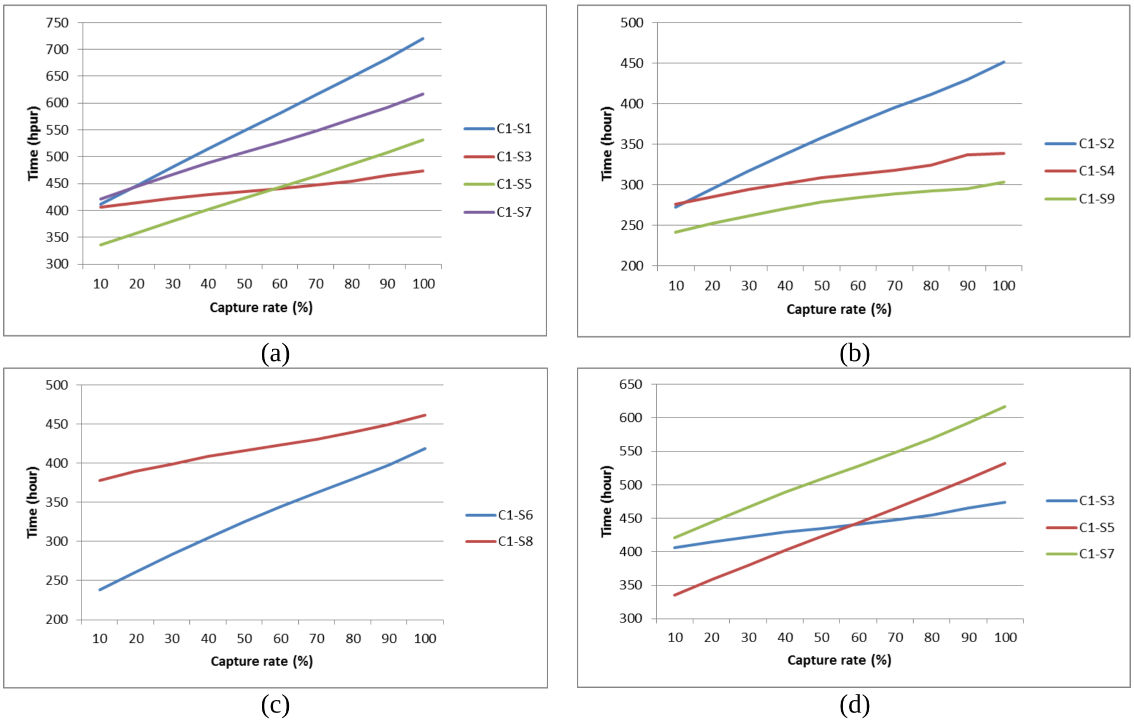


Figure 7.9 Comparison of total time spent for collection of the whole household waste stream in single collection and co-collection (a) weekly and (b) fortnightly; effect on permutations of waste type and compartment in (c) weekly co-collection and (d) fortnightly co-collection

7.3.4 Refuse collection vehicle

7.3.4.1 Single-compartment collection vehicle

Table 7.10 shows the single-compartment RCVs that consume the least fuel in collection at each collection frequency and capture rate for food waste and recyclables. The 26-tonne single-compartment vehicles do not have the best performance in fuel consumption for food waste, recyclables or residual waste collection at any capture rates and frequencies: this is as expected from the results of Chapter 6. The 7.5-tonne single-compartment RCV is the best vehicle in term of fuel use in most situations except fortnightly collection of residual waste (scenario C1-S2b) at capture rates for food waste and recyclables of 60% or below. The 12-tonne single-compartment RCV used the least fuel in those scenarios.

Table 7.10 Best single-compartment collection vehicle with respect to fuel consumption in different collection systems at capture rates from 10-100%

Capture rate of the recyclables and food waste (%)	Weekly collection			Fortnightly collection	
	Food waste	Co-recyclable	Residual waste	Co-recyclable	Residual waste
10	7.5-tonne	7.5-tonne	7.5-tonne	7.5-tonne	12-tonne
20	7.5-tonne	7.5-tonne	7.5-tonne	7.5-tonne	12-tonne
30	7.5-tonne	7.5-tonne	7.5-tonne	7.5-tonne	12-tonne
40	7.5-tonne	7.5-tonne	7.5-tonne	7.5-tonne	12-tonne
50	7.5-tonne	7.5-tonne	7.5-tonne	7.5-tonne	12-tonne
60	7.5-tonne	7.5-tonne	7.5-tonne	7.5-tonne	12-tonne
70	7.5-tonne	7.5-tonne	7.5-tonne	7.5-tonne	7.5-tonne
80	7.5-tonne	7.5-tonne	7.5-tonne	7.5-tonne	7.5-tonne
90	7.5-tonne	7.5-tonne	7.5-tonne	7.5-tonne	7.5-tonne
100	7.5-tonne	7.5-tonne	7.5-tonne	7.5-tonne	7.5-tonne

The best single-compartment collection vehicles with respect to total travelling distance and time spent in different scenarios at capture rates from 10-100% are presented in Table 7.11 and 7.12. It can be seen that the 26-tonne single-compartment RCV is never the most suitable for weekly food waste and comingled recyclable collection; however, it is the best RCV to use for weekly and fortnight collection of residual waste in terms of total travelling distance and total time at all capture rates. In the weekly comingled recyclable collection, small RCVs such as 3.5-tonnes and 7.5-tonnes work well at low capture rates. In fortnightly recyclables collection, the 18-tonne RCV was good at a capture rate of 60% or below in terms of travelling distance, while the 12-tonne RCV was ideal at low capture rates in terms of total time spent in collection and transportation. In practice, a high capture rate is expected for recyclables, thus a large collection vehicle is the best in terms of distance travelled and time spent for weekly and fortnightly recyclable waste collection.

Table 7.11 The best single-compartment collection vehicle with respect to total travelling distance in different collection systems at capture rates from 10-100%

Capture rate of the recyclables and food waste (%)	Weekly collection			Fortnightly collection	
	Food waste	Co-recyclable	Residual waste	Co-recyclable	Residual waste
10	15-tonne	3.5-tonne	26-tonne	18-tonne	26-tonne
20	15-tonne	3.5-tonne	26-tonne	18-tonne	26-tonne
30	15-tonne	7.5-tonne	26-tonne	18-tonne	26-tonne
40	15-tonne	7.5-tonne	26-tonne	12-tonne	26-tonne
50	15-tonne	15-tonne	26-tonne	18-tonne	26-tonne
60	15-tonne	15-tonne	26-tonne	18-tonne	26-tonne
70	15-tonne	15-tonne	26-tonne	26-tonne	26-tonne
80	15-tonne	15-tonne	26-tonne	26-tonne	26-tonne
90	15-tonne	15-tonne	26-tonne	26-tonne	26-tonne
100	15-tonne	18-tonne	26-tonne	26-tonne	26-tonne

Table.7.12 Best single-compartment collection vehicle with respect to total time spent in different collection systems at capture rates from 10-100%

Capture rate of the recyclables and food waste (%)	Weekly collection			Fortnightly collection	
	Food waste	Co-recyclable	Residual waste	Co-recyclable	Residual waste
10	15-tonne	3.5-tonne	26-tonne	12-tonne	26-tonne
20	15-tonne	3.5-tonne	26-tonne	12-tonne	26-tonne
30	15-tonne	7.5-tonne	26-tonne	12-tonne	26-tonne
40	15-tonne	7.5-tonne	26-tonne	12-tonne	26-tonne
50	15-tonne	15-tonne	26-tonne	26-tonne	26-tonne
60	15-tonne	15-tonne	26-tonne	26-tonne	26-tonne
70	15-tonne	15-tonne	26-tonne	26-tonne	26-tonne
80	15-tonne	15-tonne	26-tonne	26-tonne	26-tonne
90	15-tonne	15-tonne	26-tonne	26-tonne	26-tonne
100	15-tonne	18-tonne	26-tonne	26-tonne	26-tonne

7.3.4.2 Two-compartment collection vehicles

Comparing all of the scenarios, it can be observed that the performance of the pod vehicle is better than the rear split collection vehicle in terms of fuel, distance travelled and time spent. Among the pod vehicles, the Duo3 collection vehicle is the best option at most capture rates for recyclables and food waste. The suitability of the collection vehicles in different scenarios and with respect to output parameters is shown in Table 7.13, Table 7.14 and Table 7.15 and can be summarised as below:

- In terms of fuel, distance and time, the Duo 3 appears to be the most suitable two-compartment RCV for collection at 10% to 90% capture rates for recyclables and food waste, while the Twin 1 has the best performance in fuel consumption at 100% capture rates in weekly co-collection of recyclables and residual waste.
- The Duo3 is the best vehicle for fortnightly co-collection of recyclables and residual waste for fuel consumption, distance and time in all situations except at 90% capture rate.
- Weekly co-collection of recyclables and food waste: The Duo 1 and Duo 3 collection vehicles are the best option for all outputs at the all capture rates.
- Weekly co-collection of residual waste and food waste: The best vehicle is the Duo 3, which consumes the least fuel in most situations.
- Weekly food waste collection with AWC of recyclables: Generally speaking, the food waste pod vehicles, especially Duo 2 and Duo 3 are the best vehicles in term of fuel, time and distance travelled.
- Weekly food waste collection with AWC of residual waste: Duo3 collection vehicle has the best performance in terms of fuel consumption at all capture rates.

Table 7.13 The best compartmentalised collection vehicle co-collect the two type of waste at capture rates from 10-100% (Fuel consumption)

Capture rate of the recyclable and food waste (%)	Weekly co-collection			Fortnightly co-collection	Weekly food waste with alternative weekly collection of	
	Recyclable /Residual	Recyclable/ Food waste	Residual/ Food waste	Recyclable/ Residual	Recyclables	Residual
10	Duo 3	Duo 3	Duo 3	Duo 3	Duo 2	Duo 3
20	Duo 3	Duo 3	Duo 3	Duo 3	Duo 2	Duo 3
30	Duo 3	Duo 3	Duo 3	Duo 3	Duo 2	Duo 3
40	Duo 3	Duo 3	Duo 3	Duo 3	Duo 2	Duo 3
50	Duo 3	Duo 3	Duo 3	Duo 3	Duo 2	Duo 3
60	Duo 3	Duo 3	Duo 3	Duo 3	Duo 2	Duo 3
70	Duo 3	Duo 3	Duo 3	Duo 3	Duo 2	Duo 3
80	Duo 3	Duo 1	Duo 3	Duo 3	Duo 3	Duo 3
90	Duo 3	Duo 3	Duo 3	Twin 1	Duo 3	Duo 3
100	Twin 1	Duo 1	Twin 1	Duo 3	Duo 3	Duo 3

Table 7.14 The best compartmentalised collection vehicle co-collect the two type of waste at capture rates from 10-100% (Total travelling distance)

Capture rate of the recyclable and food waste (%)	Weekly co-collection			Fortnightly co-collection	Weekly food waste with alternative weekly collection of	
	Recyclable /Residual	Recyclable/ Food waste	Residual/ Food waste	Recyclable/ Residual	Recyclables	Residual
10	Duo 3	Duo 3	Duo 3	Duo 3	Duo 2	Duo 3
20	Duo 3	Duo 3	Duo 3	Duo 3	Duo 2	Duo 3
30	Duo 3	Duo 1	Duo 3	Duo 3	Duo 2	Duo 3
40	Duo 3	Duo 3	Duo 3	Duo 3	Duo 2	Duo 3
50	Duo 3	Duo 3	Duo 3	Duo 3	Duo 2	Duo 3
60	Duo 3	Duo 3	Duo 3	Duo 3	Duo 2	Duo 3
70	Duo 3	Duo 3	Duo 3	Duo 3	Duo 2	Duo 3
80	Duo 3	Duo 3	Duo 3	Duo 3	Duo 3	Duo 3
90	Duo 3	Duo 3	Duo 3	Twin 1	Duo 3	Duo 3
100	Twin 1	Duo 3	Twin 3	Duo 3	Duo 3	Duo 3

Table 7.15 The best compartmentalised collection vehicle co-collect the two type of waste at capture rates from 10-100% (Total time spent)

Capture rate of the recyclable and food waste (%)	Weekly co-collection			Fortnightly co-collection	Weekly food waste with alternative weekly collection of	
	Recyclable /Residual	Recyclable/ Food waste	Residual/ Food waste	Recyclable/ Residual	Recyclables	Residual
10	Duo 3	Duo 3	Duo 3	Duo 3	Duo 2	Duo 3
20	Duo 3	Duo 3	Duo 3	Duo 3	Duo 2	Duo 3
30	Duo 3	Duo 1	Duo 3	Duo 3	Duo 2	Duo 3
40	Duo 3	Duo 3	Duo 3	Duo 3	Duo 2	Duo 3
50	Duo 3	Duo 3	Duo 3	Duo 3	Duo 2	Duo 3
60	Duo 3	Duo 3	Duo 3	Duo 3	Duo 2	Duo 3
70	Duo 3	Duo 3	Duo 3	Duo 3	Duo 2	Duo 3
80	Duo 3	Duo 3	Duo 3	Duo 3	Duo 3	Duo 3
90	Duo 3	Duo 3	Duo 3	Twin 1	Duo 3	Duo 3
100	Twin 1	Duo 3	Twin 3	Duo 3	Duo 3	Duo 3

7.3.5 Allocation of compartments

For two-compartment collection vehicles, the question of which type of waste goes into which compartment was examined, with a view to minimising fuel use by maximising the utilisation of laden percentage in weight or volume. Figure 7.10 shows the change in laden percentage of vehicle and percentage volume utilisation of compartments for different permutations of waste type and compartment at capture rates for recyclables and food waste from 10-100%. The orange and grey lines represent the volume percentage of small and large compartments respectively, while the blue line represents the laden percentage for the RCV. From Figure 7.10, it can be seen whether weight or volume of compartment is the limiting factor, and which compartment would fill up first. It can be seen that the volume capacity is the dominant factor when recyclable and residual waste is co-collected at low capture rates (CR $\leq$ 60%). In most cases, laden percentage of RCV is the limiting factor (Figure 7.10c, 7.10d and 7.10e). However, when residual waste is collected in alternation with food waste, the volume capacity of compartments becomes the dominant factor at capture rates of 70% or below.

Recyclables and residual waste can be placed in the small and large compartments respectively at the 10% to 90% capture rates in weekly co-collection (Figure 7.10a) and at 10% to 80% capture rates in fortnightly co-collection (Figure 7.10b). When the capture rate for food waste and recyclable waste is 100%, the residual waste can be placed in the small compartment instead. This rarely happens in practice, however, because such high capture rates for both food waste and recyclables are unlikely and perhaps unachievable. The same applies to the co-collection of residual and recyclable wastes in fortnightly collection when the capture rate is 90% or above. When food waste is co-collected with recyclables or residual waste in the weekly and alternate weekly collection, the results show that the food waste should be placed in the small compartment at all capture rates (Figure 7.10d, 7.10e and 7.10f). For weekly co-collection of recyclables and food waste, food waste is better placed in the small compartment at capture rates of less than 50% (Figure 7.10c).

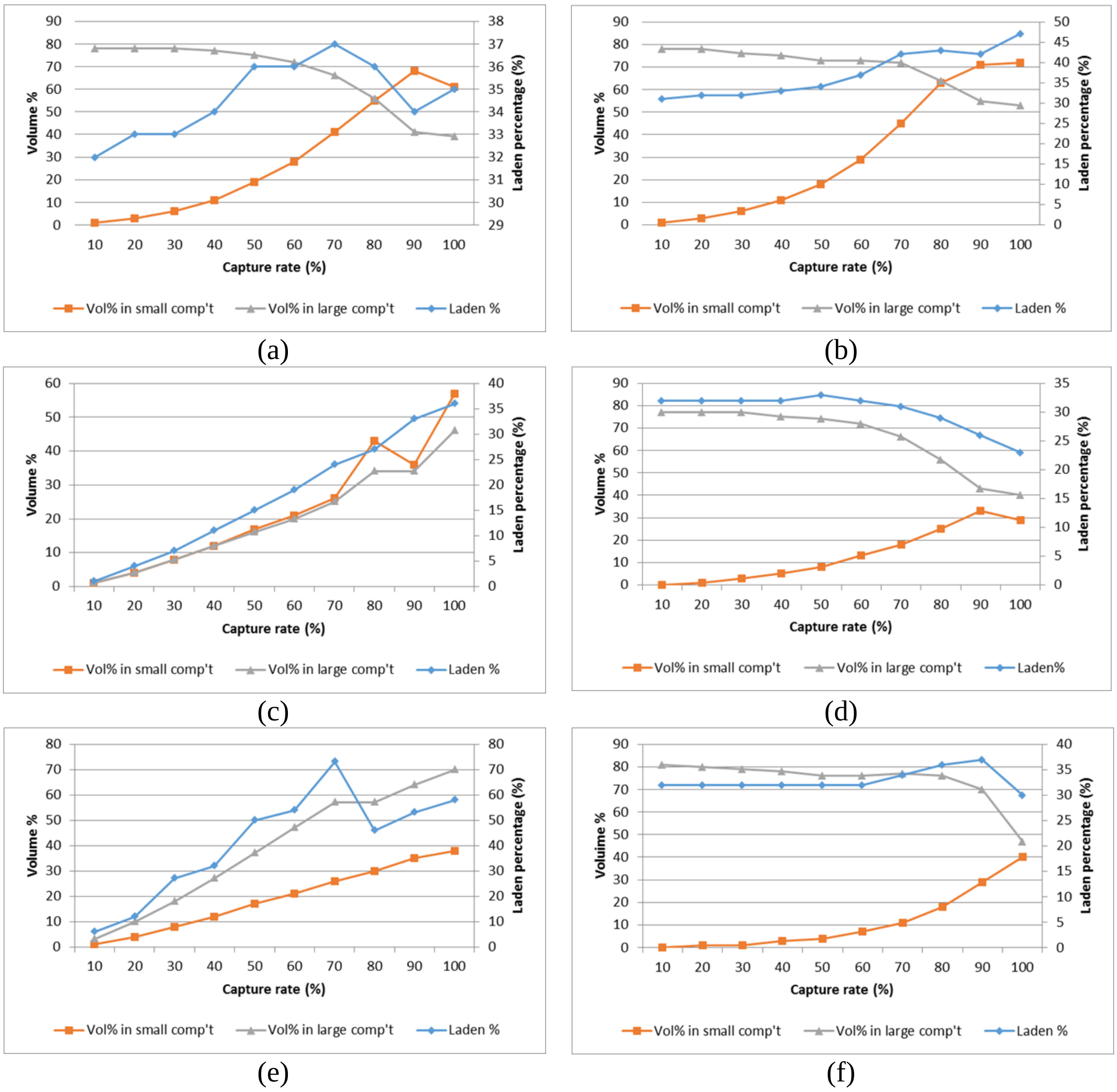


Figure 7.10 Change in laden percentage of vehicle and volume percentage of different compartments in different permutations of waste type and compartment at capture rates of recyclables and food waste from 10-100%, (a) Weekly co-collection of recyclables and residual waste; (b) Fortnightly co-collection of recyclable and residual waste; (c) Weekly co-collection of recyclable and food waste; (d) Weekly co-collection of residual waste and food waste; (e) AWC of recyclables and food waste; and (f) AWC of residual waste and food waste.

7.4 Sensitivity analysis for fuel consumption, time and distance travelled

7.4.1 Fuel consumption in household waste collection

Results from the sensitivity analysis of fuel consumption with single-compartment and compartmentalised RCVs are summarised in Table 7.16. It can be seen that the distance between properties was the parameter with the greatest effect on fuel consumption in general. When wastes are separately collected by single-compartment RCV, the extra fuel consumption factor in collection and the speed in transportation are the second most important factors affecting fuel usage. On the other hand, the density of residual waste influences the fuel consumption for co-collection of residual wastes using a two-compartment collection vehicle.

7.4.2 Total distance travelled

The result of the sensitivity analysis for total time spent by single-compartment and compartmentalised RCVs is summarised in Table 7.17. The distance between properties had the biggest effect on total distance travelled when recyclables and food waste are separately collected every week or once a fortnight (scenarios C1-S1a, S1c, S2a and S2c). Speed in transportation and the density of residual waste had similar effects on the total distance (scenarios C1-S1b and S2b). On the other hand, at low capture rates for recyclables and food waste, the density of residual waste had the biggest influence when residual and food waste were co-collected weekly, fortnightly or alternate weekly. There is a trend showing that the travelling distance is less affected by the most critical parameter when the capture rate increases, while the second most critical parameter has the greatest influence on the time spent at high capture rates. Furthermore, the distance between dwellings became the most critical parameter for weekly and alternate weekly co-collection of recyclables and food waste, and an increase in this will increase the total travelling distance at all capture rates.

7.4.3 Total time spent

A summary of the sensitivity analysis for total time spent in collection by single-compartment and compartmentalised RCVs is given in Table 7.18. Overall, the density of residual waste remained the dominant factor with respect to total time spent when residual wastes are separately collected, co-collected with recyclables or food waste, or alternate weekly collected with food waste. From Table 7.18, it can also be seen that the pick-up time for the collection bin is the most critical parameter affecting the total time spent; however, the regression coefficient is less than 0.6 when recyclables and food waste are separately collected or any co-collection of recyclable and food waste. This also becomes the second most important factor influencing the time spent in collection when residual waste is collected separately or is co-collected with other type of wastes. Last but not least, the distance between properties could also have a considerable influence on the total time spent when recyclables and food waste are co-collected.

Table 7.16 Summary of the results of sensitivity analysis for fuel consumption in separate or co-collection of household waste at capture rates from 10-100%

		Capture rates for food waste and dry recyclables (%)									
Scenario	Parameter	10	20	30	40	50	60	70	80	90	100
C1-S1a	Distance between household	0.84	0.84	0.84	0.84	0.83	0.76	0.71	0.70	0.66	0.59
	Factor on extra fuel consumption	0.33	0.33	0.33	0.33	0.34	0.32	--	--	--	--
	Speed in transportation	--	--	--	--	--	--	-0.34	0.36	0.41	0.45
C1-S1b	Density of residual waste	-0.78	-0.78	-0.77	-0.77	-0.76	-0.76	-0.74	-0.71	-0.64	0.70
	Speed in transportation	0.45	0.45	0.44	0.44	0.44	0.44	0.42	0.42	0.51	-0.45
C1-S1c	Distance between household	0.87	0.87	0.87	0.87	0.87	0.87	0.84	0.83	0.83	0.82
	Factor on extra fuel consumption	0.34	0.34	0.34	0.34	0.34	0.36	0.37	0.35	0.33	0.31
C1-S2a	Distance between household	0.88	0.89	0.89	0.89	0.85	0.82	0.83	0.77	0.73	0.69
	Factor on extra fuel consumption	0.27	0.27	0.27	0.28	0.28	0.27	0.26	0.32	0.37	-0.41
C1-S2b	Density of residual waste	-0.78	-0.78	-0.78	-0.76	-0.76	-0.76	-0.74	-0.70	-0.65	0.69
	Speed in transportation	0.46	0.47	0.46	0.46	0.46	0.45	0.44	0.44	0.47	-0.43
C1-S3	Distance between household	0.61	0.68	0.69	0.71	0.74	0.76	0.79	0.81	0.82	0.81
	Density of residual waste	-0.59	-0.51	-0.48	-0.45	-0.40	-0.35	-0.33	--	--	-0.28
	Speed in collection	--	--	--	--	--	--	--	-0.26	-0.27	--
C1-S4	Distance between household	0.66	0.66	0.68	0.69	0.72	0.76	0.79	0.81	0.79	0.78
	Density of residual waste	-0.53	-0.51	-0.49	-0.46	-0.40	-0.34	-0.30	0.25	-0.30	-0.33
C1-S5/S6	Distance between household	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.91	0.88	0.91
	Speed in collection	-0.32	-0.32	-0.32	-0.32	-0.31	-0.31	-0.31	-0.30	-0.31	-0.29
C1-S7/S8	Distance between household	0.81	0.81	0.81	0.82	0.83	0.84	0.85	0.86	0.87	0.87
	Density of residual waste	-0.34	-0.33	-0.32	-0.30	-0.27	--	--	--	--	--
	Speed in collection	--	--	--	--	--	-0.27	-0.29	-0.30	-0.30	-0.31
C1-S9a	Distance between household	0.73	0.73	0.74	0.76	0.78	0.78	0.79	0.80	0.84	0.87
	Density of residual waste	-0.43	-0.42	-0.39	-0.35	-0.33	-0.34	-0.35	-0.33	-0.27	-0.29
C1-S9b	Distance between household	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.90	0.90	0.89
	Speed in collection	-0.32	-0.32	-0.31	-0.31	-0.31	-0.30	-0.30	-0.29	-0.28	-0.27

Table 7.17 Summary of the results of sensitivity analysis for total travelling distance in the separate collection or co-collection of household waste at the capture rate from 10-100%

		Capture rates for food waste and dry recyclables (%)									
Scenario	Parameter	10	20	30	40	50	60	70	80	90	100
C1-S1a	Distance between household	0.76	0.76	0.58	0.76	0.76	0.75	0.63	0.61	0.29	0.43
	Speed in transportation	0.57	0.57	0.59	0.56	0.56	0.57	0.60	-0.37	0.69	0.75
C1-S1b	Speed in transportation	0.62	0.61	0.62	0.63	0.64	0.65	0.63	0.56	0.53	0.56
	Density of residual waste	-0.61	-0.60	-0.58	-0.55	-0.54	-0.54	-0.57	-0.64	-0.52	0.74
C1-S1c	Distance between household	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.74	0.66	0.55
	Speed in transportation	0.43	0.43	0.43	0.43	0.43	0.43	0.44	0.47	0.54	0.62
C1-S2a	Distance between household	0.73	0.73	0.73	0.74	0.73	0.73	0.73	0.73	0.68	0.53
	Speed in transportation	0.58	0.58	0.58	0.59	0.58	0.58	0.57	0.57	0.59	0.57
C1-S2b	Speed in transportation	0.62	0.62	0.61	0.61	0.62	0.61	0.59	0.53	0.52	0.57
	Density of residual waste	-0.58	-0.57	-0.56	-0.54	-0.51	-0.52	-0.55	-0.63	-0.50	0.67
C1-S3	Density of residual waste	-0.67	-0.64	-0.62	-0.59	-0.56	-0.52	-0.53	-0.37	-0.34	-0.40
	Speed in transportation	0.61	0.62	0.62	0.63	0.64	0.65	0.64	0.68	0.71	0.70
C1-S4	Density of residual waste	-0.63	-0.63	-0.61	-0.60	-0.55	-0.50	-0.48	-0.35	-0.49	-0.56
	Speed in transportation	0.58	0.58	0.59	0.59	0.60	0.63	0.64	0.66	0.63	0.57
C1-S5/S6	Distance between household	0.93	0.91	0.86	0.85	0.82	0.79	0.76	0.73	0.70	0.67
	Speed in transportation	0.28	0.34	0.39	0.44	0.48	0.52	0.55	0.58	0.61	0.63
C1-S7/S8	Density of residual waste	-0.65	-0.65	-0.65	-0.64	-0.61	-0.54	--	--	--	--
	Speed in transportation	0.51	0.52	0.52	0.52	0.52	0.55	0.57	0.60	0.65	0.66
	Distance between household	--	--	--	--	--	--	0.44	0.56	0.66	0.69
C1-S9a	Speed in transportation	0.60	0.60	0.61	0.63	0.64	0.63	0.59	0.54	0.54	0.63
	Density of residual waste	-0.59	-0.58	-0.55	-0.52	-0.52	-0.56	-0.60	-0.64	-0.50	0.62
C1-S9b	Distance between household	0.94	0.92	0.87	0.83	0.83	0.80	0.73	0.72	0.63	0.62
	Speed in transportation	0.28	0.34	0.39	0.44	0.50	0.54	0.58	0.60	0.63	0.62

Table 7.18 Summary of the results of sensitivity analysis for total time spent in separate or co-collection of household waste at the capture rate from 10-100%

		Capture rates for food waste and dry recyclables (%)									
Scenario	Parameter	10	20	30	40	50	60	70	80	90	100
C1-S1a	Pick-up time for recycling bin	0.59	0.59	0.47	0.59	0.59	0.59	0.58	0.55	0.56	0.58
	Distance between household	0.59	0.59	-0.74	0.59	0.59	0.59	0.58	0.54	0.55	0.58
C1-S1b	Density of residual waste	-0.55	-0.53	-0.50	--	--	--	--	--	--	--
	Distance between household	0.45	--	--	0.47	0.48	0.48	0.47	0.51	0.53	0.58
	Pick-up time for residual bin	--	0.46	0.47	0.49	0.50	0.51	0.49	0.48	0.56	0.58
C1-S1c	Pick-up time for food waste bin	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.59	0.58
	Number of collectors	-0.50	-0.50	-0.50	-0.50	-0.50	-0.50	-0.50	-0.50	-0.50	-0.50
C1-S2a	Pick-up time for recycling bin	0.58	0.58	0.58	0.58	0.59	0.59	0.59	0.59	0.58	0.55
	Distance between household	0.58	0.58	0.58	0.58	0.59	0.59	0.59	0.59	0.59	0.57
C1-S2b	Density of residual waste	-0.53	-0.52	-0.51	-0.47	--	--	--	--	--	--
	Pick-up time for residual bin	0.44	0.45	0.46	0.46	0.49	0.50	0.48	0.48	0.52	0.58
	Distance between household	--	--	--	--	0.45	0.46	0.46	0.46	0.51	0.55
C1-S3	Density of residual waste	-0.73	-0.62	-0.60	-0.55	-0.51	-0.46	-0.44	--	--	--
	Pick-up time for residual bin	0.42	0.46	0.47	0.49	0.51	0.55	0.56	0.61	0.61	0.63
	Distance between household	--	--	--	--	--	--	--	0.42	0.43	0.44
C1-S4	Density of residual waste	-0.64	-0.63	-0.60	-0.57	-0.50	-0.43	--	--	-0.39	-0.46
	Pick-up time for residual bin	0.44	0.44	0.47	0.48	0.52	0.55	0.57	0.58	0.56	0.53
	Distance between household	--	--	--	--	--	--	0.40	0.43	--	--
C1-S5/S6	Distance between household	0.83	0.81	0.76	0.72	0.67	0.62	0.58	0.54	0.50	-0.48
	Speed in collection	-0.47	-0.46	-0.43	--	--	--	--	--	--	--
	Pick-up time for recycling bin	--	--	--	0.42	0.49	0.55	0.60	0.63	0.66	0.68
C1-S7/S8	Pick-up time for residual bin	0.56	0.56	0.58	0.60	0.61	0.63	0.65	0.67	0.68	0.67
	Density of residual waste	-0.47	-0.46	-0.44	-0.42	0.43	--	--	--	--	--
	Number of collectors	--	--	--	--	--	-0.45	-0.47	-0.48	-0.48	-0.47
C1-S9a	Pick-up time for residual bin	0.5	0.52	0.54	0.56	0.57	0.56	0.53	0.54	0.62	0.66
	Density of residual waste	-0.53	-0.51	-0.48	-0.44	-0.42	-0.44	-0.48	-0.46	-0.43	-0.46
C1-S9b	Distance between household	0.84	0.81	0.77	0.73	0.68	0.63	0.58	0.55	0.50	0.46
	Speed in collection	-0.47	-0.46	-0.44	-0.42	--	--	--	--	--	--
	Pick-up time for recycling bin	--	--	--	--	0.48	0.54	0.58	0.62	0.64	0.65

7.5 Discussion

7.5.1 Effect of capture rates for food waste and recyclables on fuel consumption for residual waste collection

In this study, the capture rates for food waste and recyclable waste ranged from 10-100% in every scenario. In reality, capture rates for food waste and recyclables usually fall between 20-60% and 50-80%, respectively (Personal communication, A. Bond, 4R Environmental Ltd, 2012), with variations due to factors such as demographic patterns and the length of time for which the collection scheme has operated. The fuel consumption per tonne of residual waste in fortnightly collection ranges from 1.89 to 3.86 L $tonne^{-1}$. This range is wider than that reported by Larsen et al (2009) of 3.3 to 3.6 L $tonne^{-1}$ of residual waste collected from single family houses in an urban area at fortnightly intervals. This probably reflects the wider range of collection options considered in this study. The fuel consumption in this study is less than the value of 5.96 L $tonne^{-1}$ reported by Chen (2008) for a residual waste collection in Taiwan. It is difficult to suggest reasons for the difference because the studies of Chen (2008) do not provide sufficient details of the collection scheme, such as the collection frequency, collection vehicle used and the amount of waste at each household. These factors can also influence the overall fuel consumption.

The fuel consumption of the residual waste collection increases when the capture rates of food waste and recyclables increase. This is as expected, since the amount of residual waste collected per week is reduced while the travelling distance remains constant. While the specific energy consumption in collecting one tonne of residual waste is high, it is likely that residual waste collections will always be required (UnbanMine, 2014). A more relevant question in this context may be whether the additional energy required for separate collection of food waste is greater than the additional energy recovered from it by anaerobic digestion. To determine this it is necessary to consider the collection of the whole waste stream, and to compare similar options with and without source segregated food waste collection, then assess the results as part of the overall process including all stages in collection and energy production. An example of this approach using the current model is reported in VALORGAS (2013b) (see Appendix D).

Focusing on the waste collection system, it can be seen that fortnightly collection of residual waste can use much less fuel than weekly collection (section 7.3.1). Research on operational schemes has also shown that fortnightly collection of residual waste can enhance the capture rate for food waste (WRAP, 2009a). Therefore, based on both fuel use and waste recovery, it is definitely a good option to collect the recyclable and residual waste every two weeks with an additional weekly food waste collection.

7.5.2 Comparison of optimal scenarios

Scenarios C1-S1 to C1-S9 looked at the effect of using single-compartment or two-compartment vehicles and of collection frequency on the fuel consumption, distance travelled, time spent and number of RCVs required. The results clearly showed that the optimal scenario for fuel consumption is not always same as for other output parameters. This is because the bigger the vehicle is, the more the fuel is used. However, the performance in terms of total travelling distance and total time spent were fairly similar because these parameters are independent of the correction factor for the extra fuel consumption in the collection stage. The number and type of vehicles required may also be another important parameter for assessing the collection system where the results differ from those for other outputs.

Interestingly, with respect to fuel consumption, the use of a single-compartment RCV for separate collection of co-mingled recyclables, food waste and residual waste every two weeks has a better performance than any co-collection of household waste. This could be explained by the choice of optimal collection vehicle. For scenario C1-S2, the best RCV to collect food waste, recyclables and residual was a 7.5-tonne single-compartment collection vehicle. The co-collection of household wastes used 26-tonne RCVs, with a much higher gross weight than the best vehicle used in separate collection. As a result, the fuel consumption in scenario C1-S2 is the lowest among the scenarios. This result is in contradiction to the findings of Tanskanen and Kaila (2001) and Beullens et al. (2004) that a single-compartment vehicle uses several times more fuel than a compartmentalised vehicle when more fractions of waste are source separated for collection; however, the results are in line with the finding by Tanskanen and Kaila (2001) that the total time spent by a single-compartment vehicle is more than by a compartmentalised vehicle.

In terms of total travelling distance, time spent and number of RCVs required, the results of this study showed that using a compartmentalised vehicle for the collection always consumes fewer resources. The collection frequency does affect the outcome, as is clearly demonstrated in this of a hypothetical medium-sized town. Using a compartmentalised vehicle to co-collect any type of wastes with weekly single collection for the rest of the waste (scenario C1-S3, S5 and S7) always has higher usage of fuel and number of vehicles than the fortnightly single collection of recyclable and residual waste with weekly food waste collection. Putting aside the public acceptability of a reduction in frequency of the household waste collection service, the local authority can provide fortnightly single collection or co-collection of the recyclable and residual waste with weekly food waste collection to minimise fuel consumption as well as to ensure a good life-span for the vehicle fleet. Among the scenarios considered, weekly food waste collection with AWC of residual waste or recyclable waste by a two-compartment vehicle is the ideal collection scheme to operate at most capture rates in terms of the distance travelled and time spent. This result therefore adds quantitative evidence to support the choice currently being made by some UK local authorities (Smyth, 2010).

7.5.3 Collection vehicle

Development of a methodology for choosing the optimal collection vehicle for most circumstances is one of the focuses of this study. Surprisingly, looking at the fuel consumption alone, the results of the current study show that a medium size collection vehicle (7.5-tonne and 12-tonne) is good for food waste, recyclable and residual waste collection at all capture rates. Considering distance travelled and time spent, the results confirm that a medium-size collection vehicle is ideal for the collection of a small amount of waste at each pick-up point, whilst a large RCV is especially good for residual waste collection. The reason for this has been explained in Section 7.5.2. Regarding the co-collection of household waste, two types of compartmentalised vehicles were considered. Based on this theoretical study, it appears that the 70:30 split is better than the 50:50 split for any size of split-bodied vehicle (Table 7.13-7.15). When considering all the compartmentalised RCVs in this study, the pod vehicle is better than the rear split vehicle in most cases in term of fuel consumption, total distance travelled and total time spent.

Generally speaking, the compartmentalised RCV is usually not overloaded even when the compartment is fully utilised during the collection. In other words, the collection vehicle is usually limited by the volume of the compartment rather than the vehicle payload during co-collection of household waste. Therefore, the volume and the split ratio of the compartments can be considered when selecting a suitable RCV. Based on the specific fuel consumption, in this theoretical study the Duo3 vehicle performs better than the Twin3 vehicle, although the volume ratios of the compartments are about 30:70 in both cases. This is because the front compartment of the Duo3 vehicle is 1 m^3 bigger than the smallest rear compartment in Twin3 collection vehicle, which allows more household visits before the compartment is full. In comparison, although the volume of the 50:50 split vehicle is larger at 10 m^3, this may not always be ideal for collection because the second compartment fills more quickly than the largest compartment in the 30:70 split vehicles. Thus, in order to further improve collection efficiency, it is suggested that the split ratios should be kept at 30:70, and if possible the volumes of both compartments should be increased. In addition, increasing the vehicle payload by the use of a lighter material for the compartment body could improve performance, although this may conflict with the need for a robust construction. When deciding to use a larger compartmentalised RCV, however, several factors should be considered such as the width of the road and the average time needed for collection per day. Also, the balance between the size of compartment and the collection time must always be considered unless shift working is practiced.

7.5.4 Allocation of wastes to compartments

In order to determine whether the model offered an effective tool for selecting the right compartment for the collected waste, the full range of capture rates for food waste and recyclables from 10-100% was tested. The results suggest that residual waste should be switched to the small compartment when capture rates for recyclable and food waste increase to 80% or above. The results also show that food waste should always be placed in the small compartment in all conditions, e.g. in weekly, fortnightly and alternate weekly collection. This can be explained by the fact that the amount of food waste for disposal is relatively small compared to recyclable and residual wastes. Figure 7.10c shows that it is better to put recyclable waste in the small compartment when the capture rate is between 10% and 50%, whilst food waste is best placed in the small compartment when more than half of the food waste and recyclables are captured. The case shown in Figure 7.10c is different from the others in Figure 7.10 as the laden percentage and volume percentage in both compartments is far less than 100%. This is explained by the fact that that this type of collection is time dependent in most cases, with the average number of full loads in one collection day ranging from 1 to 1.004.

Scenarios C1-S6 and C1-S8 show that putting the waste in the right compartments can save up to 8% of fuel, 15% of travelling distance and 58% of total time in the household waste collection. In this case, the residual waste can be co-collected with the food waste every week by compartmentalised vehicle, while the recyclables is separately collected every fortnight if fuel consumption (scenario C1-S8) is the key criterion. Otherwise, weekly co-collection of recyclables and food waste by two-compartment RCV with fortnightly separate collection of residual waste (scenario C1-S6) should be adopted to minimise the total travelling distance and time.

In Figure 7.8d and 7.9d, it can be seen that the two lines representing scenarios C1-S3 and C1-S5 cross at capture rates of 70% for travelling distance and 60% for time spent: at high capture rates the travelling distance and time spent in the co-collection of food waste and recyclables (scenario C1-S5) is longer than in the co-collection of recyclable and residual waste (scenario C1-S3). Vehicle Duo3 has the best performance in terms of distance travelled and time spent in scenario C1-S3 at capture rates from 70% to 90%, while it also performs well for both parameters in scenario C1-S5 at capture rates of 60% or below. As a result, the minimisation of distance and time could be simply achieved by using the same vehicles with different allocations of waste and compartment at capture rates from 70% to 90%.

7.5.5 Sensitivity analysis

In this study, the density of residual waste and the distance between dwellings made the biggest contribution to uncertainty in fuel consumption, distance travelled and working time. In co-collection of food waste or recyclables with residual waste, the density of the residual waste affects the amount that can be placed in a compartment. When the density is high and the collection is volume-limited, more pick-up points can be visited, reducing the need to travel between the collection area and the unloading point and thus minimising the fuel consumption, distance travelled and working time. In practice, for collection schemes with a relatively high capture rate for recyclables and food waste, the density of the residual waste will tend to be comparatively low. This is because diversion of food waste reduces the bulk density of residual waste, and in this case the residual waste may be compacted in order to utilise the compartment fully.

It is obvious that an increase in distance travelled will increase fuel consumption in the collection. As noted in Chapter 6, the factor of distance between dwellings mainly represents the density of housing in a particular area. The results of the sensitivity analysis here again imply that areas with a high housing density, such as city centres and urban areas typically use less fuel in waste collection, while rural areas use more. As discussed in Chapter 6, to further minimise the fuel consumption, route optimisation can be considered once the right collection system is selected.

Interestingly, the effect of the pick-up time of the bins on the total collection time did not significantly affect the model outputs compared to other inputs for which the regression coefficients are usually 0.7 or above. This can be explained by the fact that the compartment size overrides the collection time in the co-collection of wastes. Although this research has added a new data set on pick-up time for bins, the results suggest it may be more important to focus research attention on refining values for other input parameters.

7.5.6 Limitations of this research

The co-collection model used in this chapter is based on the single kerbside collection model described in Chapter 4. The conditions chosen may not necessarily reflect real situations, however: for example set-out rates for residual waste are generally higher than for recyclables, while the proportion of households setting out source segregated food waste collection may be lower than for other materials. In current UK practice, for example, typical set-out rates for food waste are 20-60% and for recyclables 50-80% (Personal Communication, A. Bond, 4R Environmental Ltd, 2012). In this case, the large compartment may potentially be fully utilised for the residual waste before the other compartments have filled. These factors may lead to over-estimation or more commonly under-estimation of fuel consumption. For the current study, equal rates were chosen to show the performance when high set-out rates can be achieved for all materials. In principle, however, the model is capable of analysing the full range of conditions of this type.

Although differences between theoretical results and real data are expected, it is difficult to estimate the size of this difference. Local authorities and waste collection contractors usually record basic information such as the number of households per collection round, the amount of waste collected per vehicle, and sometimes even the participation rate in the scheme; but more detailed information such as how much waste is collected at each household and the passing rate of the vehicle in each collection round is often unavailable. One approach to the issues raised above might be to construct a probabilistic model for waste collection, to allow more accurate estimation of the likely value of outputs. Based on experience from the current work, however, this is likely to be impractical at present because of the lack of sufficient data to validate the model and provide appropriate parameters for probability functions. The current approach of using a deterministic model combined with sensitivity analysis thus appears to offer the most promising tool for comparing the expected output from different scenarios and conditions.

7.6 Conclusions on separate and co-collection of household waste

In this study, the kerbside collection model was used to calculate the fuel consumption, total travelling distance, total time spent and the number of collection vehicle required for the collection of co-mingled recyclable materials, source segregated food waste and the residual waste. The results of the modelling showed that, under the range of scenarios and conditions considered:

- The capture rate for food waste has little influence on the fuel consumption for the residual waste collection, but the capture rate of the recyclables does affect this.
- The optimum RCV in terms of fuel consumption may differ from that selected based on total distance travelled, total time spent or number of vehicles required.
- The AWC of recyclables and residual waste and weekly collection of food waste by single-compartment RCV is the best collection system in terms of fuel consumption, whilst weekly food waste collection with AWC of recyclables and residual waste by two-compartment RCV is the best collection system in terms of total travelling distance and time spent.

- Weekly co-collection of recyclables and food waste by compartmentalised RCV with weekly single collection of residual waste consumes the most fuel, while weekly separate collections of recyclables, residual and food waste by single-compartment RCV has the worst performance in terms of total travelling distance and total time spent.
- The co-collection of household waste is not always the best system, compared to the collection by single-compartment vehicles. In most cases, the co-collection of household waste could consume more fuel than the separate collection, by up to 37% for weekly co-collection and 32% for fortnightly co-collection.
- In comparison to the separate collection of household waste, the total travelling distance saved by weekly and fortnightly co-collection of household waste is up to 33% and 39% respectively.
- For the total time spent in collection and transportation, savings of up to 34% by weekly co-collection and 33% by fortnightly co-collection of household waste are possible compared to separate collection.
- Based on this theoretical study, the pod vehicle with a large compartment capacity is always better than the rear split collection vehicle. The compartmentalised collection vehicle with a compartment split into 30:70 always has a better performance than one with two compartments of equal size.
- This kerbside collection model can be used to look at which type of waste should be placed in the compartments. Placing the waste in the right compartment can reduce the fuel used by 8%, travelling distance by 15% and total time by 58%.
- For the range of values tested, uncertainty in the density of residual waste, correction factor on extra fuel consumption and the distance between properties have the biggest effect on fuel consumption, time spent on collection and total travelling distance.

Chapter 8: MODELLING KERBSIDE SOURCE SEPARATED COLLECTION OF HOUSEHOLD WASTE: KERBSIDE-SORTED COLLECTION SYSTEM

In this chapter, the kerbside collection model is used to estimate the fuel consumption, total time spent, total travelling distance and the number of vehicles required in kerbside-sorted collection systems for the whole household waste stream, including source segregated food waste, source segregated recyclables and residual waste. Two different degrees of waste separation at source were considered: fully kerbside-sorted dry recyclables collection, and two-stream recyclables collection. Section 8.1 gives the general background of the study and lists the objectives. Section 8.2 is describes the waste composition, the allocation of waste types and compartments, the scenarios considered and the general data inputs, and lists the various model inputs used in sensitivity analysis. Section 8.3 presents the model output for different combinations of waste types and compartments in the two types of collection system, and then reports on the fuel consumption and compares the best scenarios for different output parameters. Section 8.4 presents the results of sensitivity analysis for fuel consumption, total distance travelled and total time spent in collection. Section 8.5 discusses the results and their implications, and conclusions are summarised in Section 8.6.

8.1 Introduction

Kerbside-sorted collection can be defined as the separation of recyclable materials on collection at the kerbside, followed by loading into different compartments of the collection vehicle (WRAP, 2008e). Currently, only a limited amount of information is available on local authorities operating kerbside-sorted systems for dry recyclable collection from kerbside properties. WRAP (2014b) estimated that approximately 17% of local authorities in the UK (121 out of 709) provide multi-stream dry recyclable collection for kerbside properties: this figure does not only cover on-site sorting, but also includes the pre-sorting of recyclables by householders. This implies that the kerbside-sorted system has not yet gained popularity among local authorities in the UK. The provisions of the EU's Waste Framework Directive, which require local authorities to collect dry recyclables such as metal, paper, plastics and glass separately from 2015 (Defra, 2013a), may change this existing pattern, however, causing a shift from co-mingled collections to kerbside-sorted collections.

Implementation of kerbside-sorted collection systems has some positive effects. Compared to co-mingled collection, the yield of dry recyclable materials from kerbside-sorted systems may be lower, but a high recycling rate is expected (WRAP, 2011c). After the introduction of kerbside-sorted collections in Somerset, UK, an overall reduction in the generation rates for general refuse and household waste was reported: on rolling out the new scheme, the average amount of household waste generated per household per week was reduced from 15.1 kg to 11.9 kg, while the amount of general refuse was significantly reduced from 12.8 kg to 6.4 kg (Somerset Waste Partnership, 2006). In addition, WRAP (2011c) reported that carbon emissions are lower compared to those for co-mingled and two-stream collection systems. The WRAP (2011) study looked at the environmental impacts and performed a cost assessment, but did not assess other parameters such as the fuel consumption and distance travelled.

In multi-compartment collection vehicles, the decision on which kind of wastes are put into which compartments is made by the collection crew. By observation during fieldwork, placing the recyclable materials into the wrong compartments could affect the overall efficiency of collecting household waste. The current work therefore investigated the effects of combination of wastes and compartments using the kerbside collection model.

The previous chapter considered the fuel consumption, total travelling distance and other resource-related parameters in the separate collection and co-collection of source segregated food waste, co-mingled dry recyclables and residual waste. In this chapter, the same collection model is used to run several scenarios to investigate kerbside-sorted collection and partially-sorted collection with source segregated food waste collection by a multi-compartment vehicle. The objective of this study was to assess the performance of the two kinds of kerbside-sorted system under various conditions. The specific sub-objectives were as follows:

- To compare the difference in fuel consumption and other parameters (total travelling distance, total time spent and number of vehicles required) for kerbside-sorted and partially-sorted collection systems.
- To determine which scenarios have the best and worst performance for fuel and other parameters in the two collection systems.
- To determine which vehicle types are best at different capture rates.
- To investigate the effects of combination of wastes and compartments as well as the utilisation of different compartments and vehicles.
- To conduct sensitivity analysis in order to determine which factors have the biggest influence on the model outputs.

8.2 Methodology

8.2.1 Composition of kerbside household waste

The waste composition used was the same as that given in Section 7.2.1, except that the combined total of 22.15% for paper and cad was split into 17.25% paper and 4.90% card. In this study, dry recyclables (Paper, Cardboard, Plastics, Glass and Metals) are collected separately for the kerbside-sorted system, while Plastics and Metals are collected co-mingled for the two-stream partially-sorted collection. The composition used is shown in Table 8.1

Table 8.1 Composition of kerbside household waste used in the modelling

Composition [a]	Proportion [b] (%)
Paper	17.25
Cardboard	4.90
Food	21.70
Plastics	11.43
Glass	7.13
Metals	3.17
Wood	0.83
Textiles	2.69
WEEE	0.82
Others	11.42

[a] Assumed garden and other organic waste are composted on site or collected separately
[b]Adapted from Defra (2012a)

8.2.2 Options for collection vehicles

In this study, only stillage vehicles were considered in the modelling. Four types of stillage vehicle can be selected from the model database, with the specifications shown in Table 8.2. Vehicles MKS1 and CWS1 have 8 compartments: six of these are equal in size, however, and can be regarded as 3 pairs of compartments for collecting three types of recyclable material. The same also applies to vehicles KS2 and MKS4, which have 9 compartments. These were grouped to give 5 compartments in vehicles MKS1 and CWS1 used for the partially-sorted collection, and 6 compartments in vehicles KS2 and MKS4 used for kerbside-sorted systems. For residual waste collection scenarios it was assumed that a single-compartment RCV was used with the vehicle specification as described in Section 7.2.2.

Table 8.2 Specification of stillage vehicles used in collection model

				Compartment size (m^3)					
Code	GVW (tonnes)	Payload (tonnes)	Volume (m^3)	1st	2nd	3rd	4th	5th	6th
MKS1	12	5.9	15	3	3	3	3	3	--
CWS1	12	4.85	35	2.52	3	4.3	5.7	19.7	--
KS2	15	7.76	18	1.99	1.54	1.54	1.54	5.74	5.74
MKS4	13.5	4	15	2	2	2	3	3	3

8.2.3 Arrangement of wastes and compartments

The number of possible permutations of wastes and compartments is 720 for the kerbside-sorted system and 120 for the partially-sorted system. In this study twelve and seven combinations were selected for modelling with 6-compartment and 5-compartment vehicles respectively, based on some of the combinations of wastes and compartments most commonly found in practice. Details of the combinations considered are shown in Table 8.3 and Table 8.4. The arrangement of wastes and compartments in KSP1 is the current practice in Kingston. The wastes and compartments in KSP11 and KSP12 were arranged in ascending order of volume and weight of the wastes respectively; the same principle was applied to C7 and C6 for the kerbside partially-sorted system. The arrangement of wastes and compartments in P1 is one suggested by vehicle company (Romaquip Ltd, 2011); while the combinations of wastes and compartments in KSP2-KSP10 and P2-P5 were randomly selected.

Table 8.3 Allocation of wastes and compartments for kerbside-sorted system

	Compartment					
Combination	1	2	3	4	5	6
KSP1	Cans	Food waste	Paper	Glass	Plastics	Card
KSP2	Food waste	Paper	Glass	Plastics	Card	Cans
KSP3	Paper	Glass	Plastics	Card	Cans	Food waste
KSP4	Glass	Plastics	Card	Cans	Food waste	Paper
KSP5	Plastics	Card	Cans	Food waste	Paper	Glass
KSP6	Card	Cans	Food waste	Paper	Glass	Plastics
KSP7	Glass	Food waste	Paper	Cans	Plastics	Card
KSP8	Food waste	Paper	Cans	Plastics	Card	Glass
KSP9	Plastics	Card	Glass	Food waste	Paper	Cans
KSP10	Card	Glass	Food waste	Paper	Cans	Plastics
KSP11	Glass	Card	Food waste	Metal	Paper	Plastics
KSP12	Metals	Card	Glass	Plastics	Paper	Food waste

Table 8.4 Allocation of wastes and compartments for partially-sorted collection system

	Compartment				
Combination	1	2	3	4	5
P1	Food Waste	Glass	Paper	Card	MPC [a]
P2	Glass	Paper	Card	MPC [a]	Food Waste
P3	Paper	Card	MPC [a]	Food Waste	Glass
P4	Card	MPC [a]	Food Waste	Glass	Paper
P5	MPC [a]	Food Waste	Glass	Paper	Card
P6	Card	Glass	MPC [a]	Paper	Food Waste
P7	Glass	Card	Food Waste	Paper	MPC [a]

[a] MPC = Mixed Plastics and Cans

8.2.4 Scenarios

As in the preceding chapter, a hypothetical area of 25,000 households was chosen for the case study. In accordance with common practice in kerbside-sorted collection systems, it was assumed that source segregated food waste and dry recyclable materials are collected by stillage vehicle every week, whilst residual waste is separately collected by a single-compartment collection vehicle with gross weight ranging from 3.5- to 26-tonnes, on a weekly or fortnightly basis. Four scenarios were considered based on the combinations of collection frequencies, collection systems, vehicle types and waste types shown in Table 8.5. Each scenario was run with equal set-out and capture rates for food waste and recyclables ranging from 10-100%, and with each combination of wastes and compartments for the respective collection systems (see Tables 8.3 and 8.4). The different combinations of wastes and compartments were grouped to allow comparison of the differences in fuel consumption and other parameters with respect to collection method and vehicle type. The combinations of wastes and compartments were firstly compared within the same collection method, and then compared between kerbside-sorted and partially-sorted collection systems. KSP1 and P1 were used as a baseline for comparison with other options.

Table 8.5 Scenarios for different kerbside-sorted and partially-sorted collection system

Scenario	Description
C2-S1	Weekly kerbside-sorted collection of dry recyclables and food waste by 6-compartment stillage vehicle, weekly collection using single-compartment RCV for residual waste
C2-S2	Weekly kerbside-sorted collection of dry recyclables and food waste by 6-compartment stillage vehicle, fortnightly collection using single-compartment RCV for residual waste
C2-S3	Weekly kerbside partially-sorted collection of dry recyclables and food waste by 5-compartment stillage vehicle, weekly collection using single-compartment RCV for residual waste
C2-S4	Weekly kerbside partially-sorted collection of dry recyclables and food waste by 5-compartment stillage vehicle, fortnightly collection using single-compartment RCV for residual waste

To allow comparisons to be made between different methods for collection of the whole household waste stream, the values obtained in Chapter 7 for fuel consumption and other parameters in weekly and fortnightly separate residual waste collections were simply added to those for collection of recyclables and food waste in the above scenarios.

8.2.5 Model inputs

The values used in modelling are shown in Table 8.6. Most of the inputs are as described in Chapters 6 and 7: for details refer to Section 6.2.4 and Section 7.2.4. Additional inputs included pick-up and sorting times for the recycling box (used by householders to put out mixed dry recyclables for collection), travel time to intermediate unloading, number of collectors involved in kerbside-sorted collection, and bulk densities of each individual dry recyclable material and of mixed plastic and cans.

The source segregated food waste, dry recyclable materials (paper, plastics, cans and glass) and cardboard were assumed to be collected in a food waste container, a recycling box and a nylon bag. The average pick-up time used for the recycling box was 37.8 seconds per location, including sorting time. This data was based on the field data collected in Kingston. The travelling time to the unloading site from part way around the collection was assumed to be 31 minutes, which is the average travelling time spent between collection areas and unloading site for intermediate unloading in Kingston. Although the kerbside-sorted collection differs from co-collection, the size of the crew was assumed to remain at 2.5 collectors for food waste and dry recyclables collections, based on the practice in Kingston. The bulk densities of mixed plastic and cans and of individual recyclable material (except cardboard) were taken from WRAP (2010); the bulk density for cardboard was that reported by Romaquip Ltd (2011).

Table 8.6 Input values for modelling kerbside-sorted collection system in a hypothetical city of 25,000 households

Parameter	Value	Units
General information:		
Number of households	25000	no. of HH
Amount of kerbside household waste generated	2.16	kg HH^{-1} day^{-1}
Number of collectors for recyclables and food waste collection	2	no. of collectors
Number of collectors for residual waste collection	2.5	no. of collectors
Bulk density of waste:		
Food waste	600	kg m^{-3}
Paper and magazines	279	kg m^{-3}
Mixed glass	456	kg m^{-3}
Mixed cans	56	kg m^{-3}
Mixed plastics	25	kg m^{-3}
Cardboard	144	kg m^{-3}
Mixed plastics and cans	33	kg m^{-3}
Residual waste	348	kg m^{-3}
Time:		
Working hours	6	hours
Break	30	mins
Traffic congestion	0	mins
Pick up crews	5	mins
Fuel filling	10	mins
Depot to first collection point	15	mins
Last collection point to depot	15	mins
At unloading site	30	mins
To intermediate unload when full	31	mins
For intermediate unloading	15	mins
Pick-up and sorting time for food waste and recycling	37.8	s HH^{-1}
Pick-up time for residual waste bin	36	s HH^{-1}
Distance:		
From depot to first collection point	6.25	km
From last collection to unloading site	6.25	km
Between collection points	15	m
To intermediate unload when full	12.92	km
Speed:		
In transportation	25	km hr^{-1}
In collection	10	km hr^{-1}
Factor for extra fuel consumption in collection:		
3.5-tonne to 9.5-tonne RCV	1.51	
12-tonne to 18-tonne RCV	2.02	
26-tonne RCV	2.86	

8.2.6 Sensitivity analysis

Monte Carlo simulation was carried out as before, using the @Risk® software to assess the effect on model outputs of uncertainty in input values. Most of the inputs and their values for the sensitivity analysis were as described in Section 7.2.5. In addition, some values were altered and/or further inputs were added, including those for bulk density of food waste, paper, glass, cans, plastics, cardboard and mixed plastics and cans, as well as the pick-up and sorting time for dry recyclables and source segregated food waste. Probability distributions were applied to a total of 18 inputs, based on the available data and an understanding of the nature of each input. The minimum, most likely and maximum value of bulk density for mixed plastics and cans and for each recyclable material was as reported by WRAP (2010), and for cardboard as suggested by Romaquip Ltd (2011) and CWS (2012). Details for all inputs for the sensitivity analysis are given in Table 8.7.

The average values for the fuel consumption, total working time, total travelling distance and the number of vehicles required at different capture rates were used to identify the optimum scenarios for the collection system and the allocation of compartments. Source segregated food waste and kerbside-sorted dry recycling collection systems (scenarios C2-S1 and C2-S2) were combined with the combination of waste and compartment KSP1-KSP12 for the sensitivity analysis, while kerbside partially-sorted collection systems (scenarios C2-S3 and C2-S4) were combined with P1-P7. The sensitivity analysis for separate collection of residual waste is reported in Chapter 7: for details refer to scenarios C1-S1a and C1-S2b in Sections 7.2.5 and 7.3 for the methodology and results respectively.

Table 8.7 Minimum, maximum and static values of each input parameter for kerbside-sorted system

Parameter	Minimum	Static	Maximum	Distribution
Bulk density (kg m^{-3}):				
- Food waste	550	600	680	Uniform
- Paper and magazines	208	279	330	Uniform
- Mixed glass	199	456	734	Uniform
- Mixed cans	50	56	60	Uniform
- Mixed plastics	18	25	28	Uniform
- Cardboard	144	144	150	Uniform
- Mixed plastics and cans	33	33	37	Uniform
- Residual waste	69	348[a]	418.3	Triangle
Number of collectors:				
- For picking up food waste and recyclable	1	2	2.5	Uniform
- For picking up residual waste	2	2.5	3	Uniform
Pick-up time (s HH^{-1}):				
- Food waste and recyclable (included sorting time)	8.46	21.6	27.5	Uniform
- Residual waste bin	30	36	54	Uniform
Distance between collection points (m)	3.6	15	29.5	Uniform
Speed in transportation (km hr^{-1})	15.8	25	48.8	Uniform
Speed in collection (km hr^{-1})	6	10	14.7	Uniform
Correction factor for extra fuel consumption:				
12-tonne to 18-tonne RCV	1.06	2.02	2.75	Uniform

[a] Represents the most likely value when a triangular probability distribution is used.

8.3 Results

8.3.1 Best and worst combinations of wastes and compartments

8.3.1.1 Fuel consumption in collection of food waste and dry recyclables

Table 8.8 and Figure 8.1a show the fuel consumption for the collection of source segregated food waste and kerbside-sorted dry recyclables in each combination of waste types and compartments at capture rates from 10-100%. The model was run with two 6-compartment stillage vehicles for all combinations of waste types and compartments shown in Table 8.3; the result shown is for the combination giving the lowest fuel consumption. Figure 8.1 shows that as expected the fuel consumption for collecting the food waste and dry recyclables increases when the capture rates increase. Four different groups of outcomes can be seen in Figure 8.1a, with little difference in fuel consumption between KSP3-5 and 9, KSP6-7, KSP10-11 or KS2, 8 and 12. The best combination is KSP7, in which the diesel usage ranges from 409.8 L week^{-1} to 1578.4 L week^{-1} at capture rates of 10-100%. The worst combination consumes up to 3584 L week^{-1} for KSP3, 4, 5 and 9.

Table 8.8 Summary of fuel consumption for collection of food waste and kerbside-sorted dry recyclables by optimum collection vehicle for each combination (L week^{-1})

	Capture rate of food waste and recyclables (%)									
Combination	10	20	30	40	50	60	70	80	90	100
KSP1	409.2	437.1	592.9	664.5	896.7	1161.9	1309.6	1541.6	1849.2	2220.7
KSP2	409.5	463.1	595.4	710.7	971.4	1193.5	1393.8	1676.1	2060.4	2539.0
KSP3	410.0	539.8	659.5	942.6	1155.8	1475.6	1949.5	2513.4	3054.0	3570.3
KSP4	410.5	540.0	659.1	937.6	1157.1	1472.8	1948.7	2509.4	3039.8	3583.5
KSP5	409.4	539.8	659.6	940.8	1154.8	1473.3	1946.5	2506.5	3055.7	3569.5
KSP6	409.5	428.0	480.4	637.0	689.0	776.8	957.3	1240.3	1462.4	1599.2
KSP7	409.4	428.2	472.8	619.9	689.6	767.1	926.7	1154.5	1385.6	1578.4
KSP8	409.8	461.9	595.6	711.8	968.8	1192.9	1394.0	1678.1	2064.1	2541.4
KSP9	410.4	538.8	659.8	942.1	1155.6	1471.8	1952.8	2508.0	3046.2	3569.9
KSP10	410.0	428.7	479.3	637.3	690.1	778.3	952.8	1240.2	1462.8	1601.0
KSP11	409.3	427.9	471.8	619.5	689.3	767.1	925.3	1156.3	1387.0	1578.9
KSP12	409.8	461.9	595.6	711.8	968.8	1192.9	1394.0	1678.1	2064.1	2541.4

Table 8.9 and Figure 8.1b show the fuel consumption for the collection of source segregated food waste and kerbside partially-sorted collection of dry recyclables in each combination of waste types and compartments at capture rates from 10-100%. It can be seen from Figure 8.1b that the weekly fuel consumption for P1 and P7, P3 and P6, and P4 and P5 are similar for all combinations of wastes and compartments. The worst combinations were P4 and P5 which consume up to 1495 L week^{-1}, while the best was P1 and P7 which use about 488 L week^{-1} at the maximum. Comparing both collection systems, kerbside-sorted collection by 6-compartment

vehicle consumes 1.47 to 3.25 times more diesel than using a 5-compartment vehicle for kerbside partially-sorted collection.

Table 8.9 Summary of fuel consumption for collection of food waste and kerbside partially-sorted collection of dry recyclables by optimum collection vehicle for each combination (L week^{-1})

	Capture rate of food waste and dry recyclables (%)									
Combination	10	20	30	40	50	60	70	80	90	100
P1	279.3	293.4	307.5	322.6	338.1	354.1	370.4	388.4	417.9	485.5
P2	279.1	293.3	309.1	402.9	487.0	523.4	580.1	680.6	860.5	1086.3
P3	279.0	293.0	340.3	451.5	489.5	562.7	731.1	958.1	1077.7	1177.8
P4	278.6	293.0	414.3	457.9	578.2	814.4	927.7	1060.0	1259.9	1495.1
P5	278.6	293.0	414.3	457.9	578.2	814.4	927.7	1060.0	1259.9	1495.1
P6	278.6	292.9	340.5	451.2	489.3	562.5	728.7	956.2	1078.2	1176.8
P7	278.6	292.9	307.3	322.3	337.7	353.6	369.9	388.0	416.6	488.5

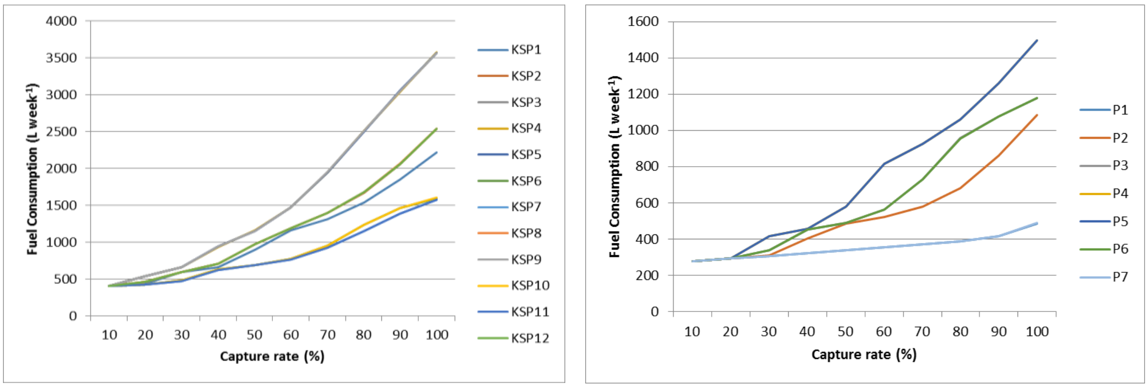


Figure 8.1 Fuel consumption for food waste and dry recyclable collection at different capture rates under optimum collection options for each combination, (a) Kerbside-sorted collection, (b) Kerbside partially-sorted collection

8.3.1.2 Total travelling distance in collection of food waste and dry recyclables

Figure 8.2 shows the best outcome with regard to travelling distance for the collection of food waste and dry recyclable materials at 10-100% capture rates in each combination of waste types and compartments. Results for total travelling distance of the kerbside-sorted collection systems are presented in Table 8.10. Figure 8.2a shows that total travelling distance increases gradually for capture rates from 10-70%, and more steeply from 70-100%. The pattern is similar to that for fuel consumption in both kerbside-sorted and partially-sorted collection systems. There is a significant difference between the worst and the best scenarios, especially at high capture rates in both systems. Putting plastics and cardboard into the largest compartments (combination KSP7 or KSP11) has the best effect on time spent, while putting food waste and paper into the largest compartments (combination KSP4) has the worst performance for kerbside-sorted collection by 6-compartment vehicle, by a factor of up to 2.54 times.

Table 8.10 Distance travelled per week in the collection of food waste and kerbside-sorted dry recyclables at different capture rates under the optimum collection vehicle for each combination (km week^{-1})

	Capture rate of food waste and dry recyclables (%)									
Combination	10	20	30	40	50	60	70	80	90	100
KSP1	640.4	757.8	1440.7	1749.2	2765.8	3927.1	4565.5	5576.0	6917.6	8539.4
KSP2	642.5	868.2	1445.4	1939.7	3076.5	4039.2	4904.1	6123.1	7792.5	9872.9
KSP3	640.9	1205.8	1725.0	2961.5	3884.8	5281.1	7355.6	9815.8	12175.1	14414.5
KSP4	641.8	1207.9	1721.2	2940.2	3893.5	5266.4	7341.8	9800.5	12112.8	14478.5
KSP5	640.8	1210.4	1730.5	2959.4	3889.2	5276.8	7349.4	9794.6	12186.2	14426.4
KSP6	640.5	715.4	940.9	1626.2	1846.0	2225.0	3012.5	4249.2	5212.5	5799.1
KSP7	641.0	716.7	904.5	1551.0	1850.3	2182.3	2872.9	3859.4	4876.6	5709.4
KSP8	641.2	860.5	1443.0	1944.3	3065.4	4035.3	4904.2	6134.5	7816.2	9885.7
KSP9	641.8	1200.8	1723.7	2956.4	3885.3	5259.3	7356.5	9780.6	12122.6	14403.2
KSP10	640.9	716.1	932.5	1625.3	1849.0	2229.0	2987.5	4244.2	5211.1	5805.1
KSP11	640.7	716.6	903.7	1550.4	1849.9	2184.7	2873.6	3879.3	4883.2	5714.4
KSP12	641.4	864.5	1445.6	1942.0	3069.0	4029.6	4902.0	6130.3	7790.1	9891.0

Table 8.11 summarises the best outcome with respect to travelling distance for the collection of food waste and kerbside partially-sorted dry recyclable materials at 10-100% capture rates. The travelling distance goes up sharply when capture rates increase, except in combinations P1 and P7 where it increases comparatively steadily. Figure 8.2b shows that placing mixed plastics and cans in the largest compartment (combination P1 and P7) gives the lowest travelling distance, whilst placing food waste, glass, paper, cardboard and mixed plastics and cans into the pair of equal-volume compartments has the worst effect on travelling distance (combination P4 and P5). The difference between the best and the worst combinations of wastes and compartments is up to 4.8 times. When comparing the best combination of wastes and compartments in kerbside-sorted and partially-sorted collection systems, the kerbside partially-sorted system has better performance with respect to total travelling distance, with 1.14 to 3.33 times shorter distances than for the kerbside-sorted collection system.

Table 8.11 Average distance travelled per week in the collection of food waste and kerbside partially-sorted dry recyclables at different capture rates under the optimum collection vehicle for each combination (km week^{-1})

	Capture rate of food waste and dry recyclables (%)									
Combination	10	20	30	40	50	60	70	80	90	100
P1	641.3	718.2	790.8	866.8	943.1	1020.0	1096.4	1182.3	1337.4	1716.8
P2	641.0	716.8	800.0	1349.2	1839.4	2041.2	2361.9	2940.3	3990.5	5307.3
P3	640.5	715.6	989.4	1640.6	1853.5	2275.9	3260.8	4587.5	5276.6	5850.4
P4	641.2	720.4	1434.0	1685.5	2382.6	3775.2	4434.4	5203.3	6375.0	7749.2
P5	641.3	720.4	1434.0	1685.5	2391.9	3775.2	4434.4	5206.0	6375.0	7749.2
P6	641.3	716.9	991.0	1640.7	1855.2	2276.1	3247.1	4578.1	5284.6	5848.1
P7	641.3	716.2	790.5	865.7	941.5	1017.8	1094.5	1180.6	1330.5	1743.1

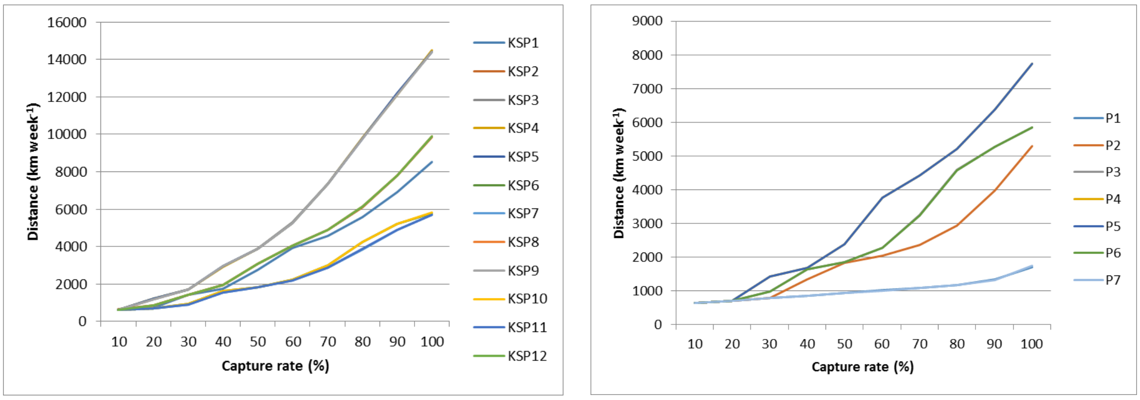


Figure 8.2 Total distances travelled for food waste and dry recyclables collection at different capture rates under optimum collection options for each combination; (a) Kerbside-sorted collection, (b) Kerbside partially-sorted collection

8.3.1.3 Total time spent in collection of food waste and dry recyclables

Table 8.12 and Figure 8.3a show the minimum time spent on collection at each capture rate for source segregated food waste and kerbside-sorted dry recyclables. As expected, the total time spent on kerbside-sorted collection of recyclables and food waste increases when the capture rate increases. The pattern in Figure 8.3 is similar to that in Figure 8.2 for the total travelling distance in both collection systems. The best allocation of waste types and compartments with respect to time spent was KSP7 or KSP11, putting the plastics in the largest compartment. The worst combination was combinations KSP3, 4, 5 and 9. The best and the worst allocations of waste and compartments take up 657 and 1286 hours per week, respectively: the difference between the best and the worst combinations is about 91%.

Table 8.12 Total time spent per week in the collection of food waste and kerbside-sorted dry recyclables at different capture rates under the optimum collection vehicle for each combination (km week^{-1})

	Capture rate of food waste and dry recyclables (%)									
Combination	10	20	30	40	50	60	70	80	90	100
KSP1	87.4	119.1	189.9	236.2	334.2	436.5	506.0	605.0	729.9	875.3
KSP2	87.5	127.1	190.2	251.0	355.0	445.3	532.5	648.1	795.3	968.7
KSP3	87.4	150.4	212.0	322.1	412.8	540.7	714.4	911.4	1098.8	1282.7
KSP4	87.5	150.4	212.0	320.7	413.2	540.1	714.8	909.9	1094.9	1286.7
KSP5	87.4	150.8	212.2	321.9	412.7	540.3	713.7	909.6	1099.9	1282.5
KSP6	87.4	115.5	155.9	226.1	264.7	316.9	398.8	508.4	597.6	662.9
KSP7	87.4	115.6	152.8	221.1	264.8	313.2	388.2	482.7	575.2	656.8
KSP8	87.4	126.6	190.2	250.9	353.9	445.0	532.3	648.2	795.7	968.9
KSP9	87.5	150.2	212.3	322.2	412.9	540.1	716.2	910.5	1097.8	1283.4
KSP10	87.5	115.6	155.6	226.1	264.9	317.3	397.5	508.4	597.8	663.4
KSP11	87.4	115.6	152.6	221.1	264.9	313.1	387.6	482.7	575.7	657.0
KSP12	87.5	126.9	190.3	251.1	354.5	444.5	532.5	648.4	795.3	970.2

Table 8.13 and Figure 8.3b summarise the minimum hours spent in collection of food waste and kerbside partially-sorted collection of dry recyclable materials at 10-100% capture rates. The time spent in collection also increases with an increasing capture rates, but the increase for P7 is mild compared with that for other combinations. Putting mixed plastics and cans in the largest compartment (combination P1 and P7) gives the lowest time spent, whilst placing food waste, glass, paper, cardboard and mixed plastics and cans into the pair of compartments with equal volumes requires the longest time to complete the collection (combination P4 and P5). The difference between the best and the worst combinations of wastes and compartments in kerbside partially-sorted collection system is a factor of up to 2.2. When comparing the difference in total time spent in kerbside-sorted and partially-sorted collection systems, the kerbside partially-sorted system used up to 1.8 times fewer hours than the kerbside-sorted system. At low capture rates (10-20%), the time spent in both collection systems is almost the same.

Table 8.13 Total time spent per week in the collection of food waste and kerbside-sorted dry recyclables at different capture rates under the optimum collection vehicle for each combination (km week^{-1})

	Capture rate of food waste and dry recyclables (%)									
Combination	10	20	30	40	50	60	70	80	90	100
P1	87.5	115.7	143.6	171.8	200.0	228.3	256.5	285.8	321.8	375.3
P2	87.4	115.6	144.6	207.8	263.9	301.2	348.9	417.3	516.5	629.7
P3	87.4	115.5	159.0	227.0	265.3	321.3	416.9	531.1	602.0	666.8
P4	87.5	116.0	189.6	230.8	307.3	427.1	496.1	575.5	687.3	815.0
P5	87.5	116.0	189.6	230.8	307.6	427.1	496.1	576.1	687.3	815.1
P6	87.5	115.6	159.3	227.0	265.3	321.3	416.2	530.5	602.1	666.2
P7	87.5	115.5	143.6	171.7	199.9	228.1	256.4	285.7	321.5	376.1

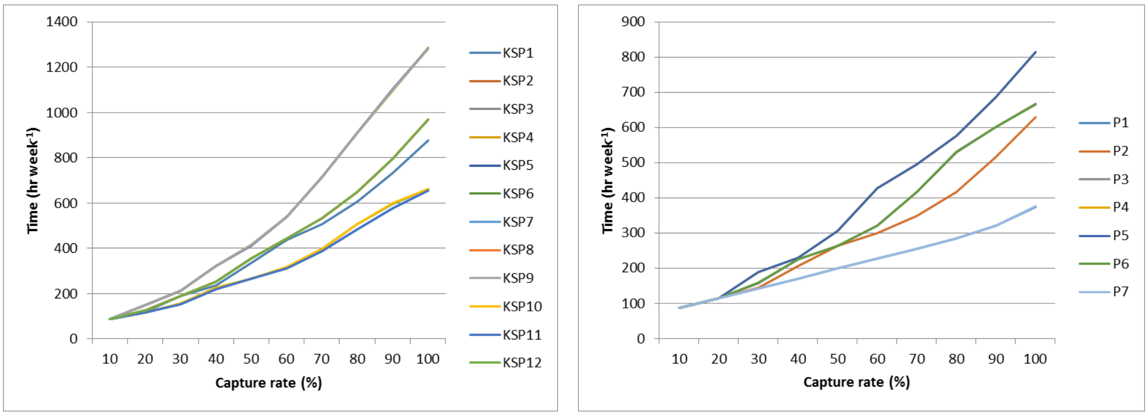


Figure 8.3 Total time spent for food waste and dry recyclable collection at different capture rates under optimum collection options for each combination, (a) Kerbside-sorted collection, (b) Kerbside partially-sorted collection

8.3.1.4 Number of vehicles required for collection of food waste and dry recyclables

The number of vehicles required for the kerbside-sorted and kerbside partially-sorted collections is shown in Table 8.14 and Table 8.15. As expected, the number of vehicles required for collection increases with increasing capture rates for food waste and recyclables, as shown in Figure 8.4. The best allocation of waste types and compartments was KSP7 at all capture rates, while KSP4 required the most stillage vehicles to complete the collection. The best allocation of waste type and compartments saves from 1 to 22 vehicles compared to the worst.

Table 8.14 Number of vehicles required in the collection of food waste and kerbside-sorted dry recyclables at different capture rates under the optimum collection option for each combination

	Capture rate of food waste and dry recyclables (%)									
Combination	10	20	30	40	50	60	70	80	90	100
KSP1	4	5	7	9	13	15	18	22	28	34
KSP2	4	5	7	10	13	16	19	24	30	36
KSP3	4	6	8	12	15	21	27	33	38	44
KSP4	4	6	8	12	15	21	27	33	38	44
KSP5	4	6	8	12	15	21	27	33	38	44
KSP6	4	5	6	8	10	12	15	18	21	23
KSP7	4	5	6	8	10	12	15	18	20	23
KSP8	4	5	7	10	13	16	19	24	30	36
KSP9	4	6	8	12	15	21	27	33	38	44
KSP10	4	5	6	8	10	12	15	18	21	23
KSP11	4	5	6	8	10	12	15	18	20	23
KSP12	4	5	7	10	13	16	19	24	30	36

For the kerbside partially-sorted collection system, the best combinations of waste types and compartments were P1 and P7 which required from 3 to 14 vehicles to complete the collection, while the worst arrangements were P4 and P5 which required from 3 to 30 vehicles. Using the best combination of both collection systems, kerbside-sorted collection requires 1.5 times more vehicles than kerbside partially-sorted collection.

Table 8.15 Number of vehicles required in the collection of food waste and kerbside partially-sorted collection of dry recyclables at different capture rates under the optimum collection option for each combination

	Capture rate of food waste and dry recyclables (%)									
Combination	10	20	30	40	50	60	70	80	90	100
P1	3	4	5	6	7	8	9	10	12	14
P2	3	4	5	8	9	10	12	15	19	22
P3	3	4	6	8	9	12	15	18	20	23
P4	3	4	7	8	12	15	17	20	25	30
P5	3	4	7	8	12	15	17	20	25	30
P6	3	4	6	8	9	12	15	18	20	23
P7	3	4	5	6	7	8	9	10	12	14

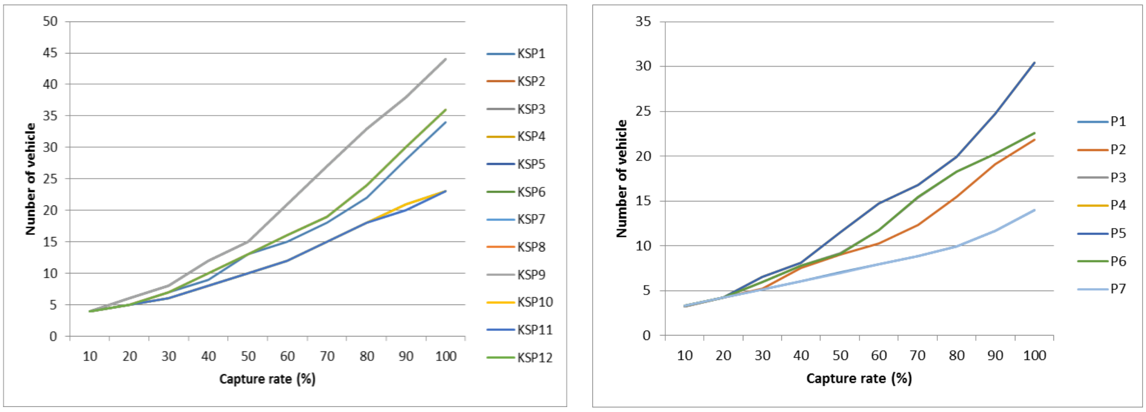


Figure 8.4 Number of vehicles required for food waste and dry recyclable collection at different capture rates under optimum collection options for each combination, (a) Kerbside-sorted collection, (b) Kerbside partially-sorted collection

8.3.2 Comparison of the best and the worst scenarios

Only the best scenario is presented in this section. This was calculated by adding the result of the best combination of waste types and compartments (Section 8.3.1) together with the best scenario for weekly or fortnightly residual waste collection (Section 7.3.2), to cover collection of the whole household waste stream. Results of all parameters except number of vehicles required were normalised using a weekly basis for the comparison.

8.3.2.1 Fuel consumption in the collection of whole household waste

Table 8.16 and Figure 8.5 show the fuel consumption for the whole household waste collection in each scenario at capture rates of 10-100% for recyclables and food waste. The fuel consumption in kerbside-sorted collection (scenarios C2-S1 and C2-S2) increases gradually when the capture rates for food waste and recyclables increase. A slight decrease in fuel consumption was seen in the kerbside partially-sorted system (scenarios C2-S3 and C2-S4) with increasing capture rates. Weekly collection of source segregated food waste with kerbside partially-sorted dry recyclables collection by 5-compartment stillage vehicle and fortnightly separate collection of residual waste by single-compartment vehicle (scenario C2-S4) is clearly the best scenario in term of fuel consumption. The weekly food waste collection and kerbside-sorted collection of recyclables with weekly residual waste collection (scenario C2-S1) had the worst performance at all capture rates. Interestingly, there is not much difference in fuel consumption between scenarios C2-S2 and C2-S3 when the capture rate is 20% or below. Comparing the difference in fuel consumption, the best scenario consumes 1.3-2.7 times less diesel than the worst scenario.

Table 8.16 Summary of the best collection option on the litre diesel consumed in collecting whole household waste stream per week ($Lweek^{-1}$)

	Capture rate of food waste and dry recyclables (%)									
Scenario	10	20	30	40	50	60	70	80	90	100
C2-S1	1026.3	1035.2	1064.3	1189.0	1226.4	1267.4	1381.1	1569.2	1749.9	1867.2
C2-S2	896.7	907.6	938.8	1070.1	1115.1	1162.4	1282.1	1464.4	1639.4	1773.6
C2-S3	895.8	900.2	899.8	891.8	875.1	853.9	825.7	802.8	780.9	774.4
C2-S4	766.1	772.6	774.3	772.9	763.8	748.9	726.7	697.9	670.4	680.7

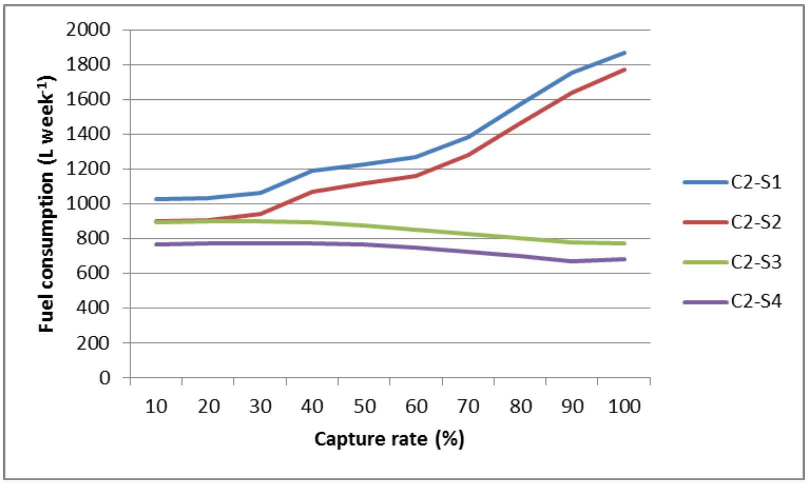


Figure 8.5 Fuel consumption for household waste collection at different capture rates under optimum collection options for each scenario

8.3.2.2 Total distance travelled in the collection of whole household waste

The best outcome regarding total travelling distance for collection of the whole household waste stream for each scenario at capture rates of 10-100% for recyclables and food waste is summarised in Table 8.17 and presented in Figure 8.6. The total travelling distance in the kerbside-sorted collection system (scenario C2-S1 and C2-S2) increases gently at low capture rates and then sharply at high capture rates. An increase in travelling distance with increasing capture rates is also seen in the kerbside partially-sorted system (scenarios C2-S3 and C2-S4) but it was very mild. As in the case of fuel consumption, the weekly collection of source segregated food waste with kerbside partially-sorted dry recyclables by 5-compartment stillage vehicle and weekly separate collection of residual waste by single-compartment vehicle (scenario C2-S4) is the best scenario for the total travelling distance. The weekly food waste collection and kerbside-sorted collection of recyclables by 6-compartment vehicle with weekly residual waste collection (scenario C2-S1) has the worst performance at all capture rates. Comparing the total travelling distance, there is a difference of 1.1-3.1 times between the worst and the best scenarios.

Table 8.17 Summary of the best collection option for each scenario with respect to distance travelled per week in collecting the whole household waste stream at different capture rates (Lweek^{-1})

	Capture rate of food waste and dry recyclables (%)									
Scenario	10	20	30	40	50	60	70	80	90	100
C2-S1	1993.1	2049.2	2210.9	2825.3	3068.8	3348.4	3997.6	4950.6	5947.9	6774.8
C2-S2	1773.6	1836.7	1996.6	2601.8	2835.8	3096.1	3678.8	4553.2	5478.5	6265.4
C2-S3	1993.2	2049.4	2097.7	2140.6	2164.4	2184.0	2219.2	2271.8	2401.8	2782.1
C2-S4	1773.6	1836.9	1883.5	1917.1	1931.3	1931.6	1900.4	1874.4	1932.4	2272.7

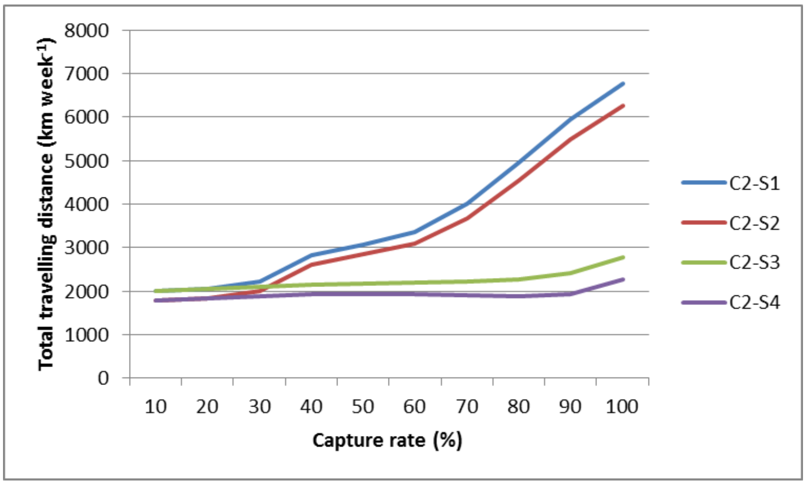


Figure 8.6 Distance travelled in household waste collection at different capture rates under the best collection option for each scenario

8.3.2.3 Total time spent in the collection of whole household waste

Figure 8.7 shows the minimum time spent in collection at each capture rate for food waste and recyclables; details of the results are summarised in Table 8.18. The time spent in all scenarios increases gradually with increasing capture rates for food waste and recyclables, as might be expected. In addition, the results continue to demonstrate that fortnightly residual waste collection with either weekly kerbside-sorted collection or kerbside partially-sorted collection requires less time to finish the collection of the whole household waste stream. The best and the worst scenarios are C2-S4 and C2-S1 respectively. The difference in total time spent between the best and worst scenarios is up to 1.7 times.

Table 8.18 Summary of the best collection option for each scenario with respect to total time spent per week in collecting whole household waste stream at different capture rates (Lweek^{-1})

	Capture rate of food waste and dry recyclables (%)									
Scenario	10	20	30	40	50	60	70	80	90	100
C2-S1	335.2	362.2	397.7	464.1	504.9	550.3	622.5	715.8	807.1	888.3
C2-S2	238.0	265.4	301.0	367.2	407.4	451.6	520.2	608.8	696.2	775.1
C2-S3	335.2	362.2	388.7	414.8	440.2	465.3	491.3	518.8	553.4	606.8
C2-S4	238.0	265.4	292.0	317.9	342.6	366.6	389.0	411.9	442.4	493.6

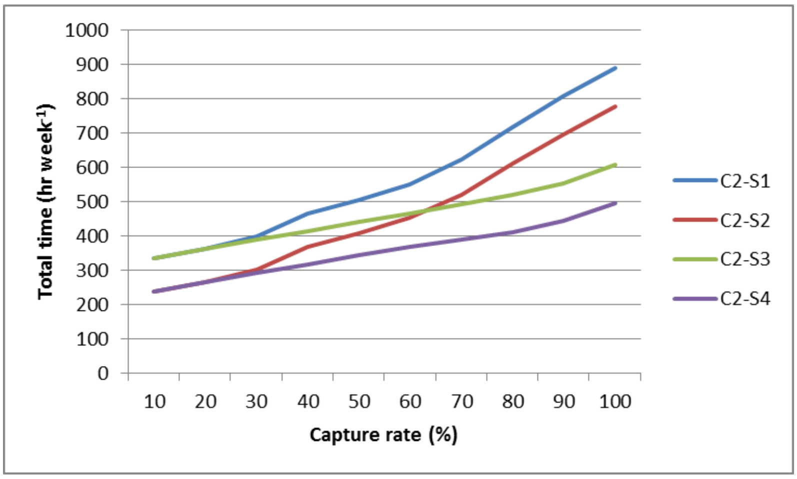


Figure 8.7 Minimum number of working hours per week to collect the whole household waste stream at different capture rates under the best collection option for each scenario

8.3.2.4 Number of vehicles required for the collection of whole household waste

The minimum number of vehicles required to complete the collection of the whole household waste stream at capture rates for food waste and recyclables from 10-100% is shown in Table 8.19 and Figure 8.8. The number of vehicles required increases gradually with increasing capture rates for food waste and recyclables in all scenarios. The best performance is for scenario C2-S4, where the number of vehicles required ranges from 10 up to a maximum of 19. The worst scenario is C2-S1 which requires up to 32 vehicles. Significant differences in fleet size are seen, especially at high capture rates for food waste and recyclables: the best scenario requires from 3 to 13 fewer vehicles than the worst scenario.

Table 8.19 Summary of the best collection option for each scenario with respect to number of vehicles used in collecting whole household waste stream at different capture rates

	Capture rate of food waste and dry recyclables (%)									
	10	20	30	40	50	60	70	80	90	100
C2-S1	13	14	15	17	19	21	24	27	29	32
C2-S2	10	11	12	14	16	18	20	23	25	28
C2-S3	13	14	15	16	17	17	18	19	21	23
C2-S4	10	11	12	13	14	14	14	15	17	19

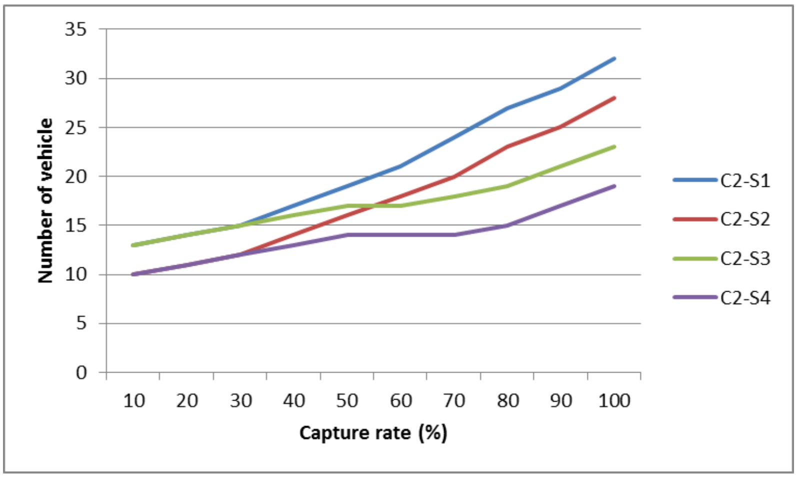


Figure 8.8 Minimum number of vehicles required for collection of the whole household waste stream at different capture rates under the best collection option for each scenario

8.3.3 Refuse collection vehicle

The 6-compartment and 5-compartment vehicles with the lowest fuel consumption in each combination of waste types and compartments at 10-100% capture rates of food waste and recyclable are shown in Table 8.20 and Table 8.21 respectively. It can be seen that vehicle MKS4 with three 2 m^3 and three 3 m^3 identical compartments performed better than vehicle KS2 in some of the combinations. Vehicle KS2 could be considered the best vehicle for the collection of food waste and kerbside-sorted dry recyclables, however, because it has the lowest fuel consumption among the combinations shown in KSP7 and KSP11 (for details refer to Section 8.3.1.1). Regarding the best vehicle for kerbside partially-sorted collection, vehicle CWS1 with five different-size compartments is the most suitable in most of the combinations considered. In addition, it also consumes the least diesel among the combinations considered. Details of the capacity of compartments of the best vehicles are examined in the following section. The best vehicles for weekly and fortnightly collection of residual waste are shown in Table 7.10 in Chapter 7.

Table 8.20 Best stillage vehicles with respect to fuel consumption in kerbside-sorted collection systems at capture rates from 10-100%

	Capture rate of recyclables and food waste (%)									
Combination	10	20	30	40	50	60	70	80	90	100
KSP1	KS2	KS2	KS2	KS2	KS2	KS2	KS2	KS2	KS2	KS2
KSP2	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4
KSP3	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4
KSP4	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4
KSP5	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4
KSP6	KS2	KS2	KS2	KS2	KS2	KS2	KS2	KS2	KS2	KS2
KSP7	KS2	KS2	KS2	KS2	KS2	KS2	KS2	KS2	KS2	KS2
KSP8	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4
KSP9	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4
KSP10	KS2	KS2	KS2	KS2	KS2	KS2	KS2	KS2	KS2	KS2
KSP11	KS2	KS2	KS2	KS2	KS2	KS2	KS2	KS2	KS2	KS2
KSP12	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4	MKS4

Table 8.21 Best stillage vehicles with respect to fuel consumption in kerbside partially-sorted collection systems at capture rates from 10-100%

	Capture rate of recyclables and food waste (%)									
Combination	10	20	30	40	50	60	70	80	90	100
P1	CWS1	CWS1	CWS1	CWS1	CWS1	CWS1	CWS1	CWS1	CWS1	CWS1
P2	CWS1	CWS1	CWS1	CWS1	CWS1	CWS1	CWS1	CWS1	CWS1	CWS1
P3	CWS1	CWS1	CWS1	CWS1	CWS1	CWS1	CWS1	CWS1	CWS1	CWS1
P4	MKS1	MKS1	MKS1	MKS1	MKS1	MKS1	MKS1	MKS1	MKS1	MKS1
P5	MKS1	MKS1	MKS1	MKS1	MKS1	MKS1	MKS1	MKS1	MKS1	MKS1
P6	CWS1	CWS1	CWS1	CWS1	CWS1	CWS1	CWS1	CWS1	CWS1	CWS1
P7	CWS1	CWS1	CWS1	CWS1	CWS1	CWS1	CWS1	CWS1	CWS1	CWS1

8.3.4 Allocation of compartments

In this section, the best vehicle with respect to fuel consumption in kerbside-sorted collection and kerbside partially-sorted collection was chosen to study the utilisation of the weight capacity of the vehicle and the volume capacity of each compartment. The performance of vehicle KS2 in combination KSP11 was selected for this purpose. Table 8.22 and Figure 8.9 show the changes in laden percentage and the volume of each compartment according to waste types at capture rates from 10-100%. The waste shown in brackets represents the type of waste collected in the corresponding compartment.

The laden percentage and the volume utilisation of each compartment increase sharply for capture rates from 10% to 30%. A decrease was observed at the capture rate of 30% and then a further increase until capture rates reached 60%. The utilisation of each compartment and the payload of the vehicle decreases steadily at capture rates from 60% to 90%, then grow slightly when all food waste and recyclables materials are captured. Figure 8.9 shows the laden percentage of the vehicle ranged from 2-8%. The biggest compartment for the plastics collection has the best utilisation, ranging from 17% to 91% at capture rates from 10-100%. The filling rate of compartments is presented in descending order: plastics, glass, cans, food waste, cardboard and paper.

Table 8.22 Summary of laden percentage of vehicle and volume percentage of compartments of the best stillage vehicle used in kerbside-sorted collection system at capture rates for recyclables and food waste from 10-100%

	Capture rate of food waste and recyclables (%)									
	10	20	30	40	50	60	70	80	90	100
Laden %	2	5	8	6	7	9	9	8	8	8
Compartment 1 (Glass)	9	28	44	34	40	48	48	46	44	45
Compartment 2 (Card)	5	15	23	17	21	25	25	24	23	23
Compartment 3 (FW)	5	15	24	19	22	26	27	25	24	25
Compartment 4 (Cans)	8	25	39	30	36	43	44	41	39	40
Compartment 5 (Paper)	2	7	11	8	10	12	12	11	11	11
Compartment 6 (Plastics)	17	54	82	64	77	90	91	85	83	85

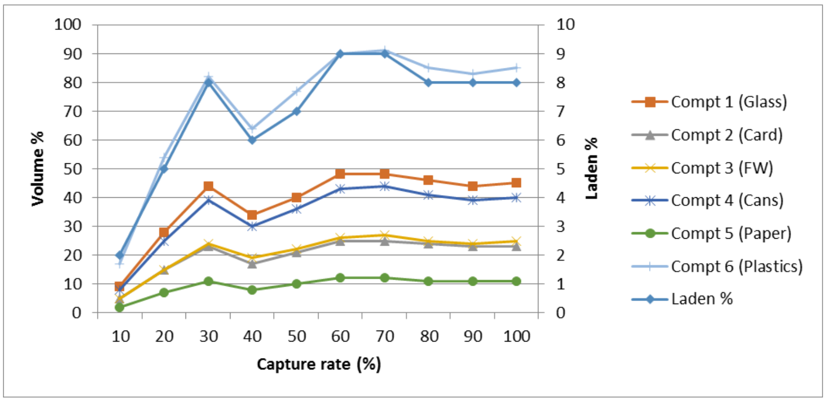


Figure 8.9 Laden percentage of vehicle and volume utilisation percentage of compartment at capture rates of recyclables and food waste from 10-100% for vehicle KS2 in combination KSP11 (Kerbside-sorted collection system)

For kerbside partially-sorted collection, vehicle CWS1 in combination P1 was selected to study the performance with regard to laden percentage and the volume percentage of compartments. Table 8.23 and Figure 8.10 show the changes in laden percentage and the volume utilisation of each compartment according to waste type at capture rates from 10-100%. Generally, the laden percentage and volume utilisation of each compartment increased steadily from capture rates of 10% to 90%; a fall was observed when 100% of food waste and recyclable materials were all captured in the recycling container. Figure 8.10 shows the laden percentage of vehicle ranged from 3% to 60%. The highest compartment utilisation was for the one with biggest volume capacity, used to collect mixed plastics and cans. The utilisation of compartments ranged from 4% to 94% at capture rates from 10-100%. The graph also shows that the compartments for collecting cardboard and glass had the same utilisation of volume capacity. The filling rate of compartments in descending order is: Mixed plastics and cans, paper, food waste, glass and cardboard.

Table 8.23 Summary of laden percentage of vehicle and volume percentage of compartments of the best stillage vehicle used in kerbside partially-sorted collection at capture rates of recyclables and food waste from 10-100%

	Capture rate of food waste and dry recyclables (%)									
	10	20	30	40	50	60	70	80	90	100
Laden %	3	8	15	23	31	40	48	56	60	55
Compartment 1 (FW)	3	9	16	24	32	41	50	58	62	58
Compartment 2 (Glass)	1	4	7	10	13	17	21	24	26	24
Compartment 3 (Paper)	3	9	17	26	35	44	54	63	67	62
Compartment 4 (Card)	1	4	7	10	13	17	21	24	26	24
Compartment 5 (MPC)	4	13	24	36	49	62	75	88	94	87

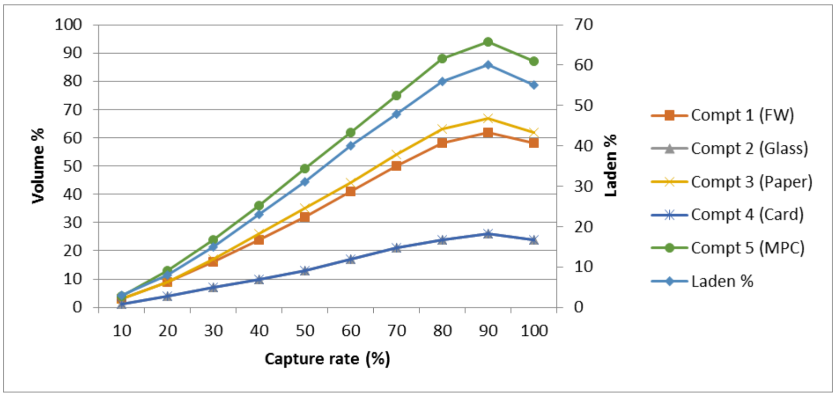


Figure 8.10 Laden percentage of vehicle and volume utilisation percentage of compartment at capture rates of recyclables and food waste from 10-100% for vehicle CWS1 and combination P1 (Kerbside partially-sorted collection system)

8.4 Sensitivity analysis for fuel consumption, time and distance travelled

8.4.1 Fuel consumption in food waste and dry recyclables collection

A summary of the sensitivity analysis for fuel consumption by stillage vehicles with six and with five compartments is given in Table 8.24 and Table 8.25. It can be seen that extra fuel consumption in collection, speed in collection and transportation and density of plastics were the parameters with the greatest effect on the fuel consumption in the kerbside-sorted collection system in general, while the same factors apart from density of plastics had a certain degree of effect on fuel consumption for the kerbside partially-sorted collection system. The sensitivity analysis of the best combination of waste types and compartments is reported for kerbside-sorted and partially-sorted collection systems.

For kerbside sorting and collection of dry recyclables with food waste by 6-compartment RCV (combination KSP7), extra fuel consumption in collection and speed in collection were the first and second most important factors affecting the fuel usage at capture rates from 10% to 60%. At capture rates of 70% or above, the density of plastics and the speed in transportation become the most influential factors on fuel consumption. Higher extra fuel consumption could increase the total fuel consumption, whilst higher speed in collection may reduce the fuel use. When food waste and dry recyclables were collected by the kerbside partially-sorted collection system in a 5-compartment stillage vehicle (combinations P1 and P7), the extra fuel consumption has the biggest positive effect on fuel consumption. Higher speed in transportation will increase the fuel consumption.

Table 8.24 Summary of results of sensitivity analysis for fuel consumption for kerbside-sorted collection at capture rates from 10-100%

		Capture rates for food waste and dry recyclables (%)									
Combination	Parameter	10	20	30	40	50	60	70	80	90	100
KSP1	Factor on extra fuel consumption	0.79	0.80	0.69	0.73	0.61	0.48	0.47	0.45	0.38	--
	Speed in collection	-0.55	-0.49	-0.60	-0.51	--	--	--	--	--	--
	Speed in transportation	--	--	--	--	0.48	0.56	0.65	0.77	0.82	0.78
	Density of mix cans	--	--	--	--	--	--	--	--	--	-0.34
KSP2	Factor on extra fuel consumption	0.82	0.76	0.62	0.55	--	--	--	--	--	--
	Density of mix plastics	--	--	--	--	-0.67	-0.65	-0.45	-0.59	-0.68	-0.69
	Speed in transportation	--	--	0.43	0.54	0.52	0.57	0.73	0.72	0.69	0.69
	Speed in collection	-0.56	-0.60	--	--	--	--	--	--	--	--
KSP3	Factor on extra fuel consumption	0.78	0.73	0.61	0.54	--	--	--	--	--	--
	Speed in collection	-0.54	-0.57	--	--	--	--	--	--	--	--
	Speed in transportation	--	--	0.41	0.54	0.52	0.59	0.74	0.73	0.71	0.70
	Density of mixed plastics	--	--	--	--	-0.69	-0.65	-0.44	-0.60	-0.69	-0.70
KSP4	Factor on extra fuel consumption	0.80	0.75	0.61	0.54	--	--	--	--	--	--
	Speed in collection	-0.55	-0.57	--	--	--	--	--	--	--	--
	Speed in transportation	--	--	0.41	0.55	0.52	0.56	0.74	0.72	0.69	0.68
	Density of mixed plastics	--	--	--	--	-0.66	-0.63	-0.44	-0.58	-0.66	-0.68
KSP5	Factor on extra fuel consumption	0.76	0.50	--	--	--	--	--	--	--	--
	Speed in collection	-0.41	--	--	--	--	--	--	--	--	--
	Speed in transportation	--	--	0.66	0.69	0.70	0.69	0.69	0.67	0.61	0.56
	Density of mixed plastics	--	-0.62	-0.56	-0.69	-0.71	-0.72	-0.72	-0.73	-0.71	-0.74
KSP6	Factor on extra fuel consumption	0.81	0.81	0.83	0.73	0.70	0.70	0.54	0.46	0.45	--
	Speed in collection	-0.56	-0.56	-0.39	-0.57	-0.59	-0.46	--	--	--	-0.42
	Speed in transportation	--	--	--	--	--	--	0.48	0.55	0.66	0.72
KSP7	Factor on extra fuel consumption	0.82	0.82	0.81	0.73	0.70	0.68	0.48	--	--	0.39
	Speed in collection	-0.56	-0.56	-0.42	-0.45	-0.58	-0.49	--	--	--	--

	Density of mixed plastics	--	--	--	--	--	--	-0.58	-0.63	-0.42	
	Speed in transportation	--	--	--	--	--	--	--	--	--	0.67
KSP8	Factor on extra fuel consumption	0.82	0.76	0.62	0.54	--	--	--	--	--	--
	Speed in collection	-0.56	-0.58	--	--	--	--	--	--	--	--
	Speed in transportation	--	--	0.42	0.56	0.53	0.57	0.76	0.74	0.72	0.71
	Density of mixed plastics	--	--	--	--	-0.68	-0.66	-0.45	-0.59	-0.59	-0.70
KSP9	Factor on extra fuel consumption	0.78	0.47	--	--	--	--	--	--	--	--
	Speed in collection	-0.40	--	--	--	--	--	--	--	--	--
	Speed in transportation	--	--	0.65	0.67	0.68	0.68	0.67	0.65	0.60	0.55
	Density of mixed plastics	--	-0.61	-0.56	-0.67	-0.68	-0.70	-0.70	-0.71	-0.69	-0.72
KSP10	Factor on extra fuel consumption	0.80	0.80	0.82	0.71	0.69	0.71	0.53	0.45	0.42	--
	Speed in collection	-0.55	-0.56	-0.37	-0.58	-0.58	-0.45	--	--	--	-0.42
	Density of mixed plastics	--	--	--	--	--	--	-0.44	--	--	--
	Speed in transportation	--	--	--	--	--	--	--	0.53	0.66	0.70
KSP11	Factor on extra fuel consumption	0.81	0.81	0.81	0.72	0.69	0.68	0.50	--	--	0.40
	Speed in collection	-0.56	-0.56	-0.40	-0.46	-0.58	-0.47	--	--	--	--
	Density of mixed plastics	--	--	--	--	--	--	-0.58	-0.66	-0.43	--
	Speed in transportation	--	--	--	--	--	--	--	0.42	0.53	0.68
KSP12	Factor on extra fuel consumption	0.83	0.83	0.74	0.66	0.51	0.51	--	--	--	--
	Speed in collection	-0.57	-0.39	-0.62	--	--	--	--	--	--	--
	Density of mixed plastics	--	--	--	-0.42	-0.51	--	-0.46	-0.62	-0.69	-0.74
	Speed in transportation	--	--	--	--	--	0.60	0.63	0.64	0.57	0.52

Table 8.25 Summary of results of sensitivity analysis for fuel consumption for kerbside partially-sorted collection at capture rates from 10-100%

		Captures rate for food waste and dry recyclables (%)									
Combination	Parameter	10	20	30	40	50	60	70	80	90	100
P1	Factor on extra fuel consumption	0.85	0.84	0.84	0.83	0.83	0.83	0.82	0.82	0.80	0.61
	Speed in collection	-0.51	-0.51	-0.52	-0.51	-0.50	-0.49	-0.48	-0.46	--	--
	Speed in transportation	--	--	--	--	--	--	--	--	0.37	0.38
P2	Factor on extra fuel consumption	0.83	0.83	0.83	0.78	0.67	0.65	0.66	0.58	0.39	0.33
	Speed in collection	-0.50	-0.51	-0.49	--	-0.53	-0.50	--	--	--	--
	Speed in transportation	--	--	--	0.34	--	--	0.58	0.65	0.62	0.72
P3	Factor on extra fuel consumption	0.84	0.83	0.85	0.70	0.68	0.68	0.46	0.38	--	0.33
	Speed in collection	-0.51	-0.51	--	-0.55	-0.52	--	--	--	-0.37	--
	Speed in transportation	--	--	0.22	--	--	0.58	0.59	0.72	0.76	0.82
P4	Factor on extra fuel consumption	0.84	0.84	0.72	0.72	0.61	0.45	--	0.39	0.34	0.28
	Speed in collection	-0.51	-0.50	-0.56	-0.50	--	--	-0.42	--	--	--
	Speed in transportation	--	--	--	--	0.54	0.69	0.73	0.84	0.90	0.92
P5	Factor on extra fuel consumption	0.84	0.84	0.72	0.72	0.61	0.45	--	0.39	0.34	0.28
	Speed in collection	-0.51	-0.50	-0.56	-0.50	--	--	-0.42	--	--	--
	Speed in transportation	--	--	--	--	0.54	-0.69	0.73	0.84	0.90	0.92
P6	Factor on extra fuel consumption	0.84	0.83	0.85	0.70	0.68	0.69	0.47	0.37	--	0.34
	Speed in collection	-0.51	-0.51	--	-0.55	-0.51	--	--	--	-0.37	--
	Speed in transportation	--	--	0.23	--	--	0.58	0.59	0.72	0.76	0.82
P7	Factor on extra fuel consumption	0.84	0.84	0.83	0.83	0.83	0.82	0.82	0.82	0.80	0.60
	Speed in collection	-0.51	-0.51	-0.51	-0.51	-0.50	-0.49	-0.48	-0.46	-0.36	--
	Speed in transportation	--	--	--	--	--	--	--	--	--	0.39

8.4.2 Total distance travelled in food waste and dry recyclables collection

The results of the sensitivity analysis for total time spent by stillage vehicles for kerbside-sorted collection and kerbside partially-sorted collection are summarised in Table 8.26 and 8.27 respectively. The speeds in transportation and collection and the pick-up time for bins were the most important factors for both systems, with the density of plastics and the density of mixed plastics and cans also affecting the total distance travelled for kerbside sorted and kerbside partially-sorted collection system respectively.

The regression coefficient of speed in transportation ranged from 0.76 to 0.94 and had the largest positive effect on total distance travelled for the best combination of waste types and compartments in kerbside-sorted collection (combination KSP7) at all capture rates. The total travelling distance is less affected by other factors, such as speed in collection and density of plastics. When food waste and dry recyclables were collected by the kerbside partially-sorted collection system by stillage vehicles with five compartments (combination P1 and P7), speed in transportation was also the most important factor that positively affects the total distance travelled. It is expected that a higher speed in transportation will increase the total distance travelled.

Table 8.26 Summary of results of sensitivity analysis for total travelling distance for kerbside-sorted collection at capture rates from 10-100%

		Capture rate for food waste and dry recyclables (%)									
Combination	Parameter	10	20	30	40	50	60	70	80	90	100
KSP1	Speed in transportation	0.90	0.77	0.92	0.97	0.84	0.94	0.97	0.99	0.99	0.96
	Speed in collection	-0.33	--	-0.29	--	--	-0.13	-0.10	--	--	--
	Density of mixed cans	--	-0.28	--	-0.11	-0.27	--	--	-0.15	-0.17	-0.21
KSP2	Speed in transportation	0.89	0.93	0.38	0.93	0.83	0.85	0.94	0.93	0.91	0.91
	Speed in collection	-0.31	-0.24	--	--	--	--	--	--	--	--
	Density of mixed plastics	--	--	-0.28	-0.33	-0.46	-0.41	-0.25	-0.33	-0.38	-0.39
KSP3	Speed in transportation	0.89	0.93	0.88	0.94	0.84	0.87	0.95	0.94	0.92	0.92
	Speed in collection	-0.31	-0.21	--	--	--	--	--	--	--	--
	Density of mixed plastics	--	--	-0.29	-0.33	-0.47	-0.41	-0.24	-0.33	-0.39	-0.40
KSP4	Speed in transportation	0.89	0.93	0.85	0.91	0.81	0.84	0.93	0.91	0.90	0.89
	Speed in collection	-0.29	-0.21	--	--	--	--	--	--	--	--
	Density of mixed plastics	--	--	-0.30	-0.32	-0.45	-0.41	-0.24	-0.33	-0.38	-0.39
KSP5	Speed in transportation	0.79	0.85	0.93	0.92	0.92	0.92	0.91	0.90	0.87	0.84
	Density of mixed plastics	-0.44	-0.47	-0.34	-0.40	-0.40	-0.41	-0.41	-0.43	-0.44	-0.48
KSP6	Speed in transportation	0.91	0.92	0.66	0.93	0.95	0.94	0.81	0.86	0.95	0.97
	Speed in collection	-0.33	-0.30	--	-0.19	-0.21	--	--	--	--	--
	Density of mixed plastics	--	--	-0.35	--	--	-0.18	-0.34	-0.21	--	--
	Pick up time for bins	--	--	--	--	--	--	--	--	0.12	0.15
KSP7	Speed in transportation	0.89	0.90	0.62	0.83	0.94	0.93	0.76	0.77	0.87	0.94
	Speed in collection	-0.33	-0.30	--	--	-0.19	--	--	--	--	--
	Density of mixed plastics	--	--	-0.46	-0.24	--	-0.24	-0.49	-0.49	-0.30	-0.14
KSP8	Speed in transportation	0.89	0.83	0.87	0.94	0.84	0.87	0.95	0.94	0.93	0.92
	Speed in collection	-0.30	-0.21	--	--	--	--	--	--	--	--
	Density of mixed plastics	--	--	-0.29	-0.33	-0.47	-0.43	-0.24	-0.33	-0.39	-0.40
KSP9	Speed in transportation	0.78	0.83	0.92	0.91	0.91	0.90	0.90	0.89	0.86	0.83
	Density of mixed plastics	-0.43	-0.46	-0.33	-0.38	-0.39	-0.39	-0.40	-0.41	-0.42	-0.46
KSP10	Speed in transportation	0.88	0.90	0.66	0.92	0.95	0.96	0.81	0.85	0.95	0.96
	Speed in collection	-0.34	-0.30	--	-0.20	-0.19	--	--	--	--	--
	Density of mixed plastics	--	--	-0.37	--	--	-0.17	-0.36	-0.24	--	--

	Pick up time for bins	--	--	--	--	--	--	--	--	0.13	0.15
KSP11	Speed in transportation	0.89	0.90	0.65	0.82	0.94	0.94	0.78	0.77	0.86	0.95
	Speed in collection	-0.33	-0.29	--	--	-0.19	--	--	--	--	--
	Density of mixed plastics	--	--	-0.46	-0.25	--	-0.24	-0.50	-0.53	-0.31	--
	Pick up time for bins	--	--	--	--	--	--	--	--	--	0.11
KSP12	Speed in transportation	0.90	0.59	0.94	0.79	0.81	0.95	0.93	0.91	0.84	0.81
	Speed in collection	-0.34	--	-0.26	--	--	--	--	--	--	--
	Density of mixed plastics	--	-0.53	--	-0.43	-0.41	-0.15	-0.30	-0.39	-0.45	-0.50

Table 8.27 Summary of results of sensitivity analysis for total travelling distance for kerbside partially-sorted collection at capture rates from 10-100%

		Capture rate for food waste and dry recyclables (%)									
Combination	Parameter	10	20	30	40	50	60	70	80	90	100
P1	Speed in transportation	0.87	0.90	0.91	0.92	0.93	0.94	0.94	0.96	0.91	0.68
	Speed in collection	-0.33	-0.29	-0.27	-0.24	-0.21	-0.18	--	--	--	--
	Pick up time for bins	--	--	--	--	--	--	0.17	0.14	--	--
	Density of mixed plastics and cans	--	--	--	--	--	--	--	--	-0.14	-0.32
P2	Speed in transportation	0.89	0.91	0.95	0.72	0.94	0.95	0.99	0.95	0.84	0.91
	Speed in collection	-0.33	-0.30	-0.20	-0.37	-0.22	-0.18	--	--	--	--
	Density of mixed plastics and cans	--	--	--	--	--	--	-0.07	-0.14	--	-0.12
	Pick up time for bins	--	--	--	--	--	--	--	--	-0.22	--
P3	Speed in transportation	0.89	0.91	0.63	0.93	0.95	0.98	0.84	0.92	0.95	0.97
	Speed in collection	-0.33	-0.30	-0.41	-0.24	-0.18	--	--	--	--	--
	Density of mixed plastics and cans	--	--	--	--	--	-0.11	--	-0.09	--	--
	Pick up time for bins	--	--	--	--	--	--	-0.21	--	0.17	0.12
P4	Speed in transportation	0.90	0.93	0.92	0.97	0.86	0.93	0.97	0.99	0.99	0.99
	Speed in collection	-0.33	-0.24	-0.27	-0.15	--	--	--	--	--	--
	Density of mixed plastics and cans	--	--	--	--	-0.19	-0.08	--	-0.08	-0.10	-0.11
	Pick up time for bins	--	--	--	--	--	--	0.15	--	--	--
P5	Speed in transportation	0.90	0.93	0.92	0.97	0.86	0.93	0.97	0.99	0.99	0.99
	Speed in collection	-0.33	-0.24	-0.27	-0.15	-0.19	--	--	--	--	--
	Density of mixed plastics and cans	--	--	--	--	--	-0.08	--	-0.08	-0.10	-0.11
	Pick up time for bins	--	--	--	--	--	--	0.15	--	--	--
P6	Speed in transportation	0.90	0.91	0.64	0.94	0.95	0.98	0.84	0.92	0.95	0.97
	Speed in collection	-0.33	-0.30	0.41	-0.24	-0.18	--	--	--	--	--
	Density of mixed plastics and cans	--	--	--	--	--	-0.11	-0.20	-0.10	--	--
	Pick up time for bins	--	--	--	--	--	--	--	--	0.18	0.13
P7	Speed in transportation	0.89	0.91	0.92	0.93	0.94	0.94	0.95	0.96	0.89	0.66
	Speed in collection	-0.34	-0.30	-0.28	-0.25	-0.21	-0.19	--	--	--	--
	Density of mixed plastics and cans	--	--	--	--	--	--	--	--	-0.13	--
	Pick up time for bins	--	--	--	--	--	--	0.17	0.13	--	-0.32

8.4.3 Total time spent in food waste and dry recyclables collection

A summary of the results of sensitivity analysis for total time spent in kerbside-sorted collection and kerbside partially-sorted collection is given in Table 8.28 and Table 8.29 respectively. Overall, the speed in collection, density of waste that first fills up the compartments, pick-up time for bins and number of collectors were the parameters influencing the total time spent in both systems on food waste and dry recyclables collection.

The results show that speed in collection is the most critical parameter in combination KSP7, which negatively affects the total time spent at capture rates from 10% to 50%. The same parameter also affects time spent in combination P7 for the kerbside partially-sorted collection at capture rates of 60% or below. Higher speeds in collection are expected to decrease the total time spent to complete whole collection. For the kerbside-sorted collection (combination KSP7), density of mixed plastics could also have a significant influence on total time spent at capture rates from 70% to 90%. When the capture rate reaches 100%, the pick-up time for bins becomes the most influential factor. For the kerbside partially-sorted collection system, the time required to pick up bins was the second most important factor at capture rates of 10% to 60% and of 90% and it became the most important factor for total time spent at capture rates of 70% to 80%. The number of collectors also slightly influenced the total time spent at capture rates of 80% to 90%.

Table 8.28 Summary of results of sensitivity analysis for total time spent for kerbside-sorted collection at capture rates from 10-100%

		Capture rate for food waste and dry recyclables (%)									
Combination	Parameter	10	20	30	40	50	60	70	80	90	100
KSP1	Speed in collection	-0.92	-0.76	-0.80	-0.69	--	-0.55	-0.52	--	--	--
	Density of mixed cans	--	-0.26	--	--	-0.65	--	--	-0.62	-0.78	-0.79
	Pick up time for bins	0.14	--	0.36	0.39	--	0.51	0.53	0.45	0.40	0.16
	Density of paper	--	--	--	--	-0.08	--	--	--	--	--
KSP2	Speed in collection	-0.91	-0.86	-0.47	-0.44	-0.07	--	--	--	--	--
	Density of mixed plastics	--	--	-0.51	-0.76	-0.91	-0.83	-0.69	-0.87	-0.97	-0.98
	Pick up time for bins	0.15	0.26	--	--	--	0.12	0.32	0.23	0.11	0.08
KSP3	Speed in collection	-0.93	-0.83	-0.50	-0.42	--	-0.12	--	--	--	--
	Density of mixed plastics	--	--	-0.50	-0.79	-0.91	-0.83	-0.70	-0.88	-0.98	-0.98
	Pick up time for bins	0.12	0.23	--	--	0.06	--	0.31	0.22	--	0.08
	Number of collectors	--	--	--	--	--	--	--	--	-0.10	--
KSP4	Speed in collection	-0.93	-0.83	-0.47	-0.43	-0.06	-0.14	--	--	--	--
	Density of mixed plastics	--	--	-0.53	-0.76	-0.9	-0.82	-0.67	-0.87	-0.97	-0.98
	Pick up time for bins	0.12	0.24	--	--	--	--	0.34	0.20	0.11	--
	Number of collectors	--	--	--	--	--	--	--	--	--	-0.08
KSP5	Density of mixed plastics	-0.61	-0.89	-0.87	-0.89	-0.99	-0.99	-0.97	-0.97	-0.89	-0.89
	Speed in collection	-0.53	-0.13	-0.32	-0.09	-0.06	-0.03	-0.03	--	--	--
	Pick up time for bins	--	--	--	--	--	--	--	0.03	--	--
	Density of mixed plastics	--	--	--	--	--	--	--	--	-0.05	--
KSP6	Speed in collection	-0.93	-0.89	-0.50	-0.73	-0.68	-0.51	--	--	--	--
	Density of mixed plastics	--	--	-0.44	--	--	--	-0.68	-0.45	--	--
	Pick up time for bins	0.13	0.27	--	0.44	0.50	0.43	0.11	--	0.59	0.62
	Number of collectors	--	--	--	--	--	--	--	-0.15	-0.48	-0.55
KSP7	Speed in collection	-0.93	-0.89	-0.52	-0.55	-0.68	-0.52	--	-0.15	--	--
	Pick up time for bins	0.13	0.26	--	0.35	0.50	0.45	0.16	--	--	0.54
	Density of mixed plastics	--	--	-0.51	--	--	--	-0.80	-0.80	-0.54	--
	Number of collectors	--	--	--	--	--	--	--	--	-0.31	-0.46
KSP8	Speed in collection	-0.93	-0.84	-0.47	-0.43	--	-0.14	-0.30	--	--	--

	Pick up time for bins	0.12	0.24	--	--	--	--	--	0.23	0.11	0.09
	Density of mixed plastics	--	--	-0.50	-0.77	-0.91	-0.83	-0.69	-0.88	-0.97	-0.98
KSP9	Density of mixed plastics	-0.64	-0.90	-0.89	-0.98	-0.99	-0.99	-0.97	-0.97	-0.90	-0.89
	Speed in collection	-0.50	-0.11	-0.28	-0.08	--	--	--	--	--	--
	Pick up time for bins	--	--	--	--	0.05	--	0.03	--	--	--
	Number of collectors	--	--	--	--	--	-0.04	--	-0.03	--	--
KSP10	Speed in collection	-0.94	-0.89	-0.46	-0.74	-0.68	-0.51	-0.12	--	--	--
	Pick up time for bins	0.12	0.25		0.42	0.49	0.44	--	--	0.57	0.61
	Density of mixed plastics	--	--	-0.46	--	--	--	-0.68	-0.49	--	--
	Number of collectors	--	--	--	--	--	--	--	-0.17	-0.52	-0.54
KSP11	Speed in collection	-0.94	-0.90	-0.50	-0.56	-0.70	-0.52	--	--	--	--
	Pick up time for bins	0.12	0.26	--	0.38	0.51	0.45	0.15	0.17	0.35	0.58
	Density of mixed plastics	--	--	-0.55	--	--	--	-0.83	-0.82	-0.54	--
	Number of collectors	--	--	--	--	--	--	--	--	--	-0.50
KSP12	Speed in collection	-0.94	-0.48	-0.82	-0.32	-0.24	-0.53	-0.35	--	--	--
	Pick up time for bins	0.13	--	0.37	--	--	0.48	--	0.18	0.07	--
	Density of mixed plastics	--	-0.61	--	-0.71	-0.68	--	-0.71	-0.91	-0.91	-0.91
	Number of collectors	--	--	--	--	--	--	--	--	--	-0.05

Table 8.29 Summary of results of sensitivity analysis for total time spent for kerbside partially-sorted collection at capture rates from 10-100%

		Capture rate for food waste and dry recyclables (%)									
Combination	Parameter	10	20	30	40	50	60	70	80	90	100
P1	Speed in collection	-0.94	-0.90	-0.84	-0.77	-0.71	-0.65	-0.59	--	--	--
	Pick up time for bins	0.14	0.28	0.38	0.47	0.53	0.58	0.62	0.64	0.60	--
	Number of collectors	--	--	--	--	--	--	--	-0.55	-0.52	-0.19
	Density of mixed plastics and cans	--	--	--	--	--	--	--	--	--	-0.43
P2	Speed in collection	-0.94	-0.89	-0.83	--	-0.69	-0.63	-0.55	--	--	--
	Density of mixed plastics and cans	--	--	--	-0.31	--	--	--	-0.40	-0.50	-0.28
	Pick up time for bins	0.12	0.26	0.34	0.19	0.51	0.55	0.56	0.37	-0.10	0.34
P3	Speed in collection	-0.94	-0.89	-0.25	-0.76	-0.69	0.57	--	--	--	--
	Density of mixed plastics and cans	--	--	-0.30	--	--	--	-0.54	--	--	--
	Pick up time for bins	0.13	0.26	--	0.45	0.50	0.50	0.08	0.41	0.64	0.63
	Number of collectors	--	--	--	--	--	--	--	-0.32	-0.57	-0.56
P4	Speed in collection	-0.93	-0.89	-0.82	-0.74	-0.19	-0.40	-0.57	--	--	--
	Pick up time for bins	0.13	0.24	0.36	0.43	--	0.38	0.58	0.55	0.53	0.50
	Density of mixed plastics and cans	--	--	--	--	-0.52	--	--	--	-0.56	-0.64
	Number of collectors	--	--	--	--	--	--	--	-0.49	--	--
P5	Speed in collection	-0.93	-0.89	-0.82	-0.74	-0.19	-0.40	-0.57	--	--	--
	Pick up time for bins	0.13	0.24	0.36	0.43	--	0.38	0.58	0.55	0.53	0.50
	Density of mixed plastics and cans	--	--	--	--	-0.52	--	--	--	-0.56	-0.64
	Number of collectors	--	--	--	--	--	--	--	-0.49	--	--
P6	Speed in collection	-0.94	-0.89	-0.26	-0.76	-0.69	-0.57	--	--	--	--
	Pick up time for bins	0.13	0.27	--	0.44	0.51	0.50	0.06	0.40	0.64	0.63
	Density of mixed plastics and cans	--	--	-0.28	--	--	--	-0.53	--	--	--
	Number of collectors	--	--	--	--	--	--	--	-0.33	-0.56	-0.57
P7	Speed in collection	-0.94	-0.89	-0.83	-0.76	-0.69	-0.63	-0.58	--	--	--
	Pick up time for bins	0.13	0.27	0.37	0.45	0.52	0.56	0.59	0.61	0.58	--
	Density of mixed plastics and cans	--	--	--	--	--	--	--	--	--	-0.44
	Number of collectors	--	--	--	--	--	--	--	-0.55	-0.51	-0.16

8.5 Discussion

8.5.1 Comparison of different allocation of waste types and compartments in kerbside-sorted collection and kerbside partially-sorted collection

Two sets of combinations, KSP1 to KSP12 and P1 to P7, looked at the effects of different allocation of waste types and compartments in different types of vehicles for kerbside-sorted collection and kerbside partially-sorted collection on fuel consumption, total distance travelled, total time spent and the number of stillage vehicles required. The results showed the best allocation of waste types and compartments for fuel consumption also applies to the other parameters, which differs slightly from the equivalent result for co-collection where the optimal scenario for fuel consumption is not always same as for other output parameters (see section 7.5.2). This is mainly because the best RCV with respect to fuel consumption (KS2 for the kerbside-sorted and CWS1 for the kerbside partially-sorted system) is also the best one for other parameters.

When setting the combination of waste types and compartments, KSP3 and KSP4 were expected to be the worst combinations, especially when collected by vehicle KS2, because placing food waste in the biggest compartment means the smaller compartments fill up first and more intermediate unloading is required in a working day. This was demonstrated in Chapter 7, and the result in this study is in line with these findings. The results showed that not only do KSP3 and KSP4 have the worst performance for fuel consumption and other parameters, but so do KSP5 and KSP9. This is due to the inefficient allocation of wastes and compartments in vehicle MKS4: plastics with low bulk density were placed in the smaller compartment which filled up more quickly than the bigger compartment that collected food waste. A similar situation is also seen in the kerbside partially-sorted collection system in combination P4 and P5 where food waste and dry recyclables were allocated to the two identical compartments with a volume of 3 m^3 in vehicle MKS1. Vehicle MKS1 is the best RCV in both combinations mainly because to the size of the identical compartments is slightly larger than the smallest compartment in vehicle CWS1.

On the other hand, combinations KSP 6, 7, 10 and 11 for kerbside-sorted collection and combinations P1 and P7 for kerbside partially-sorted collection were the best allocation of waste types and compartments, as shown by the lowest consumption of fuel and other resources. Allocating the plastic materials to the largest compartment in vehicle KS2 and mixed plastics and cans to the largest compartment in vehicle CWS1 would be the optimal options. In addition, combinations KSP11 and P7 and KSP12 and P6 were set up to investigate the effect of allocating wastes and compartments by the volume or weight of individual materials. The result confirmed that allocating the compartments according to the volume of individual material collected would be a sensible method. This implies that local authorities or waste management contractors should estimate the volume of food waste and of each dry recyclable from the bulk density and the amount of waste collected in the previous year before they start to plan the arrangement of vehicles and allocation of waste types and compartments. One of the main limitations that prevent this is lack of information, as was seen during the data collection phases of the current research. This is due to failure to measure certain useful parameters. There is therefore a strong case for waste management contractors both to overhaul their existing data collection and recording arrangements, and pro-actively to use them for data mining and analysis; and for incorporation of more on-board measurement devices to gather data on weight and volume of material collected. The use of radio frequency identification (RFID) clips in bin systems have attracted some controversy, as householders and others seen them as a step forwards to pay-per-throw systems (BBC, 2006, BBC, 2010). No such problems, however, are associated with collection of data on waste categories once the waste is loaded into the compartments or onto the vehicle, and companies are likely to be interested as the data may give them commercial advantages. Installation of on-board measurement devices may also be beneficial to vehicle manufacturers, especially when collection frequencies for some recyclable materials change, as it will allow feedback of data to the vehicle manufacturers on optimising the compartment size. The same ideas could also be applied in twin-compartment vehicles.

The results also showed that the kerbside partially-sorted collection system has the lowest fuel consumption and the best values for the other parameters. This could be explained by the fact that the constraint in these collections is always the compartment volume. The best vehicle is therefore one with the largest total compartment size and an optimised allocation of waste types to compartments, which allows it to collect the maximum amount of waste at one time.

8.5.2 Comparison of collection of the whole household waste stream by kerbside-sorted and kerbside partially-sorted collection

This part of the work considered the fuel consumption, total distance travelled, total time spent in collection and transportation and the number of vehicles required for collection of the whole household waste stream. It is clear that kerbside-sorted collection (scenarios C2-S1 and C2-S2) uses more fuel and other resources than the partially-sorted system (scenarios C2-S3 and C2-S4): a significant difference is seen at high capture rates of food waste and recyclables. In addition, there is a dramatic increase in all parameter values apart from the number of vehicles required in kerbside-sorted collection compared to those for kerbside partially-sorted collection.

This phenomenon can be explained from the breakdown of the calculation of those output parameters. The parameter values consist of two parts: a component from the kerbside-sorted or partially-sorted collection system, and another from the weekly or fortnightly single additional collection of residual waste. The breakdown of fuel consumption in scenario in C2-S1 and C2-S3 is used as an example for this explanation (see Table 8.30). The last part of Table 8.30 shows the percentage of fuel used for the collection of food waste and recyclable within the whole household waste collection. The results show that the increase of fuel consumption in kerbside-sorted collection ranges from 40% to 85%, while for kerbside partially-sorted collection this range is 31% to 66%. With increasing capture rates, there is a decrease in fuel use in collection of residual waste, and when this is combined with the results for kerbside partially-sorted collection, the net increase in fuel consumption for whole household waste collection is relatively small compared to that for kerbside sorted collection.

Table 8.30 Breakdown of fuel consumption of the collection of household waste stream per week in Scenarios C2-S1 and C2-S3 (L $week^{-1}$)

	Capture rate of food waste and recyclables (%)									
	10	20	30	40	50	60	70	80	90	100
Kerbside-sorted collection (KSP7)	409.5	428.2	472.8	619.9	689.6	767.1	926.7	1154.5	1385.6	1578.4
Weekly residual waste collection	617.2	607.3	592.5	569.5	537.4	500.3	455.8	414.8	364.3	288.9
Kerbside partially-sorted collection (P1)	276.6	287.7	299.8	312.8	326.5	340.4	355.0	396.3	493.8	572.7
Weekly residual waste collection	617.2	607.3	592.5	569.5	537.4	500.3	455.8	414.8	364.3	288.9
Percentage of fuel consumption in										
Combination KSP7	40%	41%	44%	52%	56%	61%	67%	74%	79%	85%
Combination P1	31%	32%	34%	35%	38%	40%	44%	49%	58%	66%

8.5.3 Allocation of wastes and compartments in the best stillage vehicle

Figures 8.9 and 8.10 show the change in laden percentage of vehicle and volume percentage of different compartments at capture rates for recyclables and food waste from 10-100% for the optimal allocation of compartments and waste types in kerbside-sorted collection and partially-sorted collection systems. It can be seen that the volume of compartments and the vehicle laden percentage never reaches 100%. As in the single additional case in Chapter 7, this is because the modelling used the Averaged option rather than the Flat-out option for calculation of the number of households visited per day. If the Flat-out option is assumed, it is possible the maximum capacity of compartments and vehicle could be reached; however, the Averaged option gives some flexibility to cope with seasonal and day-to-day variations in the amount of waste collected, such as when a sales promotion event for beverages or fast food leads to a slight increase in waste quantities (Personal communication, Veolia staff, 2013). In the case of larger variations, for example around public holidays such as Christmas, the whole collection calendar may be altered to deal with the larger amounts collected by adding extra trips or longer shifts with more intermediate drop-offs.

On the other hand, the pattern and the trend of the graphs in Figure 8.9 and 8.10 are quite different although both vehicles used have non-identical compartment sizes. The difference is mainly affected by the number of loads per collection day and can be explained as follows: For the kerbside-sorted collection (Figure 8.9, vehicle KS2 and combination KSP11), two peaks were observed at capture rates of 30% and 70%. The first peak occurs because of a change in constraint. At capture rates from 10 % to 30%, the number of loads per working day was equal to one, meaning that time is the constraint; the utilisation of vehicle and compartment capacity increases with increasing capture rates so a positive slope is observed. The second peak occurs because of a change in the number of loads. At capture rates from 40% to 70% there is a higher chance of 2 loads per day, and this shifts to a higher occurrence of 3 loads per day at capture rates of 80% or above (for details refer to Appendix B).

The same reasoning can be applied to the kerbside partially-sorted collection system (Figure 8.10, vehicle CWS1 and combination P1). A positive slope is seen at capture rates of 90% or below: the utilisation of vehicle and compartment keeps increasing with the increase in capture rates for food waste and recyclables because time is the constraint in that range of captures rates. A fall is seen after the maximum utilisation of capacity is reached because of the change from time constraint to vehicle constraint. The change in slope for utilisation of compartments depends on the bulk density of waste. For instance, mixed plastics and cans increase more steeply than others such as food waste, simply because mixed plastics and cans have the lowest bulk density.

8.5.4 Sensitivity analysis for allocation of waste types and compartments in kerbside-sorted and partially-sorted collection systems

The sensitivity analysis showed that the factor for extra fuel consumption made the biggest contribution to uncertainty in fuel consumption. This parameter is one of the least well-established: the field work carried out for the current study only considered a 6-compartment stillage vehicle, and the factor calculated may not apply to 5-compartment vehicles. More data are needed from collections using stillage vehicles in order to improve the reliability of this value and to understand its behaviour in different circumstances.

The speeds in transportation and in collection are the most influential factors on the total distance travelled and the time spent in the whole collection, respectively. As discussed in Chapter 5, information on vehicle speed is relatively easy to obtain through the use of GPS trackers, and waste management contractors will have increasing access to this type of data from on-board logging. Gaining access to this information for research purposes and ensuring that similar protocols are used to interpret it may be more difficult, however, so it may be some time before accurate data becomes widely available. Although the bulk density of waste has some effect on the output parameters, it was not as significant as the previous factors, and its importance can thus be downgraded in comparison with the emphasis given to this parameter in the study of separate collection of residual waste or in co-collection of residual waste with recyclables or food waste (see Section 7.5.5).

8.6 Conclusions on collection of household waste by different kerbside-sorted collection systems

In this study, the kerbside collection model was used to calculate the fuel consumption, total travelling distance, total time spent and the number of collection vehicles required for the kerbside-sorted and partially-sorted collection of source segregated food waste and dry recyclables with weekly or fortnightly collection of residual waste. The results from the modelling showed that, under the range of scenarios and conditions considered:

- In general, fuel consumption, total distance travelled, total time spent in collection and the number of vehicles required for collecting food waste and dry recyclables increases when the capture rates for co-mingled recyclables and for food waste increase.
- The combinations KSP6, 7, 10 and 11 are always the best allocation of waste types and compartments for the kerbside-sorted collection system, while combinations P1 and P7 are the best for the kerbside partially-sorted collection system in all parameters.
- The fuel consumption and other parameters of the best and the worst allocation of waste types and compartments in kerbside-sorted and partially-sorted collection were compared individually. For the kerbside-sorted collection, the worst allocation consumes up to 2.27 times more fuel, travels 2.54 times further, uses 1.91 times more hours and 2 times more vehicles than the best allocation of waste types and compartments. For the kerbside partially-sorted collection, the worst allocation consumes up to 3.08 times more fuel, travels 4.8 times further, uses 2.2 times more hours and 3.3 times more vehicles than the best allocation of waste types and compartments.
- Kerbside-sorted collection of household waste always has the worst performance in fuel use and other parameters: It consumes 1.47 to 3.25 times more diesel and uses 1.5 times more stillage vehicles than the kerbside partially-sorted collection system. In addition, the

kerbside partially-sorted system has better performance with respect to the total distance travelled which is 1.14 to 3.33 times shorter and uses 1.8 times fewer hours than the kerbside-sorted collection system.

- The best collection vehicle was the stillage vehicle with non-identical compartment sizes. Vehicles KS2 and CWS1 were ideal for the kerbside-sorted collection and kerbside partially-sorted collection systems, respectively.
- From the study of combinations of the compartments and wastes type, it was found that calculating the volumes of individual materials collected would be a sensible method to determine the optimal allocation of waste and compartments in stillage vehicle.
- The correction factor for extra fuel consumption, and the speeds in transportation and collection have the greatest influence on the fuel consumption, total distance travelled and total time spent in whole collection respectively.

Chapter 9: COMPARISON OF SEPARATE, CO-COLLECTION AND KERBSIDE-SORTED COLLECTION OF THE WHOLE HOUSEHOLD WASTE STREAM

In this chapter, the outputs of the best scenarios in separate collection, co-collection, kerbside-sorted collection and kerbside partially-sorted collection of the whole household waste stream are gathered to compare performances in terms of fuel consumption, total distance travelled, total time spent and total number of collection vehicles required. Section 9.1 gives the general background, aim and objectives of this comparative study of different collection systems. Section 9.2 summarises the scenarios and model inputs. Section 9.3 shows the model outputs from the best scenarios in each collection system. Section 9.4 discusses the results of the comparison work, and the conclusions are presented in Section 9.5.

9.1 Introduction

There is considerable scope for discussion on the types of kerbside collection schemes most suitable for adoption in different circumstances. The kerbside collection model used in the current work was constructed and validated using real life data collected from local authorities. The performances of the separate collection, co-collection, kerbside-sorted collection and kerbside partially-sorted collection of whole household waste have been separately studied in Chapters 7 and 8. In this chapter, a comparative study of the different kinds of collection systems is conducted by putting together the optimal options for each scenario in terms of fuel consumption, total travelling distance, total time spent and number of vehicles required, to allow selection of the best household waste collection systems overall.

9.2 Methodology

9.2.1 Composition of household waste, collection vehicle options and scenario setting

A hypothetical city of 25,000 households was once again used in the study. It was assumed that each household generates 788.5 kg of kerbside household waste per year, equivalent to 2.16 kg per household per day, as described in Section 3.5.2 and Section 7.2.1. The amounts of food waste, separated or co-mingled recyclables and residual waste were calculated from the generation rates for kerbside household waste and the composition of the household waste stream, as presented in Tables 7.1 and 8.1. Thirteen scenarios were considered based on the combinations of collection frequencies, vehicle types, waste types, collection methods and allocation of waste types and compartments summarised in Table 9.1. Each scenario was run with capture rates for food waste and recyclables, ranging from 10-100%. All collection vehicles involved in the studies are as described in Table 3.6 and their specifications are shown in Table 9.2.

Table 9.1 Summary of scenarios for kerbside household waste collection

Scenario	Description
C1-S1	Weekly separate collections of recyclables, residual and food waste by single-compartment RCV
C1-S2	Alternate fortnightly collection of recyclables and residual waste and weekly collection of food waste by single-compartment RCV
C1-S3	Weekly co-collection of recyclables and residual waste by two-compartment RCV, weekly collection using single-compartment RCV for food waste
C1-S4	Fortnightly co-collection of recyclables and residual waste by two-compartment RCV, weekly collection using single-compartment RCV for food waste
C1-S5	Weekly co-collection of recyclables and food waste by two-compartment RCV, weekly collection using single-compartment RCV for residual waste
C1-S6	Weekly co-collection of recyclables and food waste by two-compartment RCV, fortnightly collection using single-compartment RCV for residual waste
C1-S7	Weekly co-collection of residual waste and food waste by two-compartment RCV, weekly collection using single-compartment RCV for recyclables
C1-S8	Weekly co-collection of residual waste and food waste by two-compartment RCV, fortnightly collection using single-compartment RCV for recyclables
C1-S9	Weekly food waste collection with AWC of residual waste and recyclables by two-compartment RCV
C2-S1	Weekly kerbside-sorted collection of dry recyclables and food waste by six-compartment stillage vehicle, weekly collection using single-compartment RCV for residual waste
C2-S2	Weekly kerbside-sorted collection of dry recyclables and food waste by six-compartment stillage vehicle, fortnightly collection using single-compartment RCV for residual waste
C2-S3	Weekly kerbside partially-sorted collection of dry recyclables and food waste by five-compartment stillage vehicle, weekly collection using single-compartment RCV for residual waste
C2-S4	Weekly kerbside partially-sorted collection of dry recyclables and food waste by five-compartment stillage vehicle, fortnightly collection using single-compartment RCV for residual waste

Table 9.2 Specification of all single-compartment and compartmentalised collection vehicles used in modelling

				Compartment size (m^3)					
Code	GVW (tonnes)	Payload (tonnes)	Volume (m^3)	1st	2nd	3rd	4th	5th	6th
3.5t	3.5	0.715	5.5	5.5	--	--	--	--	--
7.5t	7.5	3.58	5	5	--	--	--	--	--
12t	12	3.74	10	10	--	--	--	--	--
15t	15	5.9	13	13	--	--	--	--	--
18t	18	7.75	15	15	--	--	--	--	--
26t	26	12.84	25	25	--	--	--	--	--
Duo1	26	11.77	18.89	5	13.9	--	--	--	--
Duo2	26	11.57	20.89	7	13.9	--	--	--	--
Duo3	26	11.26	23.45	7	16.5	--	--	--	--
Twin1	26	10.58	20	10	10	--	--	--	--
Twin2	23	9.28	15	5	10	--	--	--	--
Twin3	26	10.88	20	6	14	--	--	--	--
MKS1	12	5.9	15	3	3	3	3	3	--
CWS1	12	4.85	35	2.52	3	4.3	5.7	19.7	--
KS2	15	7.76	18	1.99	1.54	1.54	1.54	5.74	5.74
MKS4	13.5	4	15	2	2	2	3	3	3

9.2.2 Model input

The description of model inputs and the values used in modelling the scenarios were as given in Chapters 6, 7 and 8: for full details refer to sections 6.2.4, 7.2.4 and 8.2.5. Input values used for modelling the kerbside collection of household wastes are summarised in Table 9.3. Some of the model inputs (such as bulk density of food waste, time and distance to intermediate unload when full) used in Section 8.2.5 differed from those in Section 7.2.4. In order to make all of the scenarios comparable, the input values listed in Table 9.3 were used to run scenarios C2-S1 to C2-S4 again.

Table 9.3 Model inputs for running all scenarios in a hypothetical city of 25,000 households

Parameter	Value	Units
General information:		
Number of households	25000	no. of HH
Amount of kerbside household waste generated	2.16	kg HH^{-1} day^{-1}
Number of collectors for recyclables and food waste collection	2	no. of collectors
Number of collectors for residual waste collection	2.5	no. of collectors
Bulk density of waste:		
Food waste	470	kg m^{-3}
Co-mingled recyclables	405	kg m^{-3}
Paper and magazines	279	kg m^{-3}
Mixed glass	456	kg m^{-3}
Mixed cans	56	kg m^{-3}
Mixed plastics	25	kg m^{-3}
Cardboard	144	kg m^{-3}
Mixed plastics and cans	33	kg m^{-3}
Residual waste	348	kg m^{-3}
Time:		
Working hours	6	hours
Break	30	mins
Traffic congestion	0	mins
Pick up crews	5	mins
Fuel filling	10	mins
Depot to first collection point	15	mins
Last collection point to depot	15	mins
At unloading site	30	mins
To intermediate unload when full	15	mins
For intermediate unloading	15	mins
Pick-up time for food waste bin	21.6	s HH^{-1}
Pick-up and sorting time for food waste and recycling	37.8	s HH^{-1}
Pick-up time for recycling/ residual waste bin	36	s HH^{-1}
Distance:		
From depot to first collection point	6.25	km
From last collection to unloading site	6.25	km
Between collection points	15	m
To intermediate unload when full	6.25	km
Fuel consumption:		
Speed in transportation	25	km hr^{-1}
Speed in collection	10	km hr^{-1}
Factor for extra fuel consumption in collection:		
3.5-tonne to 9.5-tonne RCV	1.51	
12-tonne to 18-tonne RCV	2.02	
26-tonne RCV	2.86	

9.2.3 Comparison of optimal scenarios

The scenarios were grouped into four categories: Separate collection (scenarios C1-S1 and C1-S2), co-collection (scenarios C1-S3 to C1-S9), kerbside-sorted collection (scenarios C2-S1 and C2-S2) and kerbside partially-sorted collection of household waste (scenarios C2-S3 and C2-S4). The results were reported on a weekly basis.

9.3 Results

9.3.1 Fuel consumption in household waste collection by different collection systems

Table 9.4 and Figure 9.1 show the fuel consumption of the best options for different systems for the collection of the whole household waste stream at capture rates from 10-100%. The fuel consumption for separate collection ranges from 705 to 1039 L week^{-1}, for co-collection from 798 to 1346 L week^{-1}, for kerbside-sorted collection from 894 to 1806 L week^{-1} and for kerbside partially-sorted collection from 736 to 895 L week^{-1}. The weekly fuel consumption for the four systems followed the decreasing sequence: kerbside-sorted collection > co-collection > separate collection > kerbside partially-sorted collection. Among all possible scenarios, the weekly kerbside partially-sorted collection of dry recyclable and food waste run alongside fortnightly collection of residual waste (scenario C2-S4) is the best system in terms of fuel consumption at capture rates of 10% to 80%, while fortnightly separate collection of co-mingled recyclables and residual waste with weekly separate collection on food wastes (scenario C1-S2) is best at capture rates of 80% or above. Figure 9.1 clearly shows that the fuel consumption in the kerbside-sorted collection system (scenario C2-S1, S2) increases dramatically when the capture rates of food waste and recyclables increase. At capture rates 50% or above, it becomes the worst collection system irrespective of whether residual waste is collected weekly or fortnightly.

Table 9.4 Summary of the best collection options for different collection systems with respect to fuel consumption for collection of the whole household waste stream at capture rates 10-100%

	Capture rate of food waste and recyclable (%)									
Scenario	10	20	30	40	50	60	70	80	90	100
C1-S1	1036.9	1038.9	1036.4	1026.2	1007.6	986.6	963.3	951.5	939.4	909.5
C1-S2	803.0	803.5	799.7	794.9	788.3	780.7	767.6	749.2	725.2	705.7
C1-S3	1261.9	1256.9	1245.5	1231.6	1211.7	1193.9	1176.4	1168.3	1174.6	1176.9
C1-S4	910.9	907.8	903.3	891.9	876.1	853.2	826.4	812.5	832.0	797.8
C1-S5	1331.1	1340.4	1345.8	1342.8	1331.7	1316.0	1293.4	1274.6	1246.5	1193.8
C1-S6	1201.5	1212.8	1220.3	1223.9	1220.4	1211.0	1194.3	1169.8	1136.0	1100.2
C1-S7	1266.3	1266.8	1261.2	1253.6	1236.4	1219.5	1211.6	1211.2	1226.3	1245.9
C1-S8	1162.0	1159.0	1150.0	1141.3	1128.4	1118.5	1115.0	1113.8	1122.5	1135.7
C1-S9	1047.9	1052.8	1052.7	1049.1	1040.2	1020.3	995.0	968.2	938.0	928.3
C2-S1	1023.9	1028.5	1089.2	1158.4	1198.1	1317.7	1432.7	1520.7	1642.0	1806.3
C2-S2	894.3	900.9	963.7	1039.5	1086.8	1212.7	1333.6	1415.9	1531.5	1712.6
C2-S3	893.8	895.0	892.3	882.3	863.9	840.7	810.8	811.1	856.5	861.6
C2-S4	764.2	767.4	766.8	763.4	752.6	735.7	711.8	706.2	745.9	767.9

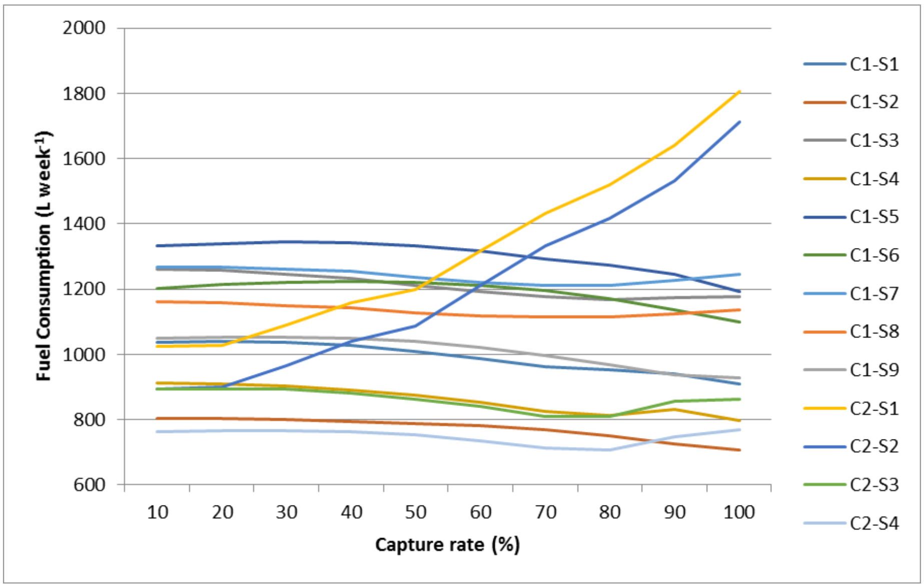


Figure 9.1 Fuel consumption in different optimal whole household waste collection systems at capture rates 10%-100%

9.3.2 Total travelling distance for household waste collection by different collection systems

The best options for total travelling distance required to collect the whole household waste stream are shown in Table 9.5 and Figure 9.2. The co-collection of whole household waste has the lowest travelling distances, ranging from 1302-2546 km week^{-1}. The travelling distances in kerbside partially-sorted and separate collection of household waste are similar, ranging from 1762-3321 km week^{-1} and 2019-3265 km week^{-1} respectively. The worst system is considered to be kerbside-sorted collection, where the total distance travelled ranges from 1762-6508 km week^{-1}.

Figure 9.2 clearly shows a rapid increase in travelling distance for kerbside-sorted collection in scenarios C2-S1 and C2-S2; a steep increase is also observed in kerbside partially-sorted collections (scenarios C2-S3 and C2-S4) at capture rates of 70% or above. The weekly kerbside-sorted collection of recyclables and food waste with weekly collection of residual waste (scenario C2-S1) has the highest travelling distance at capture rates of 50% or above, while weekly separate collection food waste, co-mingled recyclables and residual waste (scenario C1-S1) has the highest travelling distance when the capture rate is 50% or below. Comparing all scenarios, weekly food waste collection with AWC of recyclables and residual waste by two-compartment RCV (scenario S1-C9) is considered the best collection system in terms of total travelling distance.

Table 9.5 Summary of the best collection options for different collection systems with respect to total travelling distance for collection of the whole household waste stream at capture rates 10-100%

	Capture rate of food waste and recyclable (%)									
Scenario	10	20	30	40	50	60	70	80	90	100
C1-S1	2678.7	2754.7	2823.9	2889.1	2936.9	2974.8	3029.9	3094.9	3169.8	3264.7
C1-S2	2135.9	2188.6	2222.3	2243.3	2245.6	2232.9	2188.2	2138.3	2108.5	2132.6
C1-S3	2424.8	2420.5	2389.6	2352.0	2292.7	2237.8	2182.0	2160.6	2181.9	2181.6
C1-S4	2153.8	2158.9	2157.3	2131.3	2087.6	2012.1	1918.1	1868.2	1931.5	1789.8
C1-S5	2030.0	2075.1	2112.4	2142.9	2154.7	2161.9	2184.3	2214.3	2256.9	2315.4
C1-S6	1810.4	1862.6	1898.1	1919.4	1921.6	1909.5	1865.4	1816.9	1787.5	1806.0
C1-S7	2461.7	2502.3	2520.1	2531.6	2508.2	2475.7	2466.6	2460.0	2492.1	2545.5
C1-S8	2138.5	2148.7	2132.8	2109.4	2049.9	1986.1	1943.7	1900.9	1900.1	1922.8
C1-S9	1796.3	1811.3	1805.5	1788.1	1748.5	1666.1	1563.0	1451.4	1336.2	1302.0
C2-S1	1981.8	2019.0	2320.2	2689.6	2947.0	3570.3	4225.2	4748.2	5474.3	6508.3
C2-S2	1762.3	1806.5	2105.9	2466.1	2713.9	3317.9	3906.4	4350.8	5004.9	5998.9
C2-S3	1982.0	2018.2	2053.2	2083.6	2095.5	2099.7	2125.1	2323.0	2861.9	3321.1
C2-S4	1762.4	1805.7	1838.9	1860.1	1862.4	1847.3	1806.3	1925.6	2392.5	2811.7

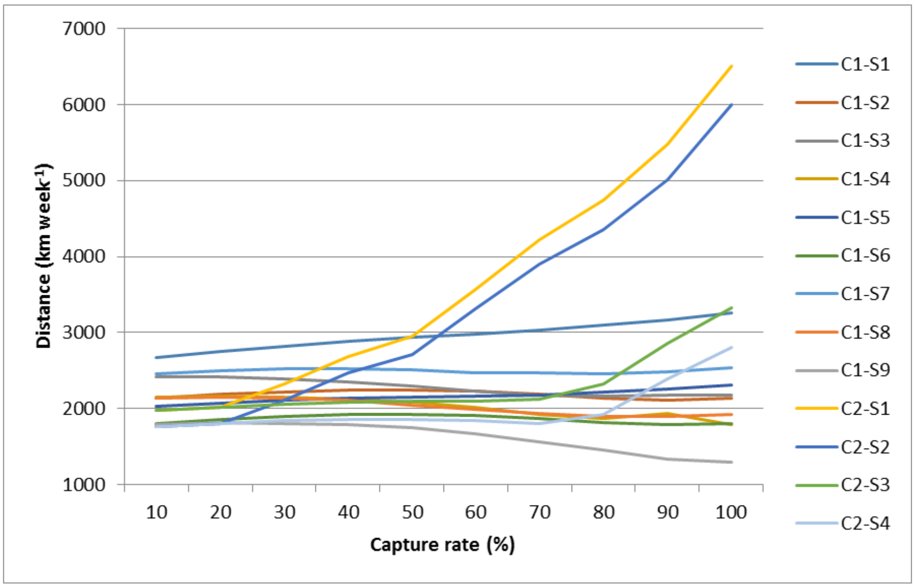


Figure 9.2 Total travelling distance for different optimal whole household waste collection systems at capture rates from 10-100%

9.3.3 Total time spent in household waste collection by different collection systems

The minimum time spent in the collection of household waste for each best collection option at each capture rate is shown in Table 9.6 and Figure 9.3. In most situations, the total time spent in household waste collection increases gradually with increasing capture rates for food waste and recyclables, but there is a dramatic increase in the total time spent for the kerbside-sorted collection system, as illustrated in Figure 9.3. This can be explained by the number of loads per day in the kerbside-sorted collection system, which increased from 1 to 2 at a capture rate of 30% and to 3 at a capture rate of 90%, whilst the average number of loads per day in other collection systems was 1 (see Appendix B). Comparing the total time spent in the four types of collection system, the co-collection of the whole household waste stream has the best performance while the worst system in most situations is separate collection. The total time spent ranges from 238-616 hours week^{-1} and 272-720 hours week^{-1}, respectively. The weekly food waste collection with AWC of recyclables and residual waste (scenario C1-S9) was considered to be the best option as it requires 242-304 hours week^{-1} for waste collection. The worst option is weekly separate collection of residual waste, recyclables and food waste (scenario C1-S1) at capture rates of 10-90%, in which the time spent ranges from 412-684 hours week^{-1} which is 1.7 to 2.4 times more than for the best collection options.

Table 9.6 Summary of the best collection options for different collection systems with respect to total time spent in collection of the whole household waste stream at capture rates from 10-100%

	Capture rate of food waste and recyclable (%)									
Scenario	10	20	30	40	50	60	70	80	90	100
C1-S1	412.1	446.9	481.1	515.1	548.6	581.2	614.9	649.1	683.7	719.6
C1-S2	272.4	295.4	316.9	338.0	358.3	377.4	395.0	411.8	429.9	451.2
C1-S3	405.9	414.8	422.3	429.4	435.1	441.1	447.2	455.0	465.6	474.2
C1-S4	275.9	285.3	294.1	301.9	308.7	313.7	317.9	324.5	337.1	338.5
C1-S5	335.5	358.1	380.1	401.8	422.6	443.2	464.6	486.4	508.8	532.1
C1-S6	238.4	261.3	283.4	304.8	325.1	344.4	362.2	379.5	397.8	418.8
C1-S7	421.0	444.4	466.7	488.6	508.7	528.0	548.5	569.7	592.7	616.4
C1-S8	378.4	389.6	399.2	408.4	415.9	422.9	430.9	439.3	449.9	461.2
C1-S9	241.5	252.3	261.9	270.9	278.8	284.5	288.8	292.5	295.7	303.7
C2-S1	330.3	351.6	388.6	427.5	462.4	517.5	572.4	622.2	684.2	762.4
C2-S2	233.1	254.9	291.9	330.6	364.9	418.8	470.1	515.3	573.2	649.2
C2-S3	330.3	351.5	372.8	394.0	414.4	434.3	455.5	488.2	537.2	580.6
C2-S4	233.1	254.8	276.2	297.0	316.9	335.5	353.2	381.3	426.3	467.4

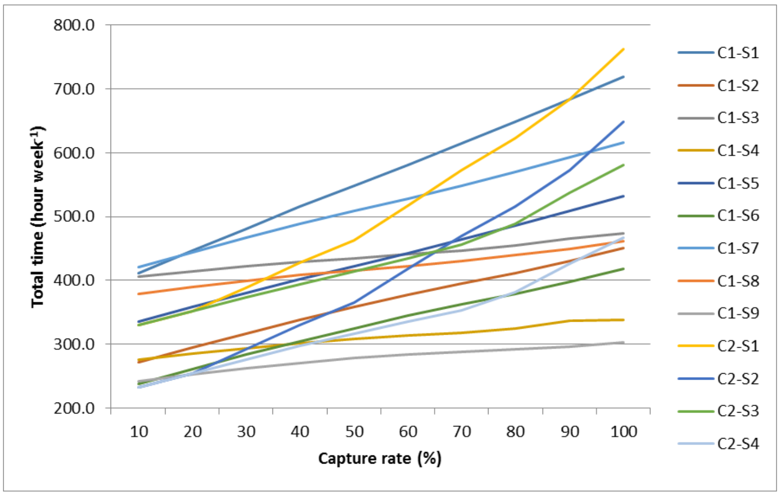


Figure 9.3 Total time spent in collection for different optimal whole household waste collection systems at capture rates from 10-100%

9.3.4 Number of vehicles required in household waste collection by different collection systems

The minimum number of vehicles required in collection of the whole household waste stream for each best collection option at each capture rate is shown in Table 9.7 and Figure 9.4. The effect of capture rates on the number of vehicles required is not straightforward in all cases, except for the kerbside-sorted and partially-sorted collection systems. The number of vehicles needed for both of these collection systems climbed sharply when the capture rates increased. Some flat sections of the graph can be seen with co-collection systems such as scenarios C1-S3 and C1-S8. These can be explained by the fact that the number of two-compartment vehicles required at higher capture rates in the given scenarios did not change at all, with 11 vehicles required at capture rates of 50% or more. At the same time, the number of single-compartment vehicles required for the rest of the collection only varies by one or two. Among the kerbside-sorted systems considered, the kerbside partially-sorted collection system requires fewest vehicles, in the range of 11 to 22, whist the kerbside-sorted collection system needs the most, ranging from 11 to 29 vehicles. Fortnightly co-collection of recyclables and residual waste by compartmentalised RCV with weekly collection using single-compartment RCV for food waste (scenario C1-S4) is the best option with respect to vehicle numbers at capture rates of 30% or above. The cost implications of vehicle requirements are considered further in Section 9.4.2.

Table 9.7 Summary of the best collection option for different collection systems based on number of collection vehicles for collection of the whole household waste stream at capture rates from 10-100%

	Capture rate of food waste and recyclable (%)									
Scenario	10	20	30	40	50	60	70	80	90	100
C1-S1	16	18	18	19	21	22	24	25	26	27
C1-S2	11	13	13	14	15	16	16	16	17	18
C1-S3	15	16	16	16	17	16	17	17	17	18
C1-S4	11	12	11	11	12	12	13	13	13	13
C1-S5	13	14	14	15	16	17	17	18	19	20
C1-S6	10	11	11	12	13	14	13	14	15	16
C1-S7	16	17	17	18	19	19	20	21	22	22
C1-S8	14	15	15	16	16	16	16	16	17	17
C1-S9	18	19	19	20	21	21	22	21	21	22
C2-S1	14	15	16	17	18	20	22	24	26	29
C2-S2	11	11	13	14	15	17	18	20	22	25
C2-S3	14	15	15	16	17	17	18	19	21	22
C2-S4	11	11	12	13	13	14	15	16	17	17

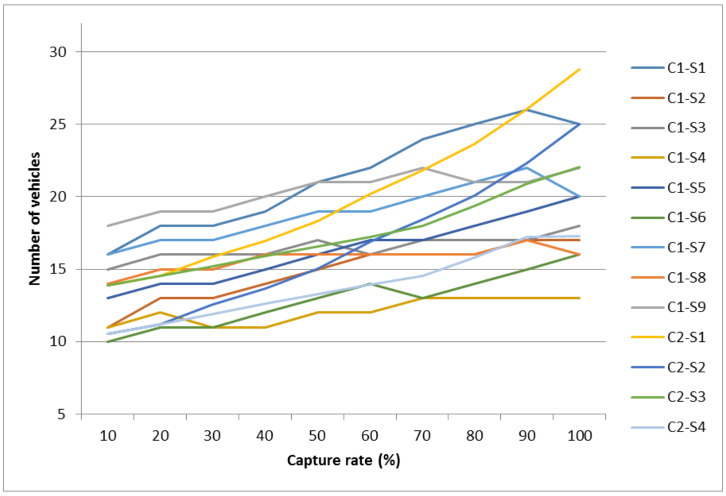


Figure 9.4 Number of vehicle required for different optimal whole household waste collection systems at capture rates from 10-100%

The best and the worst collection schemes and scenarios in fuel consumption, total travelling distance, total time spent in whole collection and the number of collection vehicle required are summarised in Table 9.8.

Table 9.8 Summary of the best and worst collection systems and scenarios for different output parameters

	Collection system		Scenario	
Parameter	The best	The worst	The best	The worst
Fuel consumption	Kerbside partially-sorted	Kerbside-sorted	C2-S4 (CR≤80%) C1-S2 (CR>80%)	C1-S5 (CR<60%) C2-S1 (CR≥60%)
Total travelling distance	Co-collection	Kerbside-sorted	C1-S9	C1-S1 (CR≤50%) C2-S1 (CR>50%)
Total time spent	Co-collection	Separate collection	C1-S9	C1-S7 (CR=10%) C1-S1 (CR=20%-90%) C2-S1 (CR≥90%)
Number of vehicle required	Co-collection	Kerbside-sorted	C1-S6 (CR≤20%) C1-S4 (CR>20%)	C1-S9 (CR≤50%) C1-S1 (CR=50-90%) C2-S1 (CR≥90%)

9.4 Discussion

9.4.1 Best collection systems for fuel consumption

The kerbside partially-sorted collection system has the lowest fuel consumption in most situations, as shown in Table 9.8. The reason for this is the vehicle type and fleet size. The constraint in these collections is always the compartment volume. The best vehicle is therefore the one with the largest total compartment size and an optimised allocation of waste types to compartments, which allows it to collect the maximum amount of waste at one time. This is represented by the stillage vehicle with a gross weight of 12 tonnes and a total compartment size of 35 m^3. On the other hand, reducing the degree of source separation of waste in partially-sorted collection system will also have an effect on fuel consumption, and to investigate this, two scenarios were considered. In scenario S2-C3 and S2-C4, it was assumed that plastics and cans were collected co-comingled while other dry recyclables such as paper, cardboard and glass were separated at the stillage vehicle. The results for these two scenarios were then compared to the kerbside-sorted collection system (scenarios C2-S1 and C2-S2). It was found that the fuel consumption was 25 and 45% lower for the partially-sorted collections (scenarios C2-S3 and C2-S4) than in the baseline scenarios C2-S1 and C2-S2. When the capture rate for food waste and recyclables increased, the difference between partially-sorted collections and kerbside-sorted collections was even higher at capture rates of 50% or above, ranging between 57 and 123%.

9.4.2 Best collection systems for number of vehicles required

It was originally assumed that co-collection of household waste would require the smallest number of collection vehicles as the optimum allocation of compartments and waste types is not as complicated as in the kerbside-sorted collection system, potentially leading to a larger round size and thus fewer vehicles.

The results of the modelling showed, however, that for the assumptions used in this study, the similar number of vehicles were required for co-collection of household waste (scenario C1-S6) and kerbside collection of food waste with partially-sorted collection of recyclables materials (scenario C2-S4) at set out rates of up to 60%. This shows that as long as the allocation of compartments and waste types approaches the optimal, the kerbside partially-sorted collection system can perform as well as co-collection in some situations. However, the co-collection of household waste remains the best in terms of the required fleet size in most cases.

As noted above in Section 9.3.4, the number of vehicles also functions as an indication of the capital cost of different scenarios. According to WRAP (2008e), stillage vehicles are less expensive than the traditional compaction collection vehicle. For collections using a combination of stillage and single-compartment vehicles (scenarios C2-S1 to C2-S4), as the capture rate for food waste and/or recyclables increases, fewer single-compartment RCVs are required. The ratio between the number of stillage vehicles and of single-compartment RCVs for residual waste collection ranges from 1.1:1 to 2.8:1 at capture rates from 10-100% (scenarios C2-S4). While the cost of RCVs varies considerably with place and time, typical or actual local values can be used in conjunction with the numbers of each type of vehicle required to provide a further metric for comparison between scenarios. As an example, the cost of a 26-tonne single-compartment RCV has been reported as around £185,000 (Transport for London, 2008, Leeds City Council, 2012) and of a stillage vehicle as around £85,000 (Gravesham Borough Council, 2013), respectively. Therefore, the capital cost of vehicles for the kerbside partially-sorted collection system in scenarios C2-S4 ranges from £1.45 million to £1.95 million. With the best scenario for co-collection of household waste (scenario C1-S4) , and assuming cost of £180,000 for a two-compartment RCV (Gravesham Borough Council, 2013), the total capital cost for vehicles ranges from £2.18 million to £2.38 million at recycling rates from 10 to 100%. Table 9.9 summaries the capital cost of the best and the worst collection systems.

Table 9.9 Cost assessment of the best and the worst in co-collection and kerbside partially-sorted collection systems

		Number of vehicles			Cost of vehicles (£ thousand)			
Scenario	Capture rate (%)	Stillage	Single-comp't	Two-comp't	Stillage	Single-comp't	Two-comp't	Total cost (£ million)
C2-S4	10	4	6	--	85	185	180	1.45
C2-S4	100	12	5	--	85	185	180	1.95
C1-S4	10	--	4	8	85	185	180	2.18
C1-S4	100	--	7	6	85	185	180	2.38

In Table 9.9 it can be seen that the kerbside partially-sorted collection system used more vehicles at high capture rate but the capital cost is lower than the co-collection system. For this reason, the kerbside partially-sorted collection system would be the preferred option. This is because such systems tend to have low contamination rates and a high quality of materials, due to the fact that the collection crew has already done the primary sorting at source (WRAP, 2008e). Thus, the need for further downstream sorting is less when compared to co-mingled collection of dry recyclables. Moreover, it may be the only practical method to use if recyclables need to be recycled but there is no MRF nearby.

9.4.3 Best collection systems for total travelling distance and time spent

As well as requiring the smallest number of vehicles, co-collection of household waste also has the best performance in total travelling distance and time spent, especially in weekly source segregated food waste collection with AWC of dry recyclables and residual waste by two-compartment vehicle (scenario S1-C9). In the second best option (scenario C1-S4), food waste is also collected every week but the recyclables and residual waste are co-collected every two weeks by two-compartment vehicle instead. Figure 9.3 shows that the time spent in scenario C1-

S4 is 1.1 times more than in scenario S1-C9 when the capture rates for food waste and recyclables increase from 10-100%.

Smyth (2010) commented that an imbalance between compartments was observed when using a split-bodied vehicle to collect food waste and another waste type because the volume of food waste collected from the setting-out households varies, meaning that one compartment reaches its capacity sooner than the other. If the residual waste and recyclable waste is co-collected by a two-compartment vehicle, however, the issue may possibly be solved due to the relatively high and stable set-out rates for recycling and residual waste bins on the collection day. Therefore, the fill-up rate for both compartments would be expected to be similar. When food waste is collected by a single-compartment RCV as an additional service (scenarios C1-S3 and C1-S4), this gives flexibility in arranging the collection rounds. In addition, this collection option also used the least diesel to complete the whole household waste collection among co-collection options by split-bodied vehicles (see Table 9.4). Due to the relatively small difference in time spent, this could be an acceptable substitute for AWC of recyclable and residual waste when the additional complexities of arrangement of waste types and compartments are taken into account.

With respect to the total travelling distance, AWC of residual waste and recyclables with weekly collection of food waste (scenario S1-C9) is definitely the best option in all situations, especially at high capture rates (see Table 9.5 and Figure 9.2). The AWC approach is currently popular, and studies have found that high recycling rates are achieved by adopting this pattern (Woodard et al., 2005, Wilson and Williams, 2007). Lyas et al. (2005) reported that using a split-bodied vehicle for AWC of household waste could also increase the recycling rate. The effect of recycling rates on the total travelling distance will be similar to that shown in Figure 9.2 because the capture rate is similar in nature to the recycling rate: more food waste and recyclables tend to be captured at high recycling rates. A further decrease in total travelling distance is observed in Figure 9.2 with increasing capture rates for food waste and recyclables.

For the best collection systems shown in Table 9.8, the modelling results suggest that kerbside partially-sorted collection is the most suitable type of collection schemes when fuel consumption is the main consideration. In reality, no information is available to show how many local authorities are currently using kerbside partially-sorted systems for their household waste collection. The data in Table 2.4 may suggest, however, that kerbside partially-sorted systems are less favoured than separate or co-collection of recyclables. The fact that kerbside partially-sorted schemes do not appear to have been widely implemented by local authorities may be due to low public acceptance (Malone, 2014) and high collection costs in term of staff time and vehicle numbers, especially in those area with high participation rates and small round sizes (WYG Lyndhurst, 2010). Other operational issues may also discourage or hinder local authorities from switching to kerbside partially-sorted collection. For example, additional space may be needed at the depot for marshalling the larger number of vehicles required, , the longer stopping times required in collection increase the potential for disturbance of other road users in narrow residential streets as well as the health and safety issues related to manual sorting. Although there are disadvantages to the system, some waste management companies and government agencies believe kerbside sorting collection is the way forward to improve recycling rate (Waste Management World, 2011, BBC, 2012).

9.4.4 Worst collection systems for fuel consumption and other parameters

In general, kerbside-sorted collection of household waste would not be considered the ideal collection system due to the dramatic change in the fuel consumption and other parameters with increasing capture rates for food waste and recyclables from 10-100%. The significant change in fuel and resources used and in particular in the number of vehicles required may make it difficult for local authorities to purchase the optimum vehicle fleet, as well as incurring extra expenditure on fuel and staffing. The higher inputs required for this system, especially at higher capture rates, can potentially be offset against the possibility of eliminating the need for a MRF, with its associated capital and operating costs. The change in vehicle requirements as capture rates increase is still an issue, however, and it may be necessary to address this in the planning stage, for example by loaning some of the vehicles rather than purchasing the vehicle when the new waste collection service is launched.

When looking in detail at the collection options, weekly co-collection of recyclables and food waste by compartmentalised vehicle (scenario C1-S5), AWC of recyclable and residual waste with food waste collection (scenario C1-S9) or weekly separate collection of household waste (scenario C1-S1) have the worst performances in fuel consumption, number of vehicles required and total travelling distance and time spent at low capture rates (see Table 9.8). At high capture rates (usually 60% or above), kerbside-sorted collection (scenarios C2-S1 and C2-S2) has the worst performance in fuel consumption, total time spent and number of vehicles required. The focus of this discussion is mainly on kerbside-sorted household waste collection, because high capture rates for recyclables are expected in practice. In reality, the capture rate for recyclables usually ranges from 60-80% (Personal communication, A. Bond, 4R Environmental Ltd, 2012) and 30%-60% for food waste , apart from in the earliest stages of introduction of a new scheme. Although equal capture rates for food waste and dry recyclables were assumed in this part of the study, meaning that a high capture rate for recyclable is accompanied by collection of a high proportion of food waste, the results from modelling showed that the compartment to collect food waste does not always fill up first (see data in section 8.3.4). This implies that the amount of food waste collected would not greatly affect the fuel and resources used, even if dissimilar recycling rates were applied for food waste and recyclables. The results for the current scenarios allow the user to look at kerbside-sorted collection of food waste and dry recyclables, but in order to consider real situations, it is also necessary to consider different capture rates for food waste and recyclables. Although this has not been addressed in this current study, the model that has been developed here makes it easy to run the scenarios with different capture rates for the material collected.

The fuel consumption of stillage vehicles is reported as low in comparison with that of other RCVs due to their relatively low gross weight. The total fuel consumption and resources required for kerbside-sorted collection are high, however, because the numbers of loads per day and of RCVs required are more than for other collection systems. For example, the best kerbside-sorted collection option requires 25 RCVs, while the best kerbside partially-sorted collection option needs only 17 RCVs to complete the collection, a reduction of 32%. Comparing the number of loads per day using the optimal option, on average the kerbside partially-sorted collection requires up to 1.2 loads per day while the kerbside-sorted collection system requires 3 loads per day. As this involves more frequent travel between the collection area and unloading sites, it also has the longest travelling distance and total time spent.

In practice, selection of the most appropriate waste collection scheme is not only based on fuel and resources use, but will also take into account other factors. Kerbside sorting of recyclables brings occupational safety and health issues (WRAP, 2008e). For separate collection and co-collection of household waste, wheeled bins are usually used to collect recyclables or residual waste. For the collection of kerbside source segregated food waste, the collector usually empties the food waste into a wheeled bin, also known as a ‘slave bin’, and these bins are then taken to the collection vehicle and loaded by a bin lifter. The collection of dry recyclables by the kerbside-sorted system involves frequent carrying of kerbside collection boxes, especially in those areas that have a high participation rate, and sorting and lifting of the boxes into the stillage vehicle. Although loading food waste into a slave bin may also cause injury to the collector, the risk is relatively small compared to that of loading sorted dry recyclables into a compartment as this always involves lifting above shoulder height. The Health & Safety Laboratory (2006) conducted a series of studies on risks for the kerbside-sorted collection system, and found that the collector may suffer from low back injury as the weight of the recycling box approaches the maximum compression force that the discs in the lower part of the spine can withstand. In addition, continuous exposure to a high level of noise from kerbside glass recycling in the stillage vehicle is also a potential risk for the collectors (Health & Safety Laboratory, 2008). When considering fuel consumption, total travelling distance, time spent, number of vehicles and occupational safety and health, the kerbside-sorted collection is definitely not the ideal collection system especially when large quantities of recyclable materials are captured from each household.

9.5 Conclusions from the comparative work

In this part of the study, the best collection options for each scenario considered in Chapters 7 and 8 were selected as the basis for a comparative study on fuel consumption, total travelling distance, total time spent and number of collection vehicles required for the collection of the whole household waste stream. The results showed that, under the assumptions and the range of conditions considered:

- Weekly food waste collection with partially-sorted collection of dry recyclables consumed the least fuel when the capture rate is 80% or below, while separate collection of food waste, recyclables and residual waste by single-compartment vehicle is the best when most of the food waste and recyclables are diverted from the residual waste bin (capture rate >80%).
- The co-collection system (Scenario C1-S4) required fewest vehicles for collection of the whole household waste stream at capture rates of 20% or above. In particular, weekly food waste collection with AWC of residual waste and recyclables by split-bodied vehicle has the best performance in total travelling distance and total time spent in collection and transportation.
- At the capture rates for recyclables and food waste typically found in practice, the kerbside-sorted collection system could be considered the worst system in term of fuel consumption, total travelling distance and number of vehicles required. These factors may however be outweighed by elimination of the need for further downstream sorting in a MRF due to the higher quality of materials captured; and if no downstream sorting facility is available, this may represent the best or only option for recovery of high-grade materials.
- Full consideration of costs and benefits is beyond the scope of the current study, but it has been shown that the model output provides the necessary data on resource inputs for the different types of collection to allow comparisons of this type to be conducted.

Chapter 10: CONCLUSIONS

10.1 Introduction

Food waste has a high energy content, making it an attractive resource for the production of renewable energy though anaerobic digestion. It is also a major component in the household waste stream, so providing separate collection systems in order to divert it from landfill could help to reduce environmental impacts and further improve recycling rates. In the context of the current research, this means the ideal collection systems will be those that require the minimum energy and resource inputs in order to maximise the net energy output. In future the focus of food waste collection may switch from biogas production through AD to production of higher value products in waste-based biorefinery systems (Lin et al., 2013, Pfaltzgraff et al., 2013). Minimising the energy used in collection will still be an important aspect of the efficiency and sustainability of these systems, however, and thus the output of this research will remain relevant.

The research has involved the development and testing of a model capable of estimating the energy used in source segregated collections, as a tool to analyse different kerbside household waste collection systems. Other parameters such as total distance travelled, total time spent, and the number and type of vehicles required were also considered, as these all have resource implications and can provide a basis for comparative costing and economic assessment of different options: in addition, the degree of utilisation of vehicle capacity (load and compartments) could provide a further indication of the effectiveness of resource use versus the flexibility in dealing with day-to-day variations in waste quantities. In practice, some of these parameters may be more influential than energy use in the selection of kerbside waste collection systems, and taken collectively they can provide a basis for a simple decision support system.

The modelling tool developed was validated using data gathered from field work at six UK sites. It was shown that the model could accurately predict the limiting factor for the collection round, the number of vehicles required, and the number of loads per day, and could provide reasonably good estimates of fuel usage for most types of collection system. The model was then applied to a number of scenarios, chosen to represent some of the most common options for kerbside waste collection systems in the UK, in order to identify key parameters and optimal solutions. The value of this research is not only in the results for these specific scenarios, however, but in the creation of a simple tool that can be used for scoping new schemes and benchmarking existing ones, as well as for research purposes.

10.2 Specific contributions

The specific contributions of this work can be divided into two main areas: model development and validation, and the results of scenario studies.

10.2.1 Model development and validation

- The waste collection model developed in this research removed the limitations in Sonesson's (2000) and Di Maria and Micales' (2013) models by taking into account all of the possible constraints on collection by RCVs (time, volume and weight capacity).
- Fuel consumptions of collection vehicles reported in the literature usually reflect a specific situation and conditions. Taking these fuel consumption values for use in assessment of alternative waste collection options can introduce errors. The model uses a more systematic approach to estimate fuel consumption for different collection vehicles in different situations by using modified fuel consumption equations based on the EMEP Emission Inventory Guidebook (2010).
- This research provides a new set of correction factors for the extra fuel consumption of RCVs in the collection phase, with values ranging from 1.06 to 3.50 depending on the size and operating mode of the vehicle and on the driving pattern. Although these values are still preliminary, and need to be supported by further data collection and analysis, they represent a useful addition to current knowledge on fuel usage in waste collection processes.
- This research provides new set of values for bin pick-up times that can be used for a range of purposes, including as secondary data for research into estimation of routing times or for route optimisation on a time basis in waste management operations.

10.2.2 Scenario studies

The scenario modelling undertaken was based on a hypothetical set of 25,000 households, chosen as being typical of a medium-sized town, with conditions and operating parameters selected to reflect those commonly encountered in practice in the UK. While the conclusions below are valid only for the scenarios tested, it is believed that they represent outcomes and trends that are representative and realistic for many real situations; while the model itself can be applied to test a wide range of alternative conditions and assumptions as required by other users.

Single additional collection of food waste

- The modelling results showed that that fuel use of the best collection vehicle (7.5-tonne RCV) ranges from 3.5 to 26.3 L $tonne^{-1}$ for weekly and 2.2 to 16.3 L $tonne^{-1}$ for fortnightly collection at set-out rates from 10-100%. This represents 6.0-70.1% of the raw energy theoretically available through methane production from the collected food waste.

- With respect to fuel use, fortnightly collection of food waste by 7.5-tonne single-compartment RCV is always the best option. When other parameters such as total distance travelled, time spent and number of vehicles required is under consideration, fortnightly collection of food waste by 26-tonne single-compartment RCV would be the ideal option. The volume utilisation is low, however, with the compartment only half-full at most: a finding that provides useful evidence in support of the advantages of two-compartment vehicles.
- A small vehicle is not always best for separate food waste collection: the modelling output showed that it is likely to use more fuel than a middle-size vehicle, especially at high set-out rates. This result contradicts the views put forward by Wilson (2007) and Holiwast (2006).
- The distance between properties is the most influential factor with respect to fuel consumption, total time spent and total distance travelled. The correction factor for extra fuel consumption in collection, and the speed in collection and transportation have comparatively smaller effects on these outputs.

Co-collection of kerbside household waste

- Weekly food waste collection with fortnightly separate collection of recyclables and residual waste has the best performance with respect to fuel consumption at all capture rates compared to any option for co-collection of household waste.
- In most cases, the co-collection of household waste will consume more fuel than separate collection, by up to 37% for weekly co-collection and 32% for fortnightly co-collection.
- Of the range of co-collection scenarios considered, fortnightly co-collection of recyclables and residual waste by twin-compartment RCV with weekly collection of food waste by a single-compartment RCV is the best option in energy terms, with a modelled fuel consumption of 2.62 to 2.85 L tonne^{-1} at capture rates from 10-100% for food waste and recyclables.
- Weekly food waste collection with AWC of residual waste and recyclables by twin-compartment vehicles gave the best performance in terms of total distance travelled and total time spent, with reductions of 33-39% in total distance travelled and up to 34% in total time spent.
- RCVs with equal-volume compartments are not always the best in terms of fuel consumption. Based on the current research, the split ratio of 30:70 is better than 50:50 but bigger compartment volumes could improve collection efficiency.
- The study found that placing the waste in the optimum compartment can reduce travelling distance by 15% and total time by 58%.

- For the range of values tested, uncertainty in the density of residual waste, correction factor on extra fuel consumption and the distance between properties have the biggest effect on fuel consumption, time spent on collection and total travelling distance.

Kerbside-sorted and partially-sorted collection of household waste

- In the range of scenarios considered, kerbside-sorted collection of household waste consumes 1.47 to 3.25 times more diesel and needs 1.5 times more stillage vehicles than the kerbside partially-sorted collection system. The total travelling distance is 1.14 to 3.33 times greater and the number of hours required to complete the collection is 1.8 times higher for kerbside sorted collection than for kerbside partially-sorted collection systems.
- In kerbside-sorted and partially-sorted collection systems, stillage vehicles with pairs of equal-volume compartments usually have the worst performance in fuel consumption for the optimal cases considered.
- Non-optimal allocation of compartments and waste types could increase fuel consumption by up to 1.1 times in co-collection, 2.27 times in kerbside-sorted collection and 3.08 times in kerbside partially-sorted collection.
- For kerbside-sorted and partially-sorted collections, accurate information on the volumes of individual materials collected is important to support better optimisation of the allocation of waste and compartments in stillage vehicles. The same is also true in co-collection.
- The correction factor for extra fuel consumption in collection has the greatest effect on total fuel consumption, while and speeds in transportation and collection are the main parameters influencing total distance travelled and total time spent in collection.

General conclusions

- Comparing the performance of the three main options for kerbside collection, kerbside partially-sorted collection has the best performance in fuel use, while the co-collection of household waste is almost always the best system in total travelling distance, time spent and number of vehicles required. The differences found between the least and most effective systems could be as much as 156% for fuel use, 131% for distance travelled, 63% for time spent and 141% for RCV required: since most if not all of these scenarios are in actual use, this indicates the potential for optimisation of waste collection systems and the need for simple robust decision support tools that are not excessively data-hungry.
- The results demonstrated that collection is not always constrained by the vehicle payload. For example, use of a 7.5-tonne RCV for the collection of food waste is limited by compartment volume rather than by weight. This confirms the necessity of including all

parameters (time, load and volume constraints) in collections modelling and illustrates the superiority of the approach used over previous models.

10.3 Limitations of the research and recommendations for further work

- During the field work it was only possible to obtain data for the total fuel consumption over certain periods: this is not ideal as a basis for calculation of fuel use in the collection and transportation phases or for estimation of accurate correction factors for the extra fuel consumption during the collection phase. Further work is therefore needed on measurement of the instantaneous fuel usage of different types and sizes of RCVs in the collection and transportation phases, so that robust experimental values can be obtained based on the exact amount of fuel used. These values will expand current knowledge on fuel use in RCVs; and could also be linked to a range of parameters for vehicle type and driving pattern as a basis for deriving predictive equations for the correction factor for extra fuel consumption during the collection phase.
- The current version of the model is designed to assess the fuel consumption and resource use for kerbside collection rounds, with pick-up from individual households or from centralised collection points. In reality, collection crews may also collect waste from houses, flats and even from schools and markets in the same round. In addition, weekly and fortnightly collection of household waste is typical in the UK and northern Europe, but not in southern Europe or many other countries. It is suggested that the model should be modified to allow a broader range of collection frequencies and of options for the type of pick-up point, making it more flexible and able to cope with an even wider range of scenarios.
- Many complex factors can influence the performance of household collection schemes waste. To reduce the complexity, the current work used a single set of collection area characteristics typical of those for a medium-sized town, and equal capture rates were assumed for recyclables and food waste. Further studies should be carried out to look at the same scenarios with different set-out and capture rates for different recyclable materials, and to investigate the effect of factors such as population density and number of users per pick-up point on the optimal collection systems.
- The model could be extended to allow assessment of the cost of different collection options, and to include sensitivity analysis as an in-built option.

Appendices

Appendix A Inputs and outputs of model validation

Table 1. Input values for the model validation in all Type I study site

	Flintshire	Broadland	Lambeth					
			Day 1	Day 2	Day 3	Day 4	Day 5	Overall
Round type	House	House	House	House	House	House	House	House
Number of household	24148	10276	1557	1631	2777	2882	1365	10152
Frequency of collection	Weekly	Weekly	Weekly	Weekly	Weekly	Weekly	Weekly	Weekly
General set out rate	55	69	45	45	45	45	45	45
Set out rate of food waste	--	--	45	45	45	45	45	45
Set out rate of dry recyclable	--	--	--	--	--	--	--	--
Time spent in collection (hr):	3.26	4.5	2.32	2.07	3.62	4.03	1.62	2.73
Number of concurrent collection	1	1	1	1	1	1	1	1
Number of collectors	1.8	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Time to pick up bin	16.1	13.88	22.1	16.4	15.94	17.2	10.4	16.4
Time per household	8.98	15.76	5.36	4.55	4.69	5.13	4.25	4.79
Amount of food waste per set out bin (kg HH^{-1} day^{-1})	0.41	0.25	0.12	0.25	0.12	0.11	0.13	0.15
Density of food waste	473	473	470	470	470	470	470	470
Gross weight of vehicle	7.5	9.5	26	26	26	26	26	26
Number of compartment	1	1	1	1	1	1	1	1
Volume capacity of compartment	5.5	5	17	17	17	17	17	17
Payload of vehicle	3.5	4	10.7	11.7	12.7	13.7	14.7	15.7
Speed (km hr^{-1}):								
- In collection	9.62	14.7	9.38	8.67	9.21	8.61	8.92	8.96
- In transportation	39.53	48.8	21.46	16.42	19.06	17.44	19.94	18.65
Average distance (km):								
From depot to collection area	8.64	8.72	3.44	4.91	4.05	4.87	1.01	4.57
Between dwelling (m)	24.36	29.45	3.6	3.85	4.65	4.76	5.88	4.57
Intermediate trip to transfer station	--	--	--	--	--	--	--	--
Intermediate trip from transfer station	--	--	--	--	--	--	--	--
Collection area to transfer station (next to depot)	--	--	--	--	--	--	--	--
Collection area to transfer station	10.66	25.82	10.1	9.57	5.47	8.77	15.88	9.89
Transfer station to depot	3.2	24.9	13.66	12.63	11.62	11.65	19.28	13.77

Table 2. Output values of the model in all Type I study site

	Flintshire	Broadland	Lambeth					
			Day 1	Day 2	Day 3	Day 4	Day 5	Overall
Time per household	8.98	15.76	1557	1631	2777	2822	1365	10152
Limiting factor	Time	Time	Time	Time	Time	Time	Time	Time
Max household per day	1307	1028	1558	1634	2777	2829	1370	2052
Number of route	19	10	1	1	1	1	1	5
Number of collection day	5	5	1	1	1	1	1	5
Number of vehicles required	4	2	1	1	1	1	1	1
Average round size per day	1208	1208	1557	1631	2777	2822	1365	2031
Laden percentage in weight	54.01	31.39	5.51	11.78	9.72	9.25	5.33	8.71
Total distance travelled per route	--	--	32.8	33.39	35.98	40.31	44.2	--
Total distance travelled per week	1038.25	897.03	--	--	--	--	--	186.95
Total distance travelled per month	4069.92	--	--	--	--	--	--	--
The outputs when factor = 1.35								
Fuel consumption per route	--	--	13.98	16.45	18.87	21.87	19.79	--
Fuel consumption per week	206.64	198.83	--	--	--	--	--	91.23
Fuel consumption per month	810.04	--	--	--	--	--	--	--
Fuel per tonne collected	5.47	15.84	23.64	13.06	18.14	22.09	34.72	19.58
km per litre diesel	5.02	4.51	2.35	2.03	1.91	1.84	2.23	2.05
The outputs after the factor is calibrated								
Factor after calibration	3.04	1.51	3.25	2.56	2.1	2.64	2.67	2.64
Fuel consumption per route	--	--	20	20.99	24.46	32.49	26	--
Fuel consumption per week	404.1	211.93	--	--	--	--	--	126.28
Fuel consumption per month	1584.06	--	--	--	--	--	--	--
Fuel per tonne collected	10.69	16.88	33.9	16.66	23.52	32.82	45.61	27.1
km per litre diesel	2.57	4.23	1.64	1.59	1.47	1.24	1.7	1.48

Table 3. Input values for the model validation in all Type II and III study site

	Bromley		Kingston			
			Day1	Day2	Day3	Overall
Round type	House	Flat	House	House	House	House
Number of household	116247	752	601	609	523	1733
Frequency of collection	Weekly	Weekly	Weekly	Weekly	Weekly	Weekly
General set out rate	84	100	87	90	91	91
Set out rate of food waste	79	100	--	--	--	--
Set out rate of dry recyclable	84	100	--	--	--	--
Time spent in collection (hr):	3.71	2.97	5.65	5.4	4.73	5.26
Number of concurrent collection	2	2	4	4	4	4
Number of collectors	2.3	2.5	2.3	2.3	2.3	2.3
Time to pick up bin	8.46	45.3	24.1	21.11	27.5	24.24
Time per household	8.08	59.7	33.79	31.9	32.5	33.11
Amount of food waste per set out bin (kg HH^{-1} day^{-1})	0.3	2.24	--	--	--	--
Density of food waste	600	600	--	--	--	--
Amount of paper and cardboard per set out bin (kg HH^{-1} day^{-1})	0.4	3.23	--	--	--	--
Density of paper and cardboard	375	375	--	--	--	--
Gross weight of vehicle	26	26	15	15	15	15
Number of compartment	2	2	9	9	9	9
Volume capacity of compartment A	5.9	5.9	1.99	1.99	1.99	1.99
Volume capacity of compartment B	11.7	11.7	1.54	1.54	1.54	1.54
Volume capacity of compartment C	--	--	1.54	1.54	1.54	1.54
Volume capacity of compartment D	--	--	1.54	1.54	1.54	1.54
Volume capacity of compartment E	--	--	5.74	5.74	5.74	5.74
Volume capacity of compartment F	--	--	5.74	5.74	5.74	5.74
Payload of vehicle	10	10	7.76	7.76	7.76	7.76
Speed (km hr^{-1}):						
- In collection	8.77	7.95	7.54	6.58	4.67	6.26
- In transportation	24.17	21.55	18.17	29.67	15.8	21.21
Average distance (km):						
From depot to collection area	6	2.77	3.07	8.58	1.9	4.52
Between dwelling (m)	10.35	75.25	8.98	12.81	7.16	9.65
Intermediate trip to transfer station	--	--	2.93	9.92	2.04	4.96
Intermediate trip from transfer station	--	--	2.6	8.1	1.69	4.13
Collection area to transfer station (next to depot)	6	6.19	2.5	8.14	1.24	3.96

Table 4. Output values of the model in all Type II and III study site

	Bromley		Kingston				
	House	Flat	Day1	Day2	Day3	Overall	Overall improved
Time per household	8.08	59.7	33.79	31.9	32.5	33.11	33.11
Limiting factor	Time	Time	Vol - plastic	Vol - plastic	Vol - plastic	Vol - plastic	Vol - plastic
Max household per day	1454	179	601	609	523	572	572
Number of route	80	5	1	1	1	6	6
Number of collection day	5	5	1	1	1	3	3
Number of vehicles required	16	1	1	1	1	2	2
Average round size per day	1454	179	601	609	523	572	572
Laden percentage in weight	57.91	57.87	26.15	20.09	18.93	10.87	21.75
Total distance travelled per route	--	--	16.5	42.53	10.61	--	--
Total distance travelled per week	2163.16	101.39	--	--	--	105.42	69.63
The outputs when factor = 1.35							
Fuel consumption per route	--	--	8.01	15.13	6.22	--	--
Fuel consumption per week	1266.14	67.7	--	--	--	30.73	30.73
Fuel per tonne collected	2.71	2.34	1.97	4.85	2.12	3.04	3.04
km per litre diesel	1.71	1.5	2.06	2.81	1.71	3.43	2.27
The outputs after the factor is calibrated							
Gross weight of vehicle	26	26	15	15	15	15	15
Factor after calibration	3.5	3.5	2.52	1.06	2.37	1.98	1.69
Fuel consumption per route			11.7	13.72	9.01	53.14	34.42
Fuel consumption per week	2725.36	146.68	--	--	--	--	--
Fuel per tonne collected	5.88	5.07	2.88	4.4	3.07	5.25	3.4
km per litre diesel	0.79	0.69	1.41	3.1	1.18	1.98	2.02

Table 5. Output values of the model in all Type IV study site

	Hackney					
	Day1	**Day2**	**Day3**	**Day4**	**Day5**	**Overall**
Round type	Flat	Flat	Flat	Flat	Flat	Flat
Number of household	122	68	104	95	83	472
Frequency of collection	Weekly	Weekly	Weekly	Weekly	Weekly	Weekly
General set out rate	100	100	100	100	100	100
Set out rate of food waste	100	100	100	100	100	100
Time spent in collection (hr):	5.76	5.3	5	4.17	5.15	5.08
Number of concurrent collection	1	1	1	1	1	1
Number of collectors	1.04	1.2	1.1	1.2	1.1	1.23
Time to pick up bin	1.82	2.64	1.62	1.48	2.05	1.92
Time per household	168.42	297.85	172.39	153.37	217.48	192.18
Amount of food waste per set out bin (kg bin^{-1} day^{-1})	18.03	28.82	17.31	13.68	28.92	21.35
Density of food waste	470	470	470	470	470	470
Gross weight of vehicle	12	12	12	12	12	12
Number of compartment	1	1	1	1	1	1
Volume capacity of compartment A	7.39	7.39	7.39	7.39	7.39	7.39
Payload of vehicle	4	4	4	4	4	4
Speed (km hr^{-1}):						
- In collection	12.22	15.62	13.11	10.42	15.69	13.41
- In transportation	27.93	18.92	22.4	30.6	24.64	24.9
Average distance (km):						
From depot to collection area	2.57	1.95	0.77	4.68	1.83	2.63
Between dwelling (m)	213.52	597.50	303.07	322.11	460.51	379.35
Collection area to transfer station	11.06	11.83	12.68	20.38	20.61	15.31
Transfer station to depot	11.81	11.9	11.74	11.83	11.83	11.82

Table 6. Output values of the model in all Type IV study site

	Hackney					
	Day 1	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Overall**
Time per household	168.42	297.85	172.39	153.37	217.48	192.18
Limiting factor	Time	Time	Time	Time	Time	Time
Max household per day	123	69	104	97	85	95
Number of route	1	1	1	1	1	5
Number of collection day	1	1	1	1	1	5
Number of vehicles required	1	1	1	1	1	2
Average round size per day	122	68	104	95	83	95
Laden percentage in weight	31.43	28	25.72	18.57	34.29	28.98
Total distance travelled per route	51.49	66.31	56.68	58.72	72.49	--
Total distance travelled per week	--	--	--	--	--	305.7
The outputs when factor = 1.35						
Fuel consumption per route	15.32	20.29	17.54	16.08	20.52	--
Fuel consumption per week	--	--	--	--	--	90.33
Fuel per tonne collected	9.14	10.35	9.74	12.27	8.44	8.91
km per litre diesel	2.56	3.27	3.23	3.65	3.53	3.38
The outputs after the factor is calibrated						
Gross weight of vehicle	12	12	12	12	12	12
Factor after calibration	2.21	1.6	2.75	2.05	1.9	2.05
Fuel consumption per route	22.03	22.93	30.19	21.02	26.01	--
Fuel consumption per week	--	--	--	--	--	124.03
Fuel per tonne collected	10.01	11.7	16.77	16.05	10.7	12.23
km per litre diesel	2.34	2.89	1.88	2.79	2.79	2.46

Appendix B Raw data from scenarios in Chapter 7-8

All the model outputs of different scenarios can be found on the CD; this appendix simply lists the number of loads per day for scenarios C1-S1 to C1-S9 and combinations KSP1-12 and P1-9.

Table 1. Number of loads per day for separate collection of household waste (scenarios C1-S1 and C1-S2)

		Capture rate (%)									
Scenario	RCV	10	20	30	40	50	60	70	80	90	100
C1-S1a	3.5-tonne	1.0	1.0	1.1	1.5	1.9	2.1	2.2	2.5	2.7	2.8
	7.5-tonne	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.2	1.4	1.5
	12-tonne	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1
	15-tonne	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	18-tonne	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	26-tonne	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
C1-S1b	3.5-tonne	4.1	4.0	4.0	4.0	3.8	3.7	3.4	3.1	2.7	2.0
	7.5-tonne	3.3	3.2	3.2	3.1	2.9	2.8	2.5	2.3	2.0	1.3
	12-tonne	2.3	2.3	2.3	2.2	2.1	2.0	1.8	1.5	1.2	1.0
	15-tonne	2.1	2.0	2.0	1.9	1.8	1.7	1.5	1.3	1.1	1.0
	18-tonne	1.9	1.9	1.8	1.7	1.7	1.5	1.3	1.2	1.1	1.0
	26-tonne	1.3	1.3	1.3	1.2	1.2	1.1	1.1	1.0	1.0	1.0
C1-S1c	3.5-tonne	1.0	1.0	1.1	1.3	1.6	1.9	2.1	2.3	2.5	2.7
	7.5-tonne	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.1	1.2	1.4
	12-tonne	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1
	15-tonne	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	18-tonne	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	26-tonne	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
C1-S2a	3.5-tonne	1.0	1.2	1.8	2.2	2.6	2.9	3.2	3.4	3.6	3.8
	7.5-tonne	1.0	1.0	1.0	1.1	1.3	1.6	1.8	2.0	2.1	2.3
	12-tonne	1.0	1.0	1.0	1.0	1.0	1.1	1.3	1.4	1.6	1.8
	15-tonne	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.2	1.3
	18-tonne	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.1
	26-tonne	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
C1-S2b	3.5-tonne	5.0	5.0	4.9	4.9	4.8	4.5	4.3	4.1	3.6	2.8
	7.5-tonne	4.2	4.1	4.1	4.0	3.9	3.7	3.5	3.2	2.7	2.1
	12-tonne	3.2	3.2	3.2	3.1	3.0	2.8	2.5	2.3	2.0	1.3
	15-tonne	2.9	2.8	2.8	2.7	2.6	2.4	2.2	2.0	1.7	1.1
	18-tonne	2.7	2.6	2.6	2.5	2.4	2.3	2.1	1.9	1.5	1.1
	26-tonne	2.1	2.1	2.1	2.0	1.9	1.8	1.5	1.3	1.1	1.0

Table 2. Number of loads per day for co-collection of household waste (scenarios C1-S3 and C1-S9)

		Capture rate (%)									
Scenario	RCV	10	20	30	40	50	60	70	80	90	100
C1-S3	Duo 1	1.7	1.6	1.6	1.5	1.4	1.3	1.2	1.2	1.3	1.5
	Duo 2	1.7	1.7	1.6	1.5	1.4	1.3	1.2	1.1	1.1	1.2
	Duo 3	1.5	1.4	1.4	1.3	1.3	1.2	1.1	1.1	1.1	1.2
	Twin1	2.1	2.1	2.0	1.9	1.8	1.7	1.5	1.3	1.1	1.0
	Twin2	2.1	2.1	2.0	2.0	1.8	1.7	1.5	1.3	1.4	1.6
	Twin3	1.7	1.6	1.6	1.5	1.4	1.3	1.2	1.1	1.2	1.3
C1-S4	Duo 1	2.4	2.4	2.3	2.3	2.2	2.1	2.0	1.9	2.1	2.3
	Duo 2	2.4	2.4	2.3	2.3	2.2	2.1	1.9	1.8	1.8	2.0
	Duo 3	2.3	2.2	2.2	2.1	2.0	1.9	1.7	1.6	1.7	2.0
	Twin1	2.9	2.8	2.7	2.7	2.5	2.4	2.3	2.1	1.7	1.6
	Twin2	2.9	2.8	2.7	2.7	2.5	2.4	2.3	2.1	2.1	2.3
	Twin3	2.4	2.4	2.3	2.3	2.2	2.1	1.9	1.8	1.9	2.1
C1-S5/S6	Duo 1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Duo 2	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Duo 3	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Twin1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Twin2	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Twin3	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
C1-S7/S8	Duo 1	1.7	1.6	1.6	1.5	1.4	1.3	1.2	1.1	1.0	1.0
	Duo 2	1.7	1.7	1.6	1.5	1.4	1.3	1.2	1.1	1.0	1.0
	Duo 3	1.5	1.4	1.4	1.4	1.3	1.2	1.1	1.0	1.0	1.0
	Twin1	2.1	2.1	2.0	1.9	1.8	1.7	1.5	1.3	1.1	1.0
	Twin2	2.1	2.0	2.0	1.9	1.8	1.7	1.5	1.2	1.1	1.0
	Twin3	1.7	1.6	1.6	1.5	1.4	1.3	1.2	1.1	1.0	1.0
C1-S9a	Duo 1	2.4	2.4	2.3	2.3	2.2	2.1	1.9	1.7	1.3	1.0
	Duo 2	2.4	2.4	2.4	2.3	2.2	2.1	1.9	1.7	1.3	1.0
	Duo 3	2.3	2.2	2.2	2.1	2.1	1.9	1.7	1.5	1.2	1.0
	Twin1	2.9	2.8	2.8	2.7	2.6	2.4	2.3	2.0	1.6	1.1
	Twin2	2.9	2.8	2.8	2.7	2.5	2.4	2.2	2.1	1.6	1.1
	Twin3	2.4	2.4	2.3	2.3	2.2	2.1	1.9	1.6	1.3	1.0
C1-S9b	Duo 1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.2
	Duo 2	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.2
	Duo 3	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1
	Twin1	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.2	1.4	1.5
	Twin2	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.2	1.4	1.5
	Twin3	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.2

Table 3. Number of loads per day for kerbside-sorted collection of recyclables and food waste (Combination KSP1-KSP12)

		Capture rate (%)									
Combination	RCV	10	20	30	40	50	60	70	80	90	100
KSP1	KS2	1.0	1.1	2.0	2.0	2.4	3.0	3.0	3.0	3.0	3.0
	MKS4	1.0	1.3	2.0	2.1	2.7	3.0	3.0	3.0	3.1	3.3
KSP2	KS2	1.0	2.0	2.8	3.0	3.1	3.6	3.9	4.0	4.0	4.0
	MKS4	1.0	1.3	2.0	2.1	2.7	3.0	3.0	3.0	3.1	3.3
KSP3	KS2	1.0	2.0	2.8	3.0	3.1	3.6	3.9	4.0	4.0	4.0
	MKS4	1.0	1.9	2.1	2.9	3.0	3.0	3.2	3.6	3.9	4.0
KSP4	KS2	1.0	2.0	2.8	3.0	3.1	3.6	3.9	4.0	4.0	4.0
	MKS4	1.0	1.9	2.1	2.9	3.0	3.0	3.2	3.6	3.9	4.0
KSP5	KS2	2.2	3.2	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.2
	MKS4	1.0	1.9	2.1	2.9	3.0	3.0	3.2	3.6	3.9	4.0
KSP6	KS2	1.0	1.0	1.2	2.0	2.0	2.0	2.2	2.7	3.0	3.0
	MKS4	1.0	1.3	2.0	2.1	2.7	3.0	3.0	3.0	3.1	3.3
KSP7	KS2	1.0	1.0	1.2	1.9	2.0	2.0	2.2	2.5	2.8	3.0
	MKS4	1.0	1.3	2.0	2.1	2.7	3.0	3.0	3.0	3.1	3.3
KSP8	KS2	1.0	2.0	2.8	3.0	3.1	3.6	3.9	4.0	4.0	4.0
	MKS4	1.0	1.3	2.0	2.1	2.6	3.0	3.0	3.0	3.1	3.3
KSP9	KS2	2.2	3.2	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.2
	MKS4	1.0	1.9	2.1	2.9	3.0	3.0	3.2	3.6	3.9	4.0
KSP10	KS2	1.0	1.0	1.2	2.0	2.0	2.0	2.2	2.7	3.0	3.0
	MKS4	1.0	1.3	2.0	2.1	2.7	3.0	3.0	3.0	3.1	3.3
KSP11	KS2	1.0	1.0	1.1	1.9	2.0	2.0	2.2	2.5	2.8	3.0
	MKS4	1.0	1.3	2.0	2.1	2.7	3.0	3.0	3.0	3.1	3.3
KSP12	KS2	1.0	2.0	2.8	3.0	3.1	3.6	3.9	4.0	4.0	4.0
	MKS4	1.0	1.3	2.0	2.1	2.7	3.0	3.0	3.0	3.1	3.3

Table 4. Number of loads per day for kerbside partially-sorted collection of recyclables and food waste (Combination KSP1-KSP12)

		Capture rate (%)									
Combination	RCV	10	20	30	40	50	60	70	80	90	100
P1	MKS1	1.0	1.0	2.0	2.0	2.2	2.9	3.0	3.0	3.0	3.0
	CWS1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.2
P2	MKS1	1.0	1.0	2.0	2.0	2.2	2.9	3.0	3.0	3.0	3.0
	CWS1	1.0	1.0	1.0	1.6	2.0	2.0	2.0	2.1	2.4	2.8
P3	MKS1	1.0	1.0	2.0	2.0	2.2	2.9	3.0	3.0	3.0	3.0
	CWS1	1.0	1.0	1.3	2.0	2.0	2.0	2.3	2.9	3.0	3.0
P4	MKS1	1.0	1.0	2.0	2.0	2.2	2.9	3.0	3.0	3.0	3.0
	CWS1	1.0	1.0	2.0	2.0	2.2	2.9	3.0	3.0	3.0	3.0
P5	MKS1	1.0	1.0	2.0	2.0	2.2	2.9	3.0	3.0	3.0	3.0
	CWS1	1.0	1.2	2.0	2.0	2.7	3.0	3.0	3.0	3.0	3.1
P6	MKS1	1.0	1.0	2.0	2.0	2.2	2.9	3.0	3.0	3.0	3.0
	CWS1	1.0	1.0	1.3	2.0	2.0	2.0	2.3	2.9	3.0	3.0
P7	MKS1	1.0	1.0	2.0	2.0	2.2	2.9	3.0	3.0	3.0	3.0
	CWS1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.2

Appendix C Kerbside collection model manual

User guide for WasteCAT waste collection assessment tool

Model created by: T. W. Chu, A.C. Lock, S. Heaven

Software implementation: A.C. Lock

Manual prepared by: T.W. Chu

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User guide for WasteCAT waste collection assessment tool

Contents

1.0 System Requirements 255
1.1 Setup and start the program 255
1.2 Using WasteCAT 255
1.3 Main Window 256
1.3.1 Input tab 256
1.3.2 RCVs tab 258
1.3.3 Output tab 259
1.4 Menu bar 260
2.0 Demonstration 260

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User guide for WasteCAT waste collection assessment tool

1.0 System Requirements

The WasteCAT tool requires the following system configuration:

- Windows operation systems
- Microsoft.NET Framework 4.5
- At least 9 MB of hard disc space
- 1280 * 960 or more pixel screen resolution recommended

To see the Help file (accessed by clicking on "?"), Adobe Reader version X or above is required

1.1 Setup and start the program

WasteCAT setup is quick and easy. Unzip the WasteCAT.zip file; find the **Setup.exe** file from the Publish Directory. Double click Setup.exe file to install and launch the program. A cover page of the tool, shown in Figure 1, is splashed once the tool is ready. Click on it to enter the first page of the tool.

Figure 1. Cover page of WasteCAT

1.2 Using WasteCAT

This section provides a detailed description of system functions. The layout of the WasteCAT main page is shown in Figure 2. The layout can be divided into two parts: Main window (Green) and menu bar (Red).

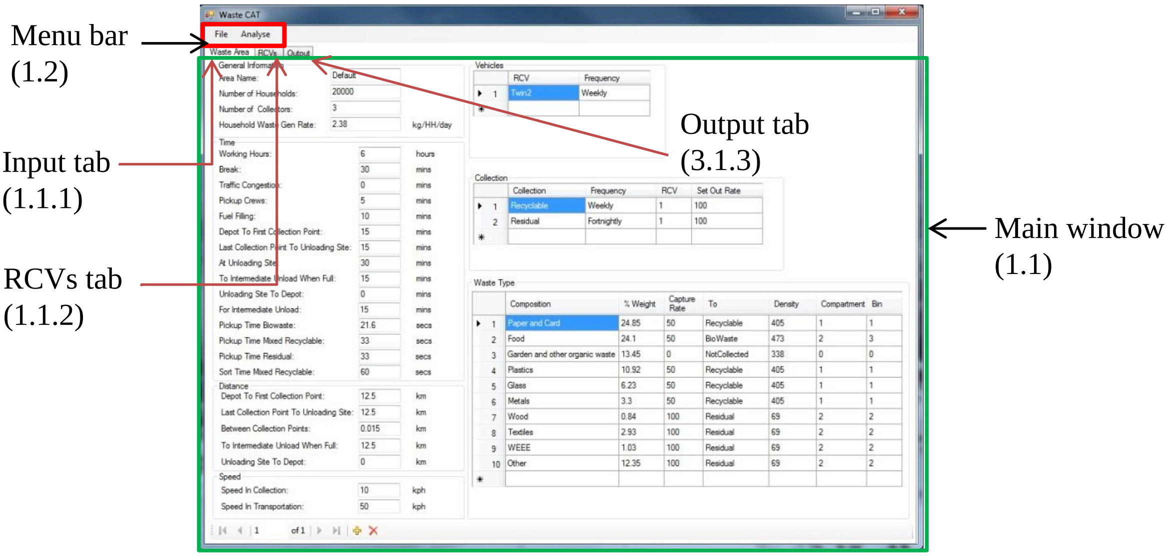


Figure 2. Layout of WasteCAT main page

1.3 Main Window

The main window has three tabs: Input, RCVs and output.

1.3.1 Input tab

The input tab is made up of 7 input tables containing general information on collection system, time, distance, speed, vehicles, collection and waste type. An explanation of inputs is given in Table 1.

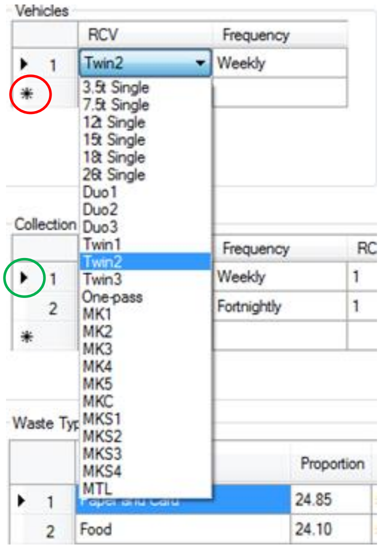
Table 1. Description of terms in input tab

Term	**Description**
Area name:	Name of the area being analysed
Number of households:	Number of households in the area.
Number of collectors:	This represents the number of staff involved in picking up household waste. Decimal fractions are accepted.
Household waste gen rate:	This is the total waste generated per household per day (kg household^{-1} day^{-1}).
Working hours:	Total length of a working day including time for non-productive activities such as breaks (hours).
At unloading site:	Time at unloading site including time queuing and unloading (min).
To intermediate unload when full:	This is the time from the last collection point to the bulking point (e.g. transfer station), and only applies when a vehicle must deposit two or more loads in one day (min).
For intermediate unload:	Time at unloading site when more than one load is deposited per day (min); normally equal to time at unloading site.
Sort time mixed recyclables:	The average time required to sort each recyclable (min).
Speed in collection:	The average speed inside collection area – first dwelling or collection point to last dwelling or collection point (min).
Speed in transportation:	The average speed outside collection area (km hour^{-1}).

In this tool, when the input value of time is changed, the distance changes automatically, and vice versa. This is because the calculation of time and distance is based on speed. On the other hand distance depends on speed, thus when the speed in transportation is changed, the distance will be recalculated.

At the right hand side of the input tab there are three input tables: vehicles, collection and waste types.

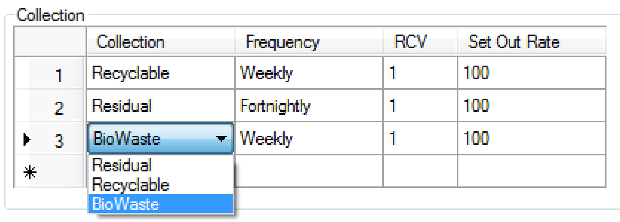
Vehicle table:



The first column of the table contains the vehicle number, which is used to identify the vehicle in the collection and waste type tables. User can select the vehicle type from the drop down list by double clicking the text field in the RCV column. More information about the vehicle type can be found on the RCVs tab. Adjacent to the RCV column is the frequency with which this particular vehicle visits each household on its route: note that this may not be the same as the frequency of collection (see Scenario 3 in examples below). Double click on this to select the option weekly or fortnightly from the drop down list.

When setting up a scenario, the user can select more than one collection vehicle by clicking "*" (red circle). To delete, click the number in the first column (green circle) so that the whole row is highlighted in blue and then press the delete key.

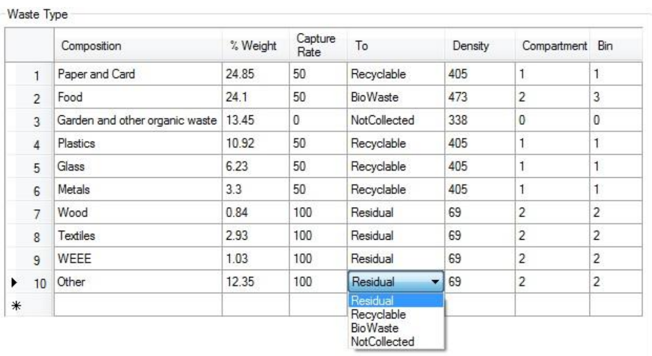
Collection table:



Waste type can be selected from the drop down list in the collection column: the categories are residual waste, recyclable and biowaste. Frequency here is different from the frequency shown in vehicle table. It represents the period of time for which waste is stored by the householder or waste generator, i.e. weekly means waste is accumulated for 7 days before the next collection day. In the RCV column, the number in text field refers to the vehicle number shown in the first column of vehicle table. It indicates which vehicle is used to collect the waste selected in the associated collection column.

Set out rate means the proportion of households that set out this bin on the collection day.

Waste type table:



Waste Type

	Composition	% Weight	Capture Rate	To	Density	Compartment	Bin
1	Paper and Card	24.85	50	Recyclable	405	1	1
2	Food	24.1	50	BioWaste	473	2	3
3	Garden and other organic waste	13.45	0	NotCollected	338	0	0
4	Plastics	10.92	50	Recyclable	405	1	1
5	Glass	6.23	50	Recyclable	405	1	1
6	Metals	3.3	50	Recyclable	405	1	1
7	Wood	0.84	100	Residual	69	2	2
8	Textiles	2.93	100	Residual	69	2	2
9	WEEE	1.03	100	Residual	69	2	2
10	Other	12.35	100	Residual	69	2	2

The composition and % weight of kerbside household waste can be modified. Waste types can be added or deleted by clicking '*' or pressing the delete key. The user can double click the input field to enter or alter the text. Capture rate refers to amount of a particular waste that is put out for separate collection in the bin, as a percentage of the total quantity of that waste in the kerbside-collected household waste stream. The minimum and maximum values of capture rate are 0 and 100 respectively. If the capture rate is set to zero, this means none of the selected waste is diverted to the selected recycling or biowaste bin and it all goes into the residual waste stream. The set out rate is fixed at 100 for waste going to the residual waste stream.

"To" column: The user can allocate the waste type to residual waste, recyclable, biowaste and not collected by selecting the waste category from the drop down list located in the "To" column. For example, if mixed recyclables (i.e. paper, card, plastics, grass and metals) are collected, then the category “Recyclable” should be chosen.

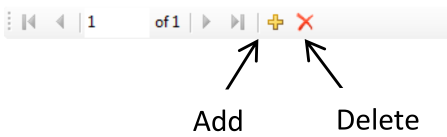
Density column: This gives the bulk density of each waste, and is associated with the waste type and the type of vehicle to be used for the collection. Default values for bulk density are based on WRAP (2008, 2009 and 2010).

Compartment column: The number in the compartment column identifies which wastes go to which compartment(s). As default, compartment 1 refers to the small compartment while compartment 2 is the larger compartment if two-compartment vehicle is selected. Details of compartment sizes are given on the RCVs tab. When a waste is not collected, “0” should be entered in the text field.

Bin column: This is used to assign which waste types go into the bins. The number is used to identify the bin, and to count the number of sorts required in a kerbside-sorted system. For example, if glass and metals are collected in the same bin but emptied separately into two compartments, this means one sorting of recyclables is required. Another example is given in section 2.

Tool bar:

The user can duplicate the scenario or create a new scenario by clicking on “+”or delete the scenario by clicking on “×”at the bottom of the input tab.



1.3.2 RCVs tab

Figure 3 shows the database of refuse collection vehicles, which contains information on each vehicle including the gross weight, payload, volume capacity of vehicle, number of compartments, volume capacity of each compartment and the factor for the hydraulic system. Details of terms are explained in Table 2.

Table 2. Description of terms in RCVs tab

Term	**Description**
Code:	This is the code for each vehicle which displayed in the drop down list in the vehicle table.
Refuse collection vehicle:	This provides the brief description of vehicle, e.g. the manufacturer, data source, type of vehicle, etc.
GVW:	Gross weight of the collection vehicle.
Payload:	Maximum load capacity of vehicle.
Number of compartments:	Total number of vehicle compartments.
Total volume:	Maximum volume capacity of vehicle.
Compartment:	Volume capacity of each compartment: click the up arrow button to show the volume capacity of other compartments.
Factor for using hydraulic system during collection:	This represents the extra fuel required to operate the hydraulic system and in the ‘stop and go’ pattern in the collection area. 35% extra fuel is assumed, thus the default value for this factor is 1.35

In addition to choosing from the 24 collection vehicles in the database, the user can create new vehicles or remove a vehicle by clicking the “+” or “×” buttons. After clicking on the “+” button, a new vehicle form appears, as shown in Figure 4. If the new created vehicle is a compartmentalised vehicle, the volume of each individual compartment must be entered in the "compartment" text field by clicking the up and down arrow buttons. The sum of the volume of each compartment should be equal to the total volume for the vehicle.

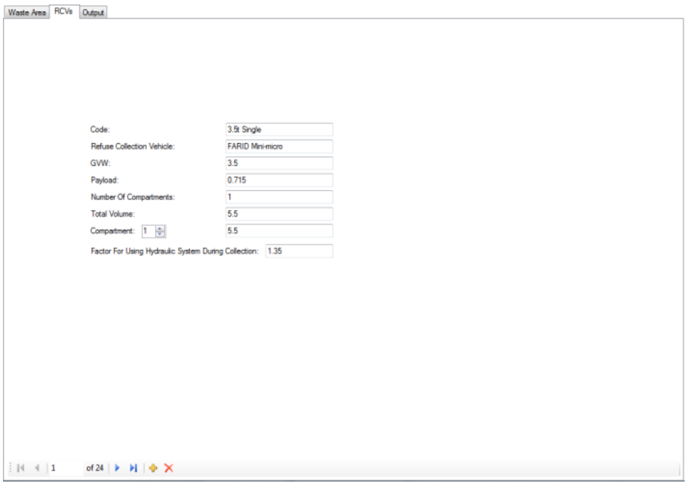


Figure 3. Layout of RCVs tab

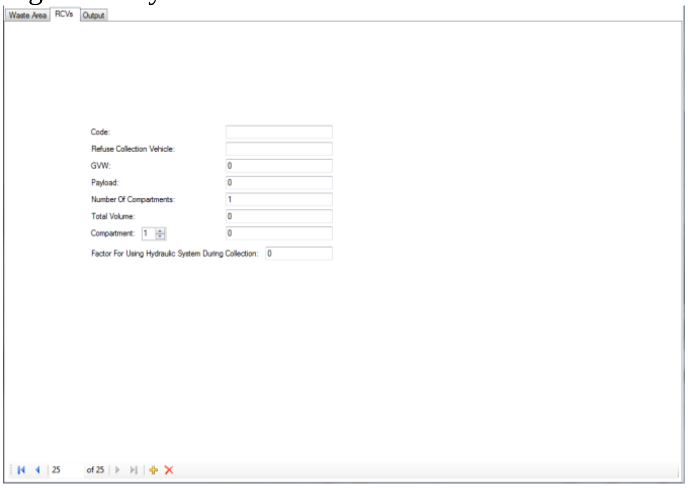


Figure 4. Form for new RCVs

1.3.3 Output tab

The output tab lists the results of the scenario modellnig. The key outputs of WasteCAT include: limiting factors, number of vehicles required, average laden percentage, total fuel consumption, energy consumption, travelled distance, total time, number of routes and litre diesel per tonne waste collected. An explanation of these terms is given in Table 3.

Table 3. Description of terms in output tab

Term	Description
Limiting collection:	This shows which compartment is filled up by the waste first.
Limited by:	This shows whether the collection round is limited by service time, payload or volume capacity of the vehicle.
Number of loads per day:	This equals the number of loads taken for transfer or disposal per day. For example if it shows 2 rounds per day, this means waste must be unloaded once before the whole round is finished.
Laden percent:	Average laden percentage in weight per vehicle.
Number of routes per collection:	This shows the total number of routes required to collect waste for the whole collection, and is equal to the number of

	collection vehicles times the number of collection days.
Total time spent in collection:	Time spent inside the collection area only.
Total time:	Time spent inside and outside the collection area, including non-productive time.

Figure 5 shows the layout of the output tab. There are two tool bars: one at the top and another at the bottom. On the top tool bar, the user can click the left and right arrow buttons to switch page and view the performance of vehicles in each scenario. To view the result of different scenarios, the tool bar at the bottom can be used to switch pages.

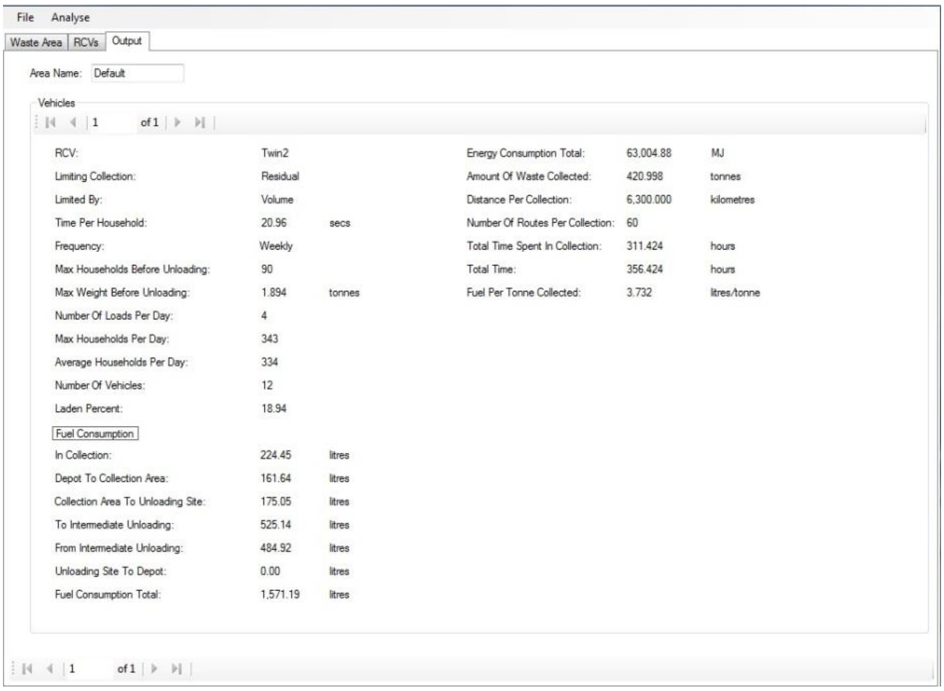
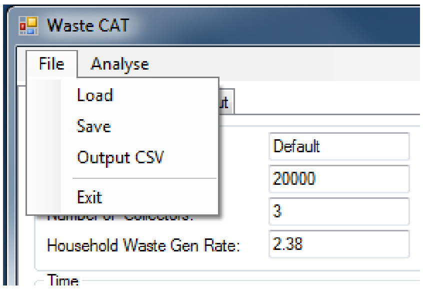


Figure 5. Layout of output tab

1.4 Menu bar

There are two buttons in the menu bar: File and Analysis. The user can save the scenarios by clicking "Save". The scenario is saved in .wmd format. To load the file, the user can click "Load", and a new window appears. All the results can also be exported in.csv format by clicking "Output CSV".



"Analyse" function: This is the command to run the tool. Once the user has set up all the required scenarios, press "Analyse" to run the model before viewing the results on the output tab.

2.0 Demonstration

Four examples are used to explain how to set up the scenario in the input tab.

Scenario 1: Weekly separate collections of recyclables, residual and food waste by a 26t single compartment vehicle.

Scenario 2: Weekly co-collection of recyclables and food waste by equal split-bodied vehicle (Twin1), fortnightly collection of residual waste by a 26t single vehicle.

Scenario 3: Weekly food waste collection with alternate weekly collection (AWC) of recyclables and residual waste by equal split-bodied vehicle (Twin1).

Scenario 4: Recyclables are kerbside sorted and food waste is collected weekly by the three-compartment vehicle (One-pass).

Figure 6 shows the setup of Scenario 1. Firstly, three 26-tonne vehicles are selected for the collection. Vehicles 1, 2 and 3 are used to collect recyclables, residual waste and biowaste respectively. The waste stream in the collection table links up to the "To" column in the waste type table and allows the user to trace which vehicle is being used to collect what kind of waste stream. In the waste type table, all wastes go to compartment 1, simply because single compartment vehicles are used.

In this scenario, three bins are used to collect wastes. It is assumed all recyclables are collected co-mingled in Bin 1. Food waste and residual waste go to Bin 2 and Bin 3 respectively.

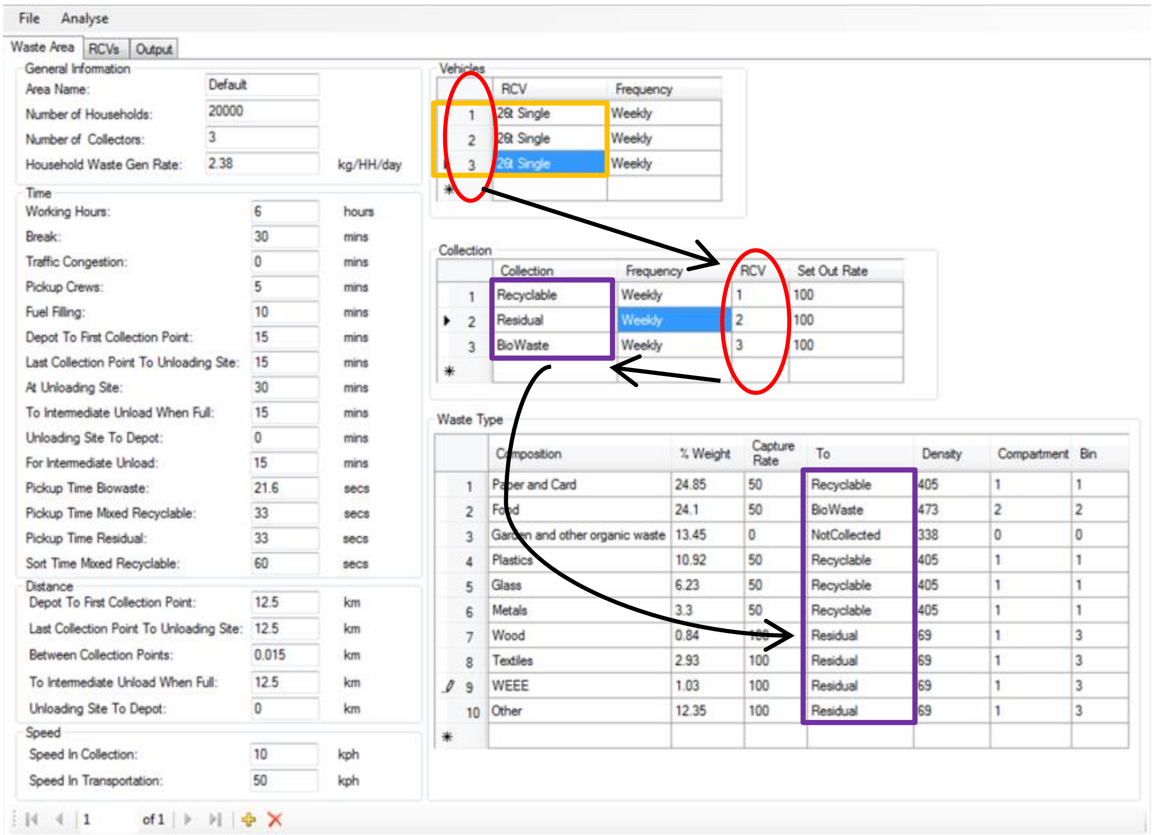


Figure 6. Input tab for Scenario 1

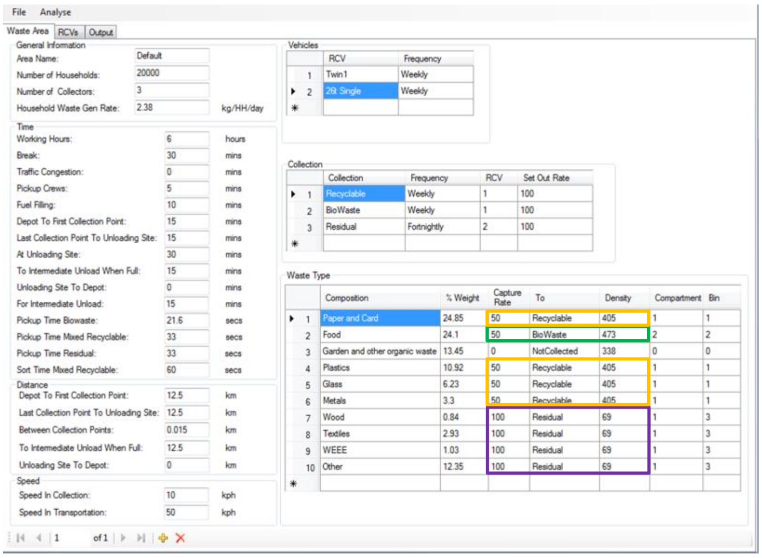


Figure 7. Input tab for Scenario 2

Figure 7 shows the input tab for Scenario 2. A Twin1 (Vehicle 1) collects the recyclable and biowaste weekly, recyclables are loaded into compartment 1 and food waste goes to compartment 2. A 26t Single (Vehicle 2) collects residual waste every fortnight, therefore the text field shows “Fortnightly” in both Frequency columns. As in scenario 1, three bins are used to collect waste. In this case, however, Bin 1 is used to collect recyclables, Bin 2 and 3 are for the collection of food waste and residual waste.

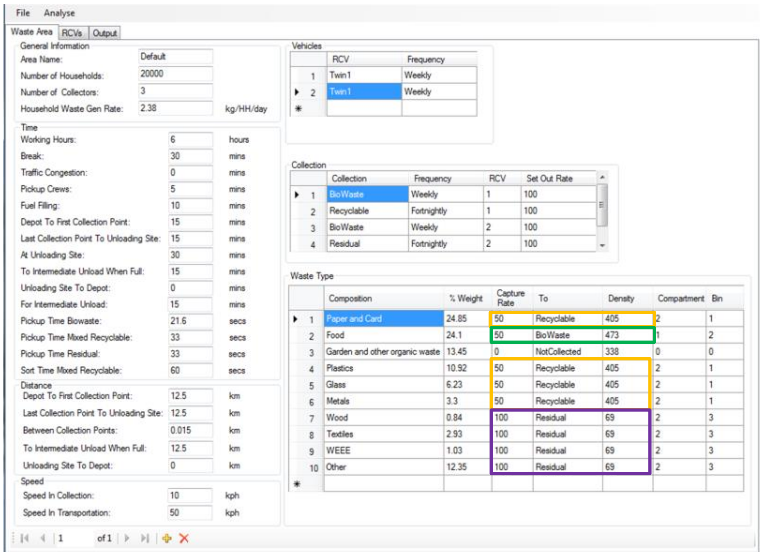


Figure 8. Input tab for Scenario 3

Figure 8 shows the input tab for AWC of household waste (Scenario 3). In this scenario, weekly is selected for all Twin1 in the vehicle table because it visits dwellings every week, but puts different waste in compartment 2 every two weeks. Fortnightly is chosen in the collection table for the recyclable and residual waste as they are stored at the household for two weeks before the next collection day. Food waste goes to compartment 1 every week, while recyclables and residual waste go into compartment 2 on alternate weeks. The arrangement of bins is the same as in Scenario 2.

Figure 9 shows the connection between compartment and bin in Scenario 4. Recyclables and food waste are collected by the One-pass vehicle. Paper and card go to compartment 1; food waste goes to compartment 2 while plastics, glass and metals go to compartment 3. The bulk density of waste is adjusted according to the vehicle and combination of waste types. Bin 1 is used to collect paper, card and plastics; Bin 2 is assigned to collect food waste only and Bin 3 is for glass and metals collection. This arrangement implies a degree of kerbside sorting of Bin 1 as recyclables are loaded in different compartments (highlighted in green square boxes).

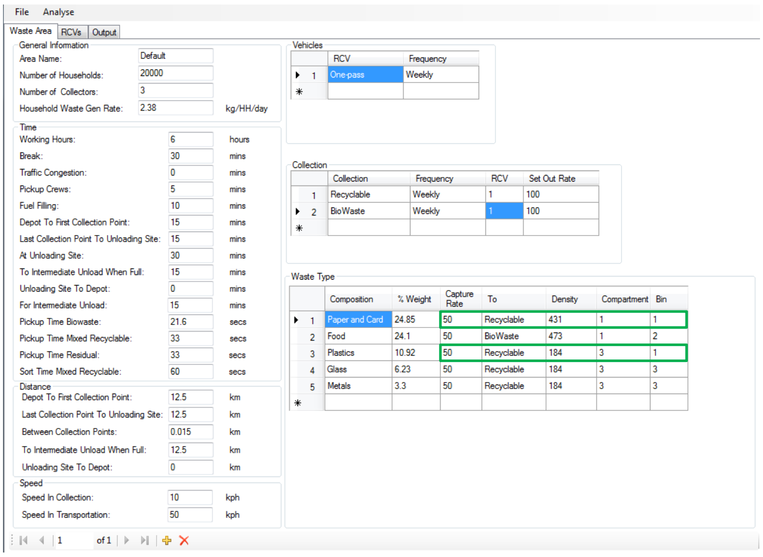


Figure 9. Input tab for Scenario 4

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WRAP (2009). Evaluation of the WRAP Separate Food Waste Collection Trials. Retrieved 19 July, 2011, from http://www.wrap.org.uk/local_authorities/research_guidance/food_waste/.

WRAP (2010). Material bulk densities. Banbury.

The WasteCAT model is available from

www.valorgas.soton.ac.uk

and from **www.bioenergy.soton.ac.uk** on the Resources page

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Appendix D VALORGA*S* Deliverable 6.3: Output from an energy and carbon footprint model verified against primary data collected as part of the research

The model developed in the current research was used in the case study reported in section 2 of this deliverable, which was carried out by the researcher.

SEVENTH FRAMEWORK PROGRAMME
THEME ENERGY.2009.3.2.2
Biowaste as feedstock for 2nd generation

VALORGAS

Project acronym: **VALORGAS**
Project full title: **Valorisation of food waste to biogas**
Grant agreement no.: 241334

D6.3: Output from an energy and carbon footprint model verified against primary data collected as part of the research

Due date of deliverable: Month 42
Actual submission date: Month 42

Project start date: 01/03/2010 Duration: 42 months

Lead contractor for this deliverable
University of Southampton (Soton)

Revision [0]

D6.3: Output from an energy and carbon footprint model verified against primary data collected as part of the research

Lead contractor for this deliverable
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David Bolzonella (UNIVR), Paolo Pavan and Cristina Cavinato (UNIVE), Charles Banks and Stephen Robertson (Soton) - AD plant modelling
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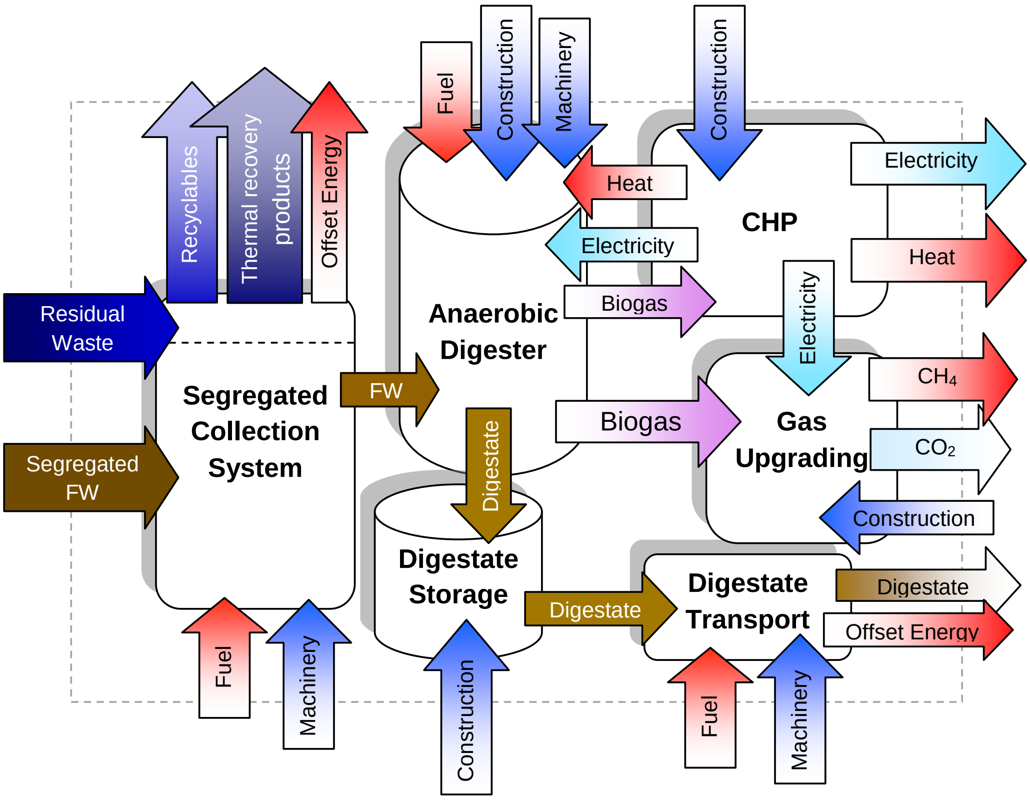
D6.3: Output from an energy and carbon footprint model verified against primary data collected as part of the research



Contents

1 Introduction 271
2 Modelling energy consumption in source segregated food waste collections 272
2.1 Assumptions 272
2.1.1 Collection scenarios 272
2.1.2 Description of the household waste collection 273
2.1.3 Input values and embodied energy 273
2.2 Results and discussion of WasteCAT collections modelling 274
2.3 Embodied energy in collection vehicles and bins 277
2.4 Conclusions from collections modelling 279
3 Energy balance modelling in anaerobic digestion – model description 281
3.1 Input waste stream 282
3.2 Digester 282
3.3 Biogas use 284
3.4 Digestate processing 286

3.5 GHG emissions...287
4 Validation of anaerobic digestion energy balance model 289
4.1 Validation of mesophilic simple AD plant..289
4.2 Validation of thermophilic complex AD plant..289
4.3 Conclusions from validation 290
5 Anaerobic digestion scenario modelling... 290
5.1 Main scenarios 291
5.2 Energy balances for electricity and heat production 292
5.3 Energy balances for upgrading to biomethane...292
5.4 Comparison of energy balances for electricity and biomethane production 297
5.4 GHG emissions...297
5.5 Use of modelling tool to investigate effects of loading rate on energy balance 299
5.6 Conclusions from scenario modelling..301
6 Overall energy and GHG balances from waste to field 302
6.1 Energy and emissions in digestate transport and utilisation...................................302
6.2 Overall balances 303
6.2.1 Energy balances 303
6.2.2 GHG emissions 304
6.2.3 Operation without digestate re-use 306
6.3 Discussion and conclusions for whole system assessment 307
6.4 AD assessment tool 308
7 Conclusions... 309
References 310

D6.3: Output from an energy and carbon footprint model verified against primary data collected as part of the research

1 Introduction

The aims of the work described in this deliverable report were firstly to provide a means for assessing the overall energy balance from collection, pre-processing and anaerobic digestion of food waste, through to utilisation of the digestate and the biogas fuel product; and secondly to apply this to selected scenarios to determine the benefits or otherwise from valorisation of source segregated domestic food waste to biogas.

For this purpose two tools were used: the collections model developed in deliverable D2.7 (VALORGAS 2013a), and a modelling tool for anaerobic digestion of organic wastes. The former was run with a range of scenarios to identify a 'typical' value for the extra energy requirement of source segregated food waste collection, which could then be used in assessing the energy balance for the whole system. The latter was based on a model originally developed in the FP6 CROPGEN project, and extended in the current research. The work made use both of literature data, and of results and experience gained during the VALORGAS project. Results from the two models were then combined to give a whole system assessment.

As VALORGAS is part of the FP7 Energy programme the modelling tools were primarily designed to calculate energy balances, while also considering some other resource and environmental parameters. A decision had been made at the project proposal stage not to attempt a full life cycle assessment (LCA) approach; the wisdom of this was confirmed by the results of deliverable D2.7. Energy, nutrients and greenhouse gas (GHG) emissions were selected, however, as capturing the most quantifiable components of LCA. The modelling outputs did not include economic costing, since this is highly subject to change with both time and location. Instead the main goal was to produce robust and reliable output data that could form a basis for economic and life cycle assessment, taking into account the specific conditions of a particular scheme.

The modelling work was not intended to identify a single 'optimum' configuration for collection and processing of source separated food waste: each scheme and location has particular characteristics and, while some options may generally be more efficient, it is unlikely that one ideal solution exists. In addition, the choice between different collection and processing options is rarely based on the energy balance alone, but must take into account many other societal and environmental factors. The purpose of the combined modelling tools is to provide a means of exploring the consequences of different options in terms of the key parameters of energy, GHG emissions and nutrients; and thus to support informed decision-making. The approaches adopted can also be used for research purposes, to identify areas where changes, in both engineering and policy terms, could bring about significant improvements in performance.

The main outputs from the research are thus the modelling tools themselves, and the conclusions from the typical scenarios considered. This deliverable report describes the second tool and presents examples of the use the two tools in combination to model selected scenarios: the results are not exhaustive or definitive, however, and it is hoped that these tools will be widely used in future to enable whole system analysis of energy production from anaerobic digestion of organic wastes.

2 Modelling energy consumption in source segregated food waste collections

In this part of the work, the WasteCAT tool developed in deliverable D2.7 (VALORGAS, 2013a) was used to determine the 'extra' energy requirement and GHG emissions for collection of source segregated domestic food waste under a variety of scenarios.

2.1 Assumptions

The case study carried out was based on a hypothetical group of 25,000 households, corresponding to a typical medium-sized town (Flacke, 2004). Each household was assumed to generate 2.5 kg day^{-1} of kerbside-collected waste, not including garden waste which was assumed to be composted or collected separately. The quantity of food waste, recyclables and residual waste collected was based on the percentage composition of kerbside-collected household waste, the capture rate and the set out rate for each waste, as described in deliverable D2.7. The values used are shown in Table 1: these were taken from a UK data source but it should be noted that the proportion varies and is typically higher in Mediterranean countries, making this a reasonably conservative assumption. For the current study, it was assumed that recyclable waste including paper, card, plastics, glass and metals were collected co-mingled, i.e. in a single recycling bin. Any waste not captured and set out for recycling or recovery is assumed to go into the residual waste bin: for example, when there is no source separated food waste collection all food waste goes in with residual waste.

Table 1. Assumed composition of kerbside-collected household waste used in the study (Adapted from Defra, 2009)

	Proportion in waste % weight	**Capture rate [a] %**	**Set-out rate [b] %**
Food waste	24.1	70	65
Co-mingled recyclables	45.3	75	100
Residual waste	17.15	100	100
Green waste	13.45	0	0

[a] Capture = waste presented for separate collection as a proportion of total household waste put out at the kerbside (WRAP, 2009); [b] Set out = proportion of households participating in the scheme

2.1.1 Collection scenarios

Seven collection scenarios were considered. Scenarios C1 and C2 are household waste collection without separate collection of food waste, at weekly or fortnightly intervals. Scenarios C3-C7 are household waste collection with separate food waste collection, with Scenarios C3 and C4 employing separate vehicles for each collection type and Scenarios C5-C7 adopting co-collection of different waste streams in twin-compartment vehicles. In all cases weekly collection of food waste was assumed, though in practice the necessary frequency will vary both from country to country and seasonally. These scenarios are only a small fraction of the range of options that can be modelled using WasteCAT, but were chosen to represent some commonly used schemes for waste collection. Details of the scenarios are shown in Table 2 and specifications for the collection vehicles chosen are given in Table 3.

Table 2. Collection scenarios

Scenario	Collection vehicle	Waste type	Frequency
C1	26t single	Residual waste	Weekly
	26t single	Co-mingle recyclables	Weekly
C2	26t single	Residual waste	Fortnightly
	26t single	Co-mingle recyclables	Fortnightly
C3	7.5t single	Food waste	Weekly
	26t single	Residual waste	Weekly
	26t single	Co-mingle recyclables	Weekly
C4	7.5t single	Food waste	Weekly
	26t single	Residual waste	Fortnightly
	26t single	Co-mingle recyclables	Fortnightly
C5	Twin 3	Food waste	Weekly
		Residual waste	Fortnightly
	Twin 3	Food waste	Weekly
		Co-mingle recyclables	Fortnightly
C6	7.5t single	Food waste	Weekly
	Twin 1	Residual waste	Fortnightly
		Co-mingle recyclables	Fortnightly
C7	26t single	Food waste	Weekly
	Twin 1	Residual waste	Fortnightly
		Co-mingle recyclables	Fortnightly

Table 3. Specification of the collection vehicles

	GVW (tonnes)	Payload (tonnes)	No. of compartments	Compartment size	
				Small (m^3)	Large (m^3)
7.5t single	7.5	3.58	1	5	--
26t single	26	12.84	1	25	--
Twin 1	26	10.58	2	10	10
Twin 2	26	10.88	2	6	14

2.1.2 Description of the household waste collection

For this study the waste collection activity was assumed to start at the depot, followed by travel to the designated collection area. Once the collection vehicle is full or the maximum service time is reached, it returns to a waste transfer station for bulking of the collected material. The exception to this is the case of a single collection vehicle collecting residual waste, which is assumed to take the material directly to a landfill site / incinerator and then return to the depot after unloading; a compartmentalised vehicle collecting residual waste is assumed to go to the transfer station for bulking of the waste before it is sent to the landfill/incinerator. It is assumed that all collected food waste is bulked at the transfer station and sent to the anaerobic digestion plant by lorry. A schematic of collection options indicating the vehicles used in different stages is presented in Figure 1.

2.1.3 Input values and embodied energy

The input values used in the WasteCAT modelling tool are shown in Table 4. For the current study it was assumed that the collection crew works 6 hours per day and five days a week. The average pick-up times for containers for food waste and for mixed recyclables or residual wastes were taken as 21.6 and 33 seconds per location, respectively (WRAP, 2009). The distance from the depot to the first and last collection points and from the last collection point to the landfill site was set at 5 km. The bulking point (transfer station) was assumed to be located at the depot.

Table 4. Input values used in modelling

	Values	Unit
Time		
Working hours	6	hour
Break	30	min
Traffic congestion	0	min
Pick up crew members	5	min
Fuel filling	10	min
Depot to first collection point	6	min
Last collection point to depot	6	min
At unloading site	30	min
Collection point to bulking when full	6	min
Bulking point to depot	0	min
Unloading at landfill site	15	min
Pick-up time for biowaste (i.e. food waste)	21.6	s
Pick-up time for mixed recyclables	33	s
Pick-up time for residual waste	33	s
Distance		
From depot to first collection point	5	km
From last collection point to depot	5	km
Between collection points	0.02	km
From last collection point to landfill site	5	km
Bulking to AD plant	15	km
Speed		
In collection	10	km $hour^{-1}$
In transportation	50	km $hour^{-1}$

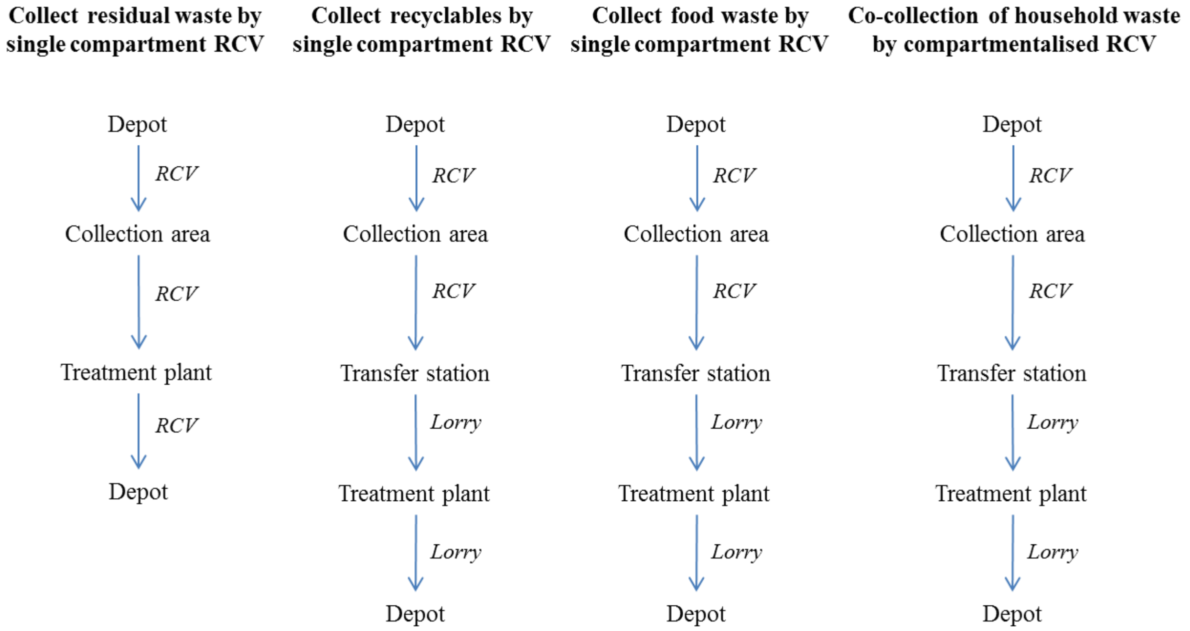


Figure 1. Schematic showing vehicle movements in household waste collection (RCV = refuse collection vehicle)

2.2 Results and discussion of WasteCAT collections modelling

The total amount of food waste collected and available for anaerobic digestion in the selected conditions is 2500 tonnes per year, equivalent to 45.5% of the total food waste generated and 11% of the total waste stream.

Energy difference with and without source separated food waste collection

Table 5 shows the number of vehicles required, service time, energy consumed as fuel and fuel-related GHG emissions in kerbside collection of the household waste stream. Scenarios C1 and C2 are the baseline values without separate food waste collection. The difference between the value for Scenario C1 or C2 and for Scenarios C3-C7 which include separate collection of food waste can thus be taken to represent the additional energy cost of separate collection for each set of conditions considered.

When compared with Scenario C2, based on fortnightly collections of recyclables and residual waste, the additional energy required to provide separate food waste collection in Scenarios C4-C7 was between 377.8-762.6 GJ year^{-1}. This is a 'like for like' comparison, providing the same level of service to customers in terms of the frequency of collection of recyclables and residual waste but with the addition of a weekly food waste collection. It should be noted, however, that when Scenarios C4-C7 are compared with Scenario C1 the introduction of a separate food waste collection leads to a decrease in the total energy required for collection of the household waste stream, because of the greater overall efficiency of the new system. When Scenario C1 is compared with the Scenario C3 an additional 776 GJ year^{-1} is required to operate the same weekly service for residual waste and recyclables with the addition of separate food waste collection. In comparison with Scenario C2, with fortnightly collection of recyclables and residual wastes, Scenario C3 requires 80% more energy. One of the motives for introducing separate weekly food waste collections, however, is that it may allow a reduction in the frequency of collections of other wastes, which would clearly offer energy savings. Scenario C3 is therefore only likely to be chosen if there are other compelling reasons to offer weekly collection of recyclables and residual wastes, such as an acute shortage of storage space at the household in very densely-populated urban areas; and in this case Scenario C1 offers the best like-for-like comparison.

While this study considers only one set of scenarios out of a huge number of potential collection configurations and parameters, the model clearly provides a useful tool for investigating both specific cases and general performance. The results suggest that the 'additional' fuel energy requirement associated with the introduction of a separate food waste collection system of this scale and type is likely to be on the order of 500 GJ year^{-1}, or around 0.2 GJ tonne^{-1} FW collected.

Fuel-based CO_2 emissions are directly proportional to the fuel use in collection and therefore present a similar pattern of increase or decrease as seen for energy use (Table 5). The additional fuel-based CO_2 emissions associated with the introduction of the separate food waste collection scheme in the study are on the order of 0.01-0.02 tonne^{-1} FW collected.

The fuel consumption, number of vehicles and staff time determined in the modelling can be used directly as a basis for economic comparison of the different options according to the applicable labour costs, fuel prices and capital financing charges.

Table 5. Summary of fuel energy consumption, number of vehicles and time required for kerbside collection of the whole household waste stream

	Scenario						
	1	2	3	4	5	6	7
Basic output parameters							
Total no. of refuse collection vehicles required	13	11	18	12	14	10	9
Total time spent on collection and transfer (hours year^{-1})	18749.2	10643.0	25606.2	16616.0	20948.7	14163.9	12963.8
Energy consumed from depot to transfer station (GJ year^{-1})	2325.3	1509.4	2946.5	1839.8	1144.7	1276.6	1529.5
Energy consumed from transfer station to plant (GJ year^{-1})	479.6	479.6	634.4	634.4	1222.1	1222.1	1222.1
Total energy consumed in collection and transfer (GJ year^{-1})	2804.9	1989.0	3580.9	2474.2	2366.9	2498.7	2751.6
Total GHG emissions from fuel consumption (tonnes CO_{2eq} year^{-1})	209.7	148.7	267.8	185.0	177.0	186.8	205.8
Extra time needed for separate FW collection							
Compared to Scenario 1 (hours year^{-1})	-	-	6857.1	-2133.2	2199.5	-4585.3	-5785.3
Compared to Scenario 2 (hours year^{-1})	-	-	14963.3	-8990.2	4332.6	-6784.8	-1200.0
Extra fuel energy needed for separate FW collection							
Compared to Scenario 1 (GJ year^{-1})	-	-	776.0	-330.7	-438.1	-306.2	-53.3
(GJ tonne^{-1} FW collected year^{-1})	-	-	0.31	-0.13	-0.18	-0.12	-0.02
% of Scenario 1 collection energy	-	-	28%	-12%	-16%	-11%	-2%
Compared to Scenario 2 (GJ year^{-1})	-	-	1591.9	485.2	377.8	509.7	762.6
(GJ tonne^{-1} FW collected year^{-1})	-	-	0.64	0.19	0.15	0.20	0.31
% of Scenario 2 collection energy	-	-	80%	14%	15%	22%	31%
Extra GHG emissions from fuel use in separate FW collection							
Compared to Scenario 1 (tonne CO_{2eq} year^{-1})	-	-	58.0	-24.7	-32.8	-22.9	-4.0
Compared to Scenario 2 (tonne CO_{2eq} year^{-1})	-	-	119.0	36.3	28.3	38.1	57.0

2.3 Embodied energy in collection vehicles and bins

The WasteCAT model does not include the embodied energy or GHG emissions in refuse collection vehicles or bins, since it is primarily intended as a tool for comparison of the 'costs' of collection schemes in terms of fuel usage and staff time (as running costs) and of vehicle numbers (capital costs), rather than for life cycle assessment. The additional embodied energy and GHG emissions associated with food waste collection can, however, be calculated and added into the overall energy balance.

Vehicles. Embodied energy and GHG emissions in the vehicles were estimated using the methods described in deliverable D2.7 and the values in Table 6.

Table 6. Energy and emissions factors for materials and assumed proportion of vehicle weight

Material	Energy factor MJ kg^{-1} material	GHG emissions factor kg CO_{2eq} kg^{-1} material	Assumed proportion of vehicle weight
Plastic	80.5	3.31	9.2%
Steel	35.4	2.89	75.6%
Glass	15	0.91	0.8%
Aluminium	155	9.16	14.4%

Energy and emissions factors shown in Table 6 were increased by 5% to allow for materials missing from the inventory, and by 20% for vehicle maintenance. To take account of the energy used in vehicle manufacture a further 80 GJ $vehicle^{-1}$ was added, equivalent to 13.71 tonnes CO_{2eq} $vehicle^{-1}$ based on the relevant UK electricity mix (VALORGAS, 2013a). For the purpose of this study the vehicles were assumed to have a 7-year lifespan typical of European conditions, although much longer working lives may be applicable elsewhere (UNEP, 2005; EUNOMIA, 2007). This gave the estimated values for embodied energy and GHG emissions shown in Table 7 and 8. It was assumed that a separate lorry would be used for each waste stream requiring transport from the transfer station.

Table 7. Estimated embodied energy and GHG emissions for each vehicle type

	7.5t Single	26t Single	26t Split	Lorry
Embodied energy of vehicle (GJ $vehicle^{-1}$)	359.7	1018.9	1158.8	919.0
GHG emission (tonne CO_{2eq} $vehicle^{-1}$)	32.6	77.0	86.4	70.3

Table 8. Estimated embodied energy and GHG emissions for each scenario

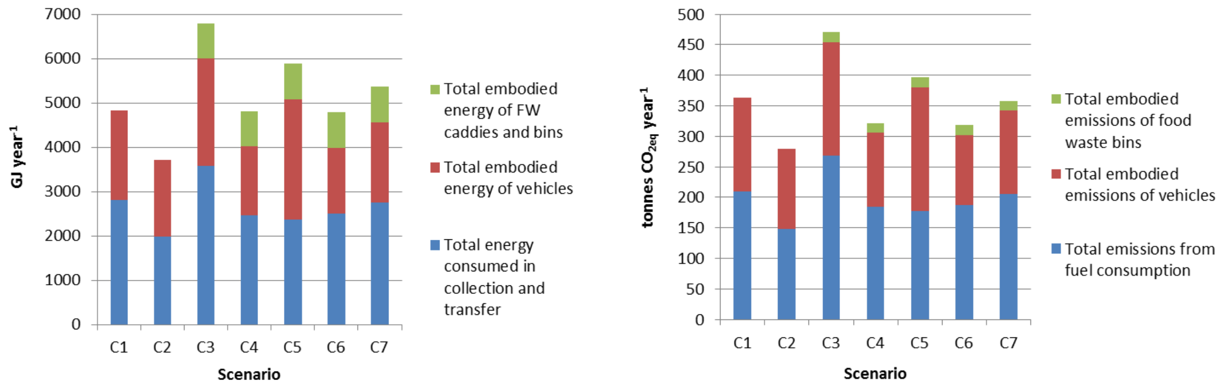
	C1	C2	C3	C4	C5	C6	C7
Embodied energy of vehicles (GJ $vehicle^{-1}$ $year^{-1}$)							
Collection vehicles	1892.28	1601.16	2149.19	1275.83	2317.52	1084.60	1409.93
Transfer lorries	131.29	131.29	262.58	262.58	393.87	393.87	393.87
Total for vehicles	2023.57	1732.45	2411.78	1538.42	2711.39	1478.47	1803.80
GHG emission (tonnes CO_{2eq} $vehicle^{-1}$ $year^{-1}$)							
Collection vehicles	143.02	121.02	166.28	100.27	172.88	85.01	105.75
Transfer lorries	10.04	10.04	20.08	20.08	30.12	30.12	30.12
Total for vehicles	153.06	131.06	186.36	120.35	203.00	115.12	135.87

Bins. In scenarios with separate food waste collection it is assumed that each household is provided with two polypropylene bins: a kerbside bin and a kitchen caddy. The assumed characteristics of the bins are shown in Table 9. These were based on those used in deliverable D2.7, except that the bin life time was taken as 7 years (Environment Agency, 2006; EUNOMIA, 2007) and energy used in distribution of the bins to households was not included. These values were used to calculate the total embodied energy and GHG emissions of the additional food waste bins.

Table 9. Characteristics of bins

Parameter	unit	value
Weight of kerbside bin	kg	1.383
Weight of kitchen caddy	kg	0.398
Energy factor for polypropylene	MJ kg^{-1}	115.1
Embodied GHG emissions for polypropylene kerbside bin	kg CO_{2eq} kg^{-1}	4.49
Additional energy and emissions in manufacturing of bins	%	10
Embodied GHG emissions for polypropylene kerbside bin	kg CO_{2eq}	4.49
Assumed lifetime of bins	years	7

Figure 2 shows the energy used and GHG emissions for kerbside collection of the whole household waste stream including the embodied energy of vehicles and of food waste bins under different scenarios, while Table 10 presents the 'additional' energy required for separate food waste collection. In Scenarios C4-C7 the additional energy required is between 1061.0-2162.1 GJ $year^{-1}$. The embodied energy in additional food waste bins forms a large proportion of this, at 805.3 GJ $year^{-1}$. This result was also noted in deliverable D2.7 and confirms the view that the use of recycled plastic for bins could have a noticeable effect on overall energy balances. The 'additional' energy is also quite sensitive to assumptions made about collection vehicle type, number of lorries used in transport, vehicle lifespan etc: the current assumptions are reasonably conservative and as far as possible in accordance with common literature values and industry or manufacturers' data, but may not be applicable in all locations.



(a) collection scheme energy (b) collection scheme emissions

Figure 2. Energy and emissions for whole waste collection scheme (including embodied energy of vehicles and additional food waste bins but excluding bins for recyclables and residual waste)

From Table 10, the 'additional' energy requirement for an efficient system in the conditions studied is around 1100 GJ $year^{-1}$; while the average for Scenarios 4-7 is on the order of 1500 GJ $year^{-1}$ or 0.6 GJ $tonne^{-1}$ FW collected. The corresponding 'additional' GHG emissions from the introduction of separate food waste collections are around 70 tonnes CO_{2eq} year $^{-1}$.

Best and worst collection systems for separate and co-collection of household waste

In terms of the additional energy required for separate food waste collection, Scenario C3 with weekly separate collection of food waste, residual waste and recyclables had the worst performance, using about 85% more energy than Scenario C6 which was the best system in this respect. The results for Scenario C4 provide a baseline for determining the difference between separate collection and co-collection of household waste.

For the purposes of this study, values of 1500 GJ year^{-1} and 70 tonnes CO_{2eq} year^{-1} will be taken forward to the next stage of the assessment as potentially typical of the 'additional' energy requirement and GHG emissions associated with introducing a separate food waste collection system of this scale and type. If recycled material is substituted for new plastic in the bins, the additional energy required could reduce to around 1100 GJ year^{-1}; the change in GHG emissions would be much lower. It is important to note, however, that values for both the total and 'additional' collection energy are dependent on the assumptions used in modelling, such as the housing density (distance between properties) and the distance to the AD plant. These are properties of the scheme considered, and cannot necessarily be improved or optimised: it is clear that collection and transportation of food waste will consume a higher amount of energy in a less densely populated area where travel distances are larger, or where the AD plant is located far away the collection scheme. The value of the WasteCAT tool is that it allows rational estimation of energy usage and other parameters in a given case, and comparison of the performance of a wide range of collection options. The total and 'additional' values including embodied energy and GHG emissions for vehicles and bins are considerably more speculative and depend on fundamental assumptions in the life cycle assessment approach.

2.4 Conclusions from collections modelling

To assess the energy demand associated with separate collection of food wastes it is necessary to analyse the collection of the whole waste stream, so that any collection energy saved through reduction in the quantity of residual waste is taken into account. This part of the study demonstrated the usefulness of the WasteCAT model as a tool for estimating the absolute and comparative energy consumption of schemes involving separate collection of food waste. The output from the model can be combined with literature data on the embodied energy and GHG emissions of waste collection vehicles and bins, to provide an estimate of the total 'additional' energy required for separate food waste collection. For the scenarios modelled in the current study, typical values for 'additional' collection energy and GHG emission were estimated as 1500 GJ year^{-1} and 70 tonnes CO_{2eq} year^{-1}, and these will be taken forward to contribute to a whole system energy balance.

Table 10. Summary of energy and GHG emissions for kerbside collection of the whole household waste stream including embodied energy of collection vehicles and additional food waste bins

	Scenario						
	C1	C2	C3	C4	C5	C6	C7
Total energy consumed in collection and transfer (GJ $year^{-1}$)	2804.9	1989.0	3580.9	2474.2	2366.9	2498.7	2751.6
Total embodied energy of vehicles (GJ $year^{-1}$)	2023.6	1732.5	2411.8	1538.4	2711.4	1478.5	1803.8
Total embodied energy of FW caddies and bins (GJ $year^{-1}$)	0.0	0.0	805.3	805.3	805.3	805.3	805.3
Total energy used by collection system (GJ $year^{-1}$)	4828.5	3721.5	6798.0	4817.9	5883.6	4782.5	5360.7
Total GHG emissions from fuel consumption (tonnes CO_{2eq} $year^{-1}$)	209.7	148.7	267.8	185.0	177.0	186.8	205.8
Total embodied GHG emissions of collection vehicles (tonnes CO_{2eq} $year^{-1}$)	153.1	131.1	186.4	120.4	203.0	115.1	135.9
Total embodied GHG emissions of FW caddies and bins (tonnes CO_{2eq} $year^{-1}$)	0.0	0.0	16.4	16.4	16.4	16.4	16.4
Total GHG emissions of collection system (tonnes CO_{2eq} $year^{-1}$)	362.8	279.8	470.6	321.8	396.4	318.4	358.0
Extra energy needed for separate FW collection							
Compared to Scenario 1 (GJ $year^{-1}$)	-	-	1969.5	-10.6	1055.1	-46.0	532.2
(GJ $tonne^{-1}$ FW collected $year^{-1}$)	-	-	0.79	0.00	0.42	-0.02	0.21
% of Scenario 1 collection energy	-	-	41%	0%	22%	-1%	11%
Compared to Scenario 2 (GJ $year^{-1}$)	-	-	3076.5	1096.5	2162.1	1061.0	1639.2
(GJ $tonne^{-1}$ FW collected $year^{-1}$)	-	-	1.23	0.44	0.86	0.42	0.66
% of Scenario 2 collection energy	-	-	83%	29%	58%	29%	44%
Extra GHG emissions for separate FW collection							
Compared to Scenario 1 (tonne CO_{2eq} $year^{-1}$)	-	-	107.8	42.0	-74.1	-3.4	-38.4
Compared to Scenario 2 (tonne CO_{2eq} $year^{-1}$)	-	-	190.8	42.0	116.6	38.6	78.3

3 Energy balance modelling in anaerobic digestion – model description

Each part of the anaerobic digestion process has an energy requirement and related GHG emissions. By considering these it is possible to determine the net energy output and therefore the potential replacement of fossil fuel derived energy sources, with the associated reduction in long term GHG emissions. Modelling of the process allows comparison of the various options without extensive laboratory trials or expensive prototype and full-scale development.

The current project built upon previous work carried out in the EU FP6 CROPGEN project (www.cropgen.soton.ac.uk) and the RELU programme (www.AD4RD.soton.ac.uk), and reported in Salter and Banks 2009 and Salter et al. (2011), to derive a tool specifically for modelling the anaerobic digestion of organic wastes (Salter, 2013). This section of the report describes the model. The output was then validated by comparison with data from two full-scale AD plants monitored in the VALORGAS project; and the tool was subsequently applied to modelling a number of scenarios for anaerobic digestion of source segregated food waste based on information gathered in VALORGAS workpackages.

Once the collected waste has been delivered the waste processing system can be divided into four components (Figure 3), each of which can assume varying levels of complexity:

- pre-processing (waste sorting)
- digester (including feeding, mixing and emptying)
- biogas use
- digestate (including separation and composting).

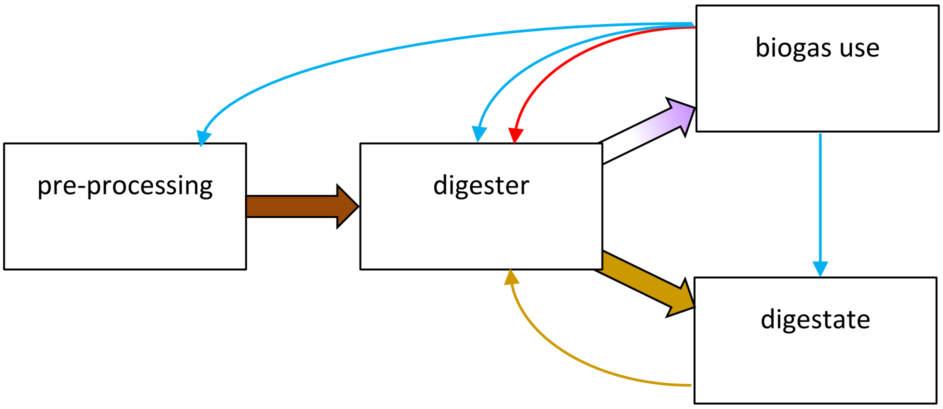


Figure 3. Main components of the waste processing system

Each of these can be divided into a number of sub-components for which energy requirements can be calculated. By comparing the energy requirements for the system against energy production it is possible to develop an energy balance, either as an overall total or per tonne of input material (waste). The basic input and output streams can be divided into energy (electricity, heat and embodied energy), plus material streams (feedstock and digestate) as shown in Figure 4.

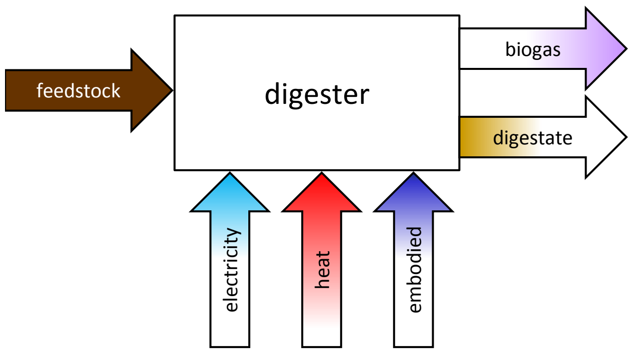


Figure 4. Inputs and outputs for a digester sub-system

Electricity is required to operate pumps, macerators, mechanical mixing systems, biogas upgrading, digestate separators etc. Heat is required to raise the temperature of the feedstock to that of the digester (and/or pasteuriser) and to maintain the digester at the required operating temperature. The embodied energy is that contained in the equipment and structures that make up the digestion plant. This will include concrete and steel for structure bases, reinforced concrete or steel and rubber or PVC used in digester construction and materials included in CHP units, upgrading plant and digestate separators. In order to give an annual embodied energy value the total for the relevant equipment is divided by the life expectancy of the equipment.

The tool allows modelling of different anaerobic digestion scenarios, including the processing of municipal solid waste. The application contains a range of pre-determined values (taken from personal communications and the literature) and calculations which enable the production of a potential energy balance for the input waste stream.

3.1 Input waste stream

A number of pre-determined waste streams are available for selection. These include source separated food waste, the key component in the current project; and also card packaging and biodegradable municipal waste (BMW), with values derived from Zhang et al. (2010). The default food waste characteristics are: TS 24% of FM, VS = 92% of TS, methane yield 0.42 m^3 CH_4 kg^{-1} VS_{added}, 8 g N kg^{-1} FM, 1.3 g P kg^{-1} FM and 3.33 g K kg^{-1} FM. These values were compared with those reported in deliverable D2.1 (VALORGAS, 2011) for food waste samples from Finland, Italy, Portugal and the UK, and were accepted as representative.

Each waste stream has an associated parasitic energy requirement for digestion, including any maceration and pumping required to get the feedstock into the digester. Values for this range from 4 to 40 kWh $tonne^{-1}$ fresh matter (FM) depending on the nature of the material (Chesshire pers. comm. 2012, Börjesson and Berglund, 2006).

3.2 Digester

Once the quantity and type of input materials have been selected the required working volume of the digester(s) can be calculated. This can be done on the basis of volatile solids loading, retention time or capacity.

volatile solids loading:
capacity (m^3) = VS in feedstock (kg day^{-1}) / VS loading rate (kg m^{-3} day^{-1})

retention time:
capacity (m^3) = feedstock (tonnes day^{-1}) * required retention time (days)

capacity:
as specified, loading rate and retention time are then calculated on this basis.

For construction and operational reasons digesters typically have a volume less than 3500 m^3. To control the volume of individual digesters, the number of digesters to be used for feedstock processing can be specified. The digesters are assumed to be all of the same size and construction, and the working volume is calculated by dividing the required capacity by the number of digesters. Having determined the working volume of a digester a decision is made on whether the biogas will be stored within the digester or separately. If separately then 10% of the working volume is added to allow some freeboard within the digester. If the gas is to be stored within the digester then 30% of the working volume is added for gas storage.

Digesters are assumed to be cylindrical with a user-specified height to width ratio. The main construction materials are either reinforced concrete surrounded with polyurethane foam insulation and protective galvanised steel; or stainless steel surrounded by polyurethane foam with a galvanised steel cover. Both types are assumed to have a reinforced concrete base. In the case of a concrete digester the roof is assumed to be a membrane cover constructed from two layers of neoprene rubber. From the dimensions and materials used in construction the embodied energy and carbon is calculated based on the information given in Table 11 (adapted from Hammond and Jones, 2011). A value of 25% of the calculated embodied value is added to allow for ancillary infrastructure.

Table 11. Embodied energies (Hammond and Jones, 2011)

	embodied energy (GJ $tonne^{-1}$)	density (tonne m^{-3})	embodied carbon (tonne CO_2eq $tonne^{-1}$)
concrete	1.03	2.4	0.163
reinforcing steel	10.4	7.8	0.45
sheet steel (galvanised)	22.6	7.8	1.54
stainless steel	56.7	8	6.15
insulation (polyurethane rigid foam)	101.5	0.036	4.26
neoprene rubber	90	1.23	2.85
PVC	77	1.41	3.1

Given the digester volume, shape and construction the heat loss can be determined. Heat requirements for digestion are made up of two components: heat required to raise the temperature of the feedstock to the digester operating temperature, and heat required to replace that lost through the surfaces of the digester. Heat loss is calculated using the equation

$hl = UA\Delta T$ where hl = heat loss, (kJ s^{-1})
U = overall coefficient of heat transfer, (W m^{-2} K^{-1})
A = cross-sectional area through which heat loss is occurring, (m^2)
ΔT = temperature drop across surface in question, (K).

The coefficients of heat transfer used are shown in Table 12.

Table 12. Heat transfer coefficients

construction materials	U (W m^{-2} K^{-1})
reinforced, insulated concrete	0.734
insulated steel	0.35
membrane roof	1.00

The energy required to raise the temperature of the feedstock to that of the digester depends on the ambient and digester operating temperatures and on whether pasteurisation is required. Pasteurisation can occur either before digestion or after. If before, it is assumed that any materials requiring pasteurisation are heated to 70 °C and require no further heating before being added to the digester. Any materials not requiring pasteurisation are added directly to the digester and require heating only to the digester operating temperature. In the case of post digestion the temperature of all of the digestate must be increased from digester operating to pasteurisation temperature. The heat energy required is calculated using the equation

$q = CQ\Delta T$ where q = heat required to raise feedstock to digester temperature, (kJ s^{-1})
C = specific heat of the feedstock (kJ kg^{-1} K^{-1})
Q = volume to be added (m^3)
ΔT = temperature difference, (K).

Pasteurisation is assumed to be a batch process. The material must be heated to 70 °C and maintained at this temperature for one hour. One further hour is allowed for loading and unloading the pasteuriser. The volume of the pasteuriser is therefore calculated as the daily feedstock volume requiring pasteurisation divided by 12. Pasteuriser construction is assumed to be insulated steel on a reinforced concrete base.

If a separate biogas holder is specified the volume is calculated on a user specified number of hours with a default value of 2 (Lewis, pers comm, 2013). The gas holder is assumed to be spherical in shape and constructed from two layers of PVC 1 mm thick on a reinforced concrete base 200 mm thick.

Some digester systems have a separate mixing tank installed before the digester. Users can specify the size of the tank by giving the number of days' feedstock supply to be held by the tank. The tank itself is assumed to be an unheated reinforced concrete tank in the shape of a cube.

If the Animal by-products Regulation (EC 1069/2009) (ABPR) applies then an ABPR-compliant building may be required. This is assumed to be a steel-clad on steel frame building standing on a reinforced concrete pad. The building is rectangular in shape with a central peaked roof. Length, width and height dimensions can be specified.

3.3 Biogas use

The amount of biogas produced is determined from information provided for the imported materials used for feedstock. Methane production is calculated based on the equation

methane volume (m^3) = feedstock (kg) * TS (%) * VS (% of TS) * specific methane production (m^3 kg^{-1} VS added).

In this version of the AD tool it is assumed that the full methane potential as specified by the user is created and captured. Depending on the input values this may lead to an overestimate of total methane production, for example if biochemical methane potential values obtained from long-term batch testing are used.

The amount of biogas is then calculated by dividing the methane volume by the predicted methane in biogas percentage. Some biogas may be lost in the AD process before upgrading or combustion in the CHP unit, for example due to leaks between pipes or from the biogas storage; this is accounted for in the calculations through a user specified percentage biogas loss.

Various energy options are available in terms of how the biogas is used as shown in Table 13.

Table 13. Biogas use

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="3">upgrading</td></tr>
<tr><td>none</td><td>upgrading only</td><td>upgrading & compression</td></tr>
<tr><td rowspan="3">energy generation</td><td>none</td><td colspan="3">all of the biogas is flared, heat and electricity for the digester and upgrading processes, if selected, are imported</td></tr>
<tr><td>boiler</td><td>all of the biogas is burnt in a boiler to produce heat. The default value for efficiency is 85%. Excess heat can be exported</td><td colspan="2">sufficient biogas is burnt in a boiler to provide the heat required by the digester and pasteuriser and the rest is upgraded. Electricity for the digester and upgrading processes are imported</td></tr>
<tr><td>CHP</td><td>All of the biogas is used in the CHP unit which is sized according to potential electrical output. Excess heat and electricity can be exported</td><td colspan="2">Biogas is used in CHP unit which is sized to provide enough electricity for the digester and upgrading requirements. Excess heat can be exported. The rest of the biogas is upgraded.</td></tr>
</table>

In the case of no upgrading, CHP units are sized according to electrical production based on the methane available, the load factor (number of hours per year in which the CHP unit is operational allowing for repairs and maintenance) and electrical conversion efficiency according to the equation:

CHP unit size (kW) = methane (m^3) * 35.82 (MJ m^{-3}) * 0.2778 (kWh MJ^{-1}) * conversion efficiency (%) / load factor (hours $year^{-1}$)

Conversion efficiency is user specified (default value 35%).

Where upgrading and/or compression occurs the CHP unit (if selected) is sized according to the parasitic requirements of the digester (based on CHP unit electrical efficiency) and electrical energy requirements for upgrading and compression. For biogas upgrading the energy requirement can be divided into two parts: upgrading to remove the impurities and compression if the upgraded gas is to be used for vehicle fuel. The energy requirement is in the form of electricity for pumps and the compressor. Values for upgrading vary from 0.3 to 0.67 kWh m^{-3} biogas (Electrigaz Technologies Inc, 2008) and between 3 to 6% energy in upgraded gas (Persson, 2003). Total energy for upgrading and compression has been given as 0.6 kWh m^{-3} upgraded gas (Kalmari, H, pers comm. Aug 2008 and VALORGAS, 2013b) and 0.75 kWh m^{-3} upgraded gas (Murphy et al., 2004). The default values used are 0.3 kWh m^{-3} biogas for the upgrading and 0.3 kWh m^{-3} gas for compression (Nijaguna, 2002, VALORGAS, 2013b). The modelling tool also allows input of user-specified values.

Energy output from gas upgrading is expressed in the form of upgraded biomethane (GJ or m^3) and of diesel equivalent (GJ or litres) where the net calorific value of diesel is taken as 35.73 MJ l^{-1} (AEA, 2010). It is assumed here that a user specified percentage (default 2%) of the methane is contained in the off-gas produced during the upgrading process. This leads to an equivalent reduction in the energy available as biomethane.

Where the electrical energy production is lower than that needed for the digester parasitic energy requirements (for example when the biogas is consumed in a boiler), electricity is assumed to be imported from the national grid.

Heat requirements for the digester and pasteuriser can be produced by combustion of the biogas in the CHP unit or boiler. In the case the overall efficiency of energy conversion of the CHP unit is assumed to be 85%. Heat energy produced is therefore calculated as 0.85 - electrical efficiency * energy value of methane available. Where the heat supply is insufficient extra heat is assumed to be provided by combustion of a user specified fuel in a boiler at an efficiency of 85%.

The embodied energy of the CHP unit is estimated based on example weights and power provided in the literature (GE-energy, 2013, MAN, 2013, Primas, 2007). Using this information the mass can be derived as a function of the electrical capacity using the equation

mass (kg) = 19.869 * capacity (kW) + 7497

This value includes a transport container and for simplicity it is assumed that the mass is all steel.

The container is assumed to stand on a reinforced concrete pad.

A similar process is applied where upgrading is included, based on literature values (HyGear, 2013, BioSling, 2013, Greenlane, 2013, Persson, 2003, Persson et al., 2006). In this case the mass of the upgrading unit is proportional to the capacity of the unit

mass (kg) = 30.1 * capacity ($Nm^3\ h^{-1}$) + 6205

It is assumed that the upgrading unit is containerised, that the mass is half steel and half stainless steel, and that it also stands on a reinforced concrete pad.

3.4 Digestate processing

The amount of digestate produced is calculated from the total feedstock input minus the mass of biogas produced. The digestate is assumed to contain all of the nutrients (N, P, K) that were in the original feedstock material. The total solids content of the digestate is calculated on the basis that all of the biogas is produced from volatile solids, which themselves were part of the original total solids. The digestate solids content is calculated using the equation

digestate solids (%) = (feedstock (tonnes) * TS (%) - biogas (tonnes)) / digestate (tonnes)

The digestate can be left untreated or separated to reduce the moisture content, splitting the digestate into fibre and liquor fractions. The methods available for this include:

- belt press
- decanter centrifuge
- screw press
- sieve centrifuge
- sieve drum

each having an operational efficiency and energy requirement as shown in Table 14 (Burton and Turner, 2003). Embodied energy is determined based on a predicted weight for the separator derived from details given by manufacturers (Bernstad et al., 2013, Ekofinn, 2013, Vincent corp., 2013, EYS, 2013, PBS Velká Bíteš, 2013, GN Solids Control, 2013) and assuming that the construction is all steel. The separator is assumed to have an operating life of 10 years.

Table 14. Separator efficiencies and energy requirement

		separation efficiency					
	flowrate	dry matter	N	P	K	volume reduction	specific energy
	m^3 $hour^{-1}$	%	%	%	%	%	kWh m^{-3}
belt press	3.3	56	32	29	27	29	0.7
decanter centrifuge	10	61	30	65	13	25	3.7
none	0	0	0	0	0	0	0
screw press	11	45	17	20	12	15	1.3
sieve centrifuge	3.7	33	18	15	21	17	4.5
sieve drum	14	41	18	18	17	18	1

The fibre fraction of the digestate may be further processed by composting. This involves an energy requirement supplied by electricity and diesel, which is proportional to the amount of material processed and dependent on the type of composting, open windrow or closed vessel (van Haaren, 2009, Cabaraban et al., 2008, White, 2012, Martínez-Blanco et al., 2009, Finnvedan et al., 2000, Cadena et al., 2009, ROU, 2003). Values used are shown in Table 15. It may not be possible to return fibre fraction to land as a fertiliser/conditioner, due to quality standards or for other regulatory reasons. In this case the fibre fraction must be disposed of e.g. to landfill, which may involve a further requirement for transport.

Table 15. Energy requirement for composting

	electricity (MJ $tonne^{-1}$)	diesel (MJ $tonne^{-1}$)
open windrow	28.4	275.7
closed vessel	214.4	150.6

The liquor fraction may receive further processing in order to make it suitable for recycling or disposal to sewer, if land application is not possible. This has an energy requirement, which can be specified by the user based on the treatment applied.

3.5 GHG emissions

Where energy is expended there will be emission of greenhouse gases. The emissions in this report are presented as CO_2 equivalent which takes into account CO_2, CH_4 and N_2O. Each of these gases has a different global warming potential which can be converted to a CO_2 equivalent by multiplying the amount of each gas by a conversion factor. The relative global warming potentials are shown in Table 16, adapted from IPCC (2007) .

Table 16. Global warming potentials

CO_2	CH_4	N_2O
1	25	298

The emissions produced in the manufacture and supply of each of the embodied materials considered are shown in Table 11. The emission factors used for fuels and energy sources; where electricity, heat or transport fuels are required are shown in Tables 17 and 18.

Table 17. Energy values and emissions (AEA, 2010)

emissions from consumption of fuels	kg CO_{2eq} MJ^{-1}	NCV MJ l^{-1}
diesel oil	0.075	35.73
LPG	0.064	23.33
natural gas	0.057	35.50
Petrol	0.071	32.85

Table 18. GHG emissions for electricity generation (DECC, 2010)

	tonne GWh^{-1}	kg MJ^{-1}
All fossil fuels	598	0.166
All fuels (including nuclear and renewables)	452	0.126
Coal	915	0.254
Gas	405	0.113
Oil	633	0.176

The emission factor for the CHP unit is taken as 0.0553 tonne CO_{2eq} GJ^{-1} biogas consumed (IPCC, 2006). This is mainly CO_2 resulting from combustion plus some unburnt CH_4 and N_2O. The off-gas from the upgrading unit is assumed to be added to the biogas supplied to the CHP unit so does not contribute further to GHG emissions.

Digestate provides a source of nutrients which can be used in crop production. Unlike animal slurries, which are returned to land as part of the farming operation, food waste has not generally been applied to land, but has typically been deposited in landfill or destroyed. In these cases the nutrients removed from the soil are not returned and must be replaced using alternative sources, usually in the form of fossil fuel based mineral fertilisers. The digestate can therefore be considered as a replacement for mineral fertilisers and can substitute the GHG emissions produced during their manufacture. The values of energy required and GHG emissions resulting from the manufacture of mineral fertilisers are shown in Table 19.

Table 19. Fertiliser energy and emissions

	N	P_2O_5	K_2O
GHG (kg CO_2eq kg^{-1})	7.01	1.665	1.735
production energy (MJ kg^{-1} product)	40.3	3.4	7.3
packing & transport (MJ kg^{-1} product)	2.595	2.595	2.595

4 Validation of anaerobic digestion energy balance model

Validation of the anaerobic digestion energy balance modelling tool was carried out by comparing its output with the results from two full-scale AD plants monitored in the VALORGAS project.

4.1 Validation of mesophilic simple AD plant

The tool was used to model a mesophilic, simple AD system which could be compared with the South Shropshire biodigester reported in deliverable D4.2 (VALORGAS, 2012b). Default values were used, apart from for the annual tonnage of source separated food waste (3752 tonnes), the digester size (801 m^3 working volume), the operating temperature (40.2 °C) and the electrical efficiency of the CHP unit (32%). Ambient temperatures for the town of Ludlow were taken from Meoweather.com (2013). A comparison of the results of the modelling with those presented in deliverable D4.2 is given in Table 20.

Table 20. Model of South Shropshire biodigester

	units	model	D4.2	model with reported data
waste	t $year^{-1}$	3752	3752	3752
TS	% of FM	24	27.8	27.8
VS	% of TS	92	88.5	88.5
methane yield	m^3 CH_4 kg^{-1} VS	0.42	0.422	0.422
loading rate	kg VS m^{-3} day^{-1}	2.8	2.54	3.2
methane yield	m^3 $year^{-1}$	347945	355342	389550
CHP electrical capacity	kW	132	195	148
Parasitic electricity	GJ $year^{-1}$	540.3	768.3	540.3
parasitic heat	GJ $year^{-1}$	2167	1397	2161

The results show good agreement with those recorded in deliverable D4.2. The parasitic electrical requirement is higher in deliverable D4.2 as it includes electricity for offices and demonstration rooms not included in the modelling. The parasitic heat requirement in the model is higher than that reported. This is partly due to the way the model derives the size of the pasteuriser, based on a continuous process of small 2-hourly batches rather than a larger pasteuriser (0.7 m^3 modelled compared to 60 m^3 actual); and possibly also due to differences in the thermal conductivity of the digester insulation compared to the values assumed in modelling. Electrical capacity at the plant is higher but this is due to a difference in the method of calculation. The plant has a fixed-capacity installed unit, the size of which will have been based on predicted biogas production allowing for temporal variation and changes in the feedstock. The model does not take these factors into account, but works on the basis of a continuous potential methane yield with no allowance for day-to-day variation. The electrical capacity required based on modelling is further reduced by the slightly lower predicted methane yield. Using the reported values for feedstock characteristics in the model increases the methane yield to 389550 m3, and the CHP unit to 148 kW.

4.2 Validation of thermophilic complex AD plant

The tool was used to model a complex thermophilic system as reported for Lisbon, Portugal in VALORGAS deliverable D4.3 (VALORGAS, 2012a). This system involves pre-processing, digesters operating at 50 °C and post digestion processing including dewatering and composting. Temperatures in the model were set to average Lisbon values (World Weather online, 2013) and the digester capacity was defined by specifying it as equal to that of the Valorsul plant, with two digesters of 3500 m^3 each. A comparison of the results is presented in Table 21.

Table 21. A thermophilic, complex plant

	units	model	D4.3	model with reported data
waste	tonne $year^{-1}$	30496	30496	30496
added water	tonne $year^{-1}$	21758	21758	21758
TS	% of FM	24	28	28
VS	% of TS	92	87.3	87.3
methane yield	m^3 CH_4 kg^{-1} VS	0.42	0.408	0.408
loading rate	kg VS m^{-3} day^{-1}	2.8	2.2	3.1
methane yield	m^3 $year^{-1}$	2828077	3042459	3041412
CHP electrical capacity	kW	1175	1600	1263
Electricity produced	GJ	35101	30456	37749
Parasitic electricity	GJ $year^{-1}$	13280	11588	13410
parasitic heat	GJ $year^{-1}$	8681	7904	8681
diesel for composting	GJ $year^{-1}$	3207	0	0

The parasitic heat requirement in the model is slightly higher than that reported for the plant, probably due to the fact that the model currently does not include heat recirculation. The Valorsul plant uses electricity only in its composting so there is no diesel requirement (Vaz, pers comm 2013). As with the mesophilic plant, the modelled CHP electrical capacity is lower than the installed capacity. This reflects the fact that the size of the plant in the model is based the assumption of uniform biogas production throughout the year. Using the feedstock characteristics reported for the plant rather than the default values, the methane production values are very similar. The difference in loading rate may be explained by the fact that the loading rates reported by Valorsul in D4.3 are based on the volatile solids content of the feed entering the digester, rather than the total mass of volatile solids entering the plant, and therefore do not take account of any solubilisation during the pre-processing stages. The electricity produced is higher than that reported which may imply that the CHP unit at the plant has a lower efficiency than modelled (28.2% rather than 35%), or that some of the electricity produced at the plant is not recorded. In general, however, the modelled values are a good match to those reported for the plant.

4.3 Conclusions from validation

Validation of modelled output against the data sets from two full-scale plants indicated that the modelling tool was capable of accurately simulating their performance, and by extension of a range of anaerobic digestion plants of this or similar types.

5 Anaerobic digestion scenario modelling

The energy balance modelling tool was used to simulate a number of scenarios, as described below.

5.1 Main scenarios

Two sets of scenarios were developed, based on the production of electricity and heat in a CHP unit, and of methane through biogas upgrading. In each case these were run with two alternative assumptions from the three options below:

i) Feedstock quantities of 2,500 or 10,000 tonnes year^{-1}. The first of these is equivalent to the food waste from a population of around 25,000 households, as used in the collections modelling in section 2. The second was chosen to correspond to a medium-size city, or e.g. to four separate towns of 25,000 households, with the aim of indicating any significant differences in the energy balance at these different scales of operation.

ii) Operation of the AD plant at mesophilic (35 °C) or thermophilic (55 °C) temperatures.

iii) Simple or complex digestion process. The simple process consists only of a digester followed by a pasteuriser, with biogas stored in a separate gas-holder and then burnt in a CHP unit, and with digestate storage. The complex process includes pre-processing (assuming e.g. a contaminated initial waste stream which needs to be sorted before digestion), digestate separation and composting. For pre-processing a value of 78.5 MJ tonne^{-1} waste was used, derived from that measured at the Valorsul plant as reported in deliverable D4.3 (VALORGAS, 2012a). This pre-processing energy consumption is in addition to the parasitic energy requirements determined by the waste type digested, and falls within the range of values reported by Bernstad et al. (2013) as shown in Table 22. Where applicable, digestate separation was assumed to be by belt press (Table 14).

Table 22. Pre-treatment energy requirements (adapted from Bernstad et al., 2013)

facility	Energy use (MJ tonne^{-1} waste)	Water use (m^3 tonne^{-1} waste)	reference
A	99.7	0.6	
B	32.8	0.1	(Bernstad et al., 2013)
C	17.6	0	
D	300.6	1.1	
Valorsul plant	78.5	0.7	(VALORGAS, 2012a)

Energy required for transport of the feedstock from a central collection point (e.g. transfer station) to the digestion plant was not included: this option is available in the modelling tool, but in the current study this component of the energy balance was taken into account in the collections modelling in section 2. Energy for transport and application of the digestate as a fertiliser replacement, or for any extra processing where digestate cannot be returned to land, is also not included: these cases are considered separately in section 6.

It was assumed in all cases that the digesters are of steel construction with a separate gas holder (capacity for 2 hours production of biogas). Other assumptions were that pasteurisation occurs after digestion, there is 1% process loss of biogas and the biogas generated is used in CHP units to produce electricity (at 35% conversion efficiency) and heat. The CHP unit has a load factor of 8300 hours. Digestate storage in a steel tank for up to 6 months is included, as is a steel clad building measuring 20 m by 25 m with 3 m walls and 5 m high ridge, to comply with ABPR requirements. Ambient temperatures were based on Southampton (UK).

Scenarios/examples are identified using the following codes:
M = mesophilic, T = Thermophilic

S = simple process, C = complex process
2 = 2500 tonnes waste $year^{-1}$, 10 = 10,000 tonnes waste $year^{-1}$
e = biogas used in CHP unit for electricity/heat generation, u = biogas upgraded to biomethane

So for example MS2e is a mesophilic digester in a simple process plant processing 2,500 tonnes of waste and producing electricity for export.
Unless specified, all loading rates are 4 kg VS m^{-3} day^{-1}.

5.2 Energy balances for electricity and heat production

Summary energy balances for the scenarios based on production of electricity and heat in a CHP unit are shown in Table 23, while detailed results are presented in Tables 24 and 25.

Table 23. Summary energy balances for electricity and heat production

2,500 tonne scenarios		MS2e	MC2e	TS2e	TC2e
energy balance total	GJ $year^{-1}$	4820	4232	4545	3957
	GJ $tonne^{-1}$ waste	1.93	1.69	1.82	1.58
energy balance electrical	GJ $year^{-1}$	1386	798	1249	660
	GJ $tonne^{-1}$ waste	0.55	0.32	0.50	0.26
10,000 tonne scenarios		**MS10e**	**MC10e**	**TS10e**	**TC10e**
energy balance total	GJ $year^{-1}$	19820	17466	19009	16656
	GJ $tonne^{-1}$ waste	1.98	1.75	1.90	1.67
energy balance electrical	GJ $year^{-1}$	5903	3549	5498	3144
	GJ $tonne^{-1}$ waste	0.59	0.35	0.55	0.31

Greater complexity leads to an increase in energy requirement for processing, and increased temperature leads to an increasing demand for heat. In all eight cases the energy available from digesting the waste is sufficient to provide both the electrical and heat energy required for operating the plant with some remaining electricity and heat that can be exported to provide an alternative to fossil fuel based energy sources.

In each case the larger plants (10,000 tonnes) show a slightly higher net energy balance due to the higher volume to surface ratio of the digesters, which thus have smaller heat losses in proportion to the heat supplied. The difference for a 4-fold increase in feedstock volume is not large, however, being equivalent to around 4% of the total: this suggests that smaller local AD plants can be reasonably efficient.

5.3 Energy balances for upgrading to biomethane

Table 26 shows the energy inputs and outputs and process details for AD with upgrading and compression of the biogas. The size of the on-site CHP unit used to provide electricity for the site and heat for the digester and pasteuriser varies according to site requirements. The larger the CHP unit needed for the on-site requirement, the smaller the amount of biogas available for upgrading.In other respects the trends seen are similar to those for electricity production, as expected, with larger plants appearing slightly more efficient than small ones and more complex plants having a lower net energy output than simple.

Table 24. Energy inputs and outputs for electricity and heat production at 2,5000 tonnes waste input

details		MS2e	MC2e	TS2e	TC2e
digester input	tonnes	2500	2500	2500	2500
digester loading rate	kg m^{-3} day^{-1}	4	4	4	4
total digester capacity required	m^3	416	416	416	416
retention time	days	55	55	55	55
methane produced	m^3	231840	231840	231840	231840
methane available	m^3	229522	229522	229522	229522
biogas	m^3	386400	386400	386400	386400
=	tonnes	470	470	470	470
digestate	tonnes	2030	2030	2030	2030
Energy balance ($year^{-1}$)					
pre-processing electricity	GJ	0	196.25	0	196.25
digester electricity requirement	GJ	360	360	360	360
electricity for upgrading	GJ	0.0	0.0	0.0	0.0
electricity for composting	GJ	0.0	16.7	0.0	16.7
heat for digester	GJ	375.7	375.7	683.9	683.9
heat for pasteuriser	GJ	300.9	300.9	130.4	130.4
diesel for composting	GJ	0.0	162.3	0.0	162.3
total	**GJ**	**1036.7**	**1411.9**	**1174.3**	**1549.6**
embodied energy					
digester embodied	GJ	51.2	51.2	51.2	51.2
pasteuriser embodied	GJ	0.7	0.7	0.7	0.7
CHP embodied	GJ	7.4	7.4	7.4	7.4
upgrading embodied	GJ	0.0	0.0	0.0	0.0
gas holder embodied	GJ	1.6	1.6	1.6	1.6
ABPR building embodied	GJ	18.1	18.1	18.1	18.1
digestate storage	GJ	15.4	15.4	15.4	15.4
separator embodied	GJ	0.0	0.2	0.0	0.2
feedtank embodied	GJ	0.2	0.2	0.2	0.2
total	**GJ**	**95**	**95**	**95**	**95**
on-site boiler/CHP		CHP	CHP	CHP	CHP
CHP electrical capacity	kW	96	96	96	96
energy in methane produced	GJ	8305	8305	8305	8305
generated electricity	GJ	2878	2878	2878	2878
generated heat	GJ	4111	4111	4111	4111
imported electricity	GJ	0	0	0	0
imported heat	GJ	0	0	0	0
exported electricity	GJ	2518	2305	2518	2305
	MWh	699	640	699	640
exported heat	GJ	3434	3434	3296	3296
	MWh	954	954	916	916

Table 25. Energy inputs and outputs for electricity and heat production at 10,000 tonnes waste input

		MS10e	MC10e	TS10e	TC10e
details					
digester input	tonnes	10000	10000	10000	10000
digester loading rate	kg m^{-3} day^{-1}	4	4	4	4
total digester capacity required	m^3	1664	1664	1664	1664
retention time	days	55	55	55	55
methane produced	m^3	927360	927360	927360	927360
methane available	m^3	918086	918086	918086	918086
biogas	m^3	1545600	1545600	1545600	1545600
=	tonnes	1880	1880	1880	1880
digestate	tonnes	8120	8120	8120	8120
Energy balance ($year^{-1}$)					
pre-processing electricity	GJ	0	785	0	785
digester electricity requirement	GJ	1440	1440	1440	1440
electricity for upgrading	GJ	0.0	0.0	0.0	0.0
electricity for composting	GJ	0.0	66.8	0.0	66.8
heat for digester	GJ	1325.7	1325.7	2413.2	2413.2
heat for pasteuriser	GJ	1200.0	1200.0	517.9	517.9
diesel for composting	GJ	0.0	649.3	0.0	649.3
total	**GJ**	**3965.7**	**5466.8**	**4371.1**	**5872.1**
embodied energy					
digester embodied	GJ	128.7	128.7	128.7	128.7
pasteuriser embodied	GJ	1.7	1.7	1.7	1.7
CHP embodied	GJ	11.3	11.3	11.3	11.3
upgrading embodied	GJ	0.0	0.0	0.0	0.0
gas holder embodied	GJ	3.1	3.1	3.1	3.1
ABPR building embodied	GJ	18.1	18.1	18.1	18.1
digestate storage	GJ	38.2	38.2	38.2	38.2
separator embodied	GJ	0.0	1.0	0.0	1.0
feedtank embodied	GJ	0.4	0.4	0.4	0.4
total	**GJ**	**201**	**202**	**201**	**202**
on-site boiler/CHP		CHP	CHP	CHP	CHP
CHP electrical capacity	kW	385	385	385	385
energy in methane produced	GJ	33218	33218	33218	33218
generated electricity	GJ	11510	11510	11510	11510
generated heat	GJ	16443	16443	16443	16443
imported electricity	GJ	0	0	0	0
imported heat	GJ	0	0	0	0
exported electricity	GJ	10070	9218	10070	9218
	MWh	2797	2561	2797	2561
exported heat	GJ	13917	13917	13512	13512
	MWh	3866	3866	3754	3754

Table 26. energy inputs and outputs including biogas upgrading and compression

Energy		MS2u	MC2u	TS2u	TC2u	MS10u	MC10u	TS10 u	TC10 u
digester input	tonnes	2500	2500	2500	2500	10000	10000	10000	10000
Energy balance (year^{-1})									
pre-processing electricity	GJ	0	196.25	0	196.25	0	785	0	785
digester electricity requirement	GJ	360	360	360	360	1440	1440	1440	1440
electricity for upgrading	GJ	546.8	463.9	546.8	463.9	2187.3	1855.5	2187.3	1855.5
electricity for composting	GJ	0	184.1	0	184.1	0	736.5	0	736.5
heat for digester	GJ	375.7	375.7	683.9	683.9	1325.7	1325.7	2413.2	2413.2
heat for pasteuriser	GJ	300.9	300.9	130.4	130.4	1200	1200	517.9	517.9
diesel for composting	GJ	0	162.3	0	184.1	0	649.3	0	649.3
total	**GJ**	**1583.5**	**2043.3**	**1721.1**	**2202.7**	**6153**	**7992.1**	**6558.3**	**8397.4**
embodied energy									
total	**GJ**	**111**	**111**	**111**	**111**	**223**	**223**	**223**	**223**
CHP electrical capacity	kW	30	40	30	40	121	161	121	161
energy in methane produced	GJ	8305	8305	8305	8305	33218	33218	33218	33218
generated electricity	GJ	907	1204	907	1204	3627	4817	3627	4817
generated heat	GJ	1295	1720	1295	1720	5182	6882	5182	6882
exported heat	GJ	619	1044	481	906	2656	4356	2251	3950
	MWh	172	290	134	252	738	1210	625	1097
upgraded biomethane	m^3	153808	130479	153808	130479	615233	521916	615233	521916
energy in upgraded CH_4	GJ	5509.4	4673.8	5509.4	4673.8	22037.6	18695	22037.6	18695
diesel equivalent of CH_4	litres	154176	130791	154176	130791	616704	523164	616704	523164
energy balance total [a]	GJ year^{-1}	4434	3563	4158	3266	18318	14836	17507	14025
	GJ tonne^{-1} waste	1.77	1.43	1.66	1.31	1.83	1.48	1.75	1.4
energy balance biomethane [b]	GJ year^{-1}	3815	2520	3677	2360	15662	10480	15256	10075
	GJ tonne^{-1} waste	1.53	1.01	1.47	0.94	1.57	1.05	1.53	1.01

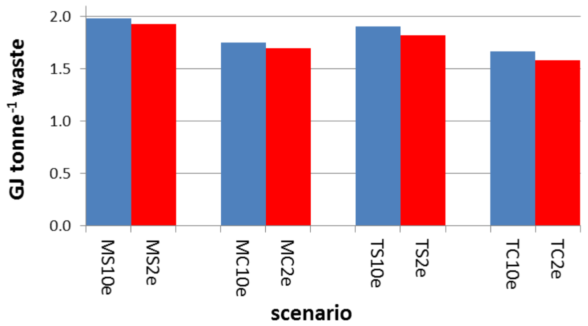
[a] including upgraded biomethane, exported heat

[b] including upgraded biomethane but not exported heat

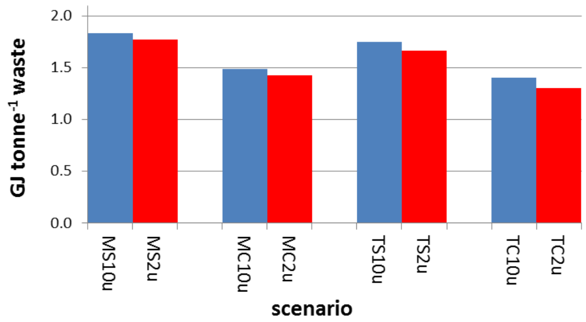
5.4 Comparison of energy balances for electricity and biomethane production

The total exportable energy is slightly higher for scenarios involving electricity and heat production than for biomethane and heat, due to the assumed overall energy conversion efficiencies and embodied energies for the two technologies (Figure 5a and b). In many locations, however, finding a use for surplus heat is highly problematic. Figure 5c and d show the exportable energy in terms of electricity and biomethane only, not taking heat into account.

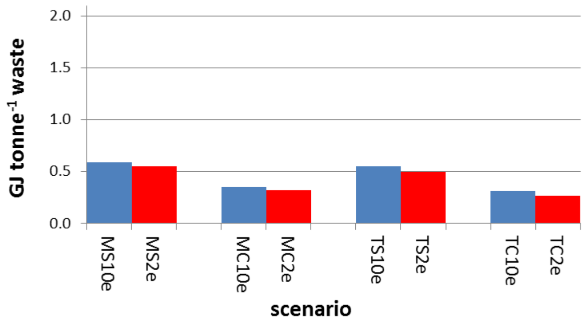
The net energy output for the electricity options is much lower, as electricity produced via CHP accounts for only 35% of the energy in the consumed biogas due to the inefficiency of the CHP unit and the heat produced. Upgrading is more efficient in terms of the energy produced and provides a better source of energy production if there is no use for the heat produced by the CHP unit.



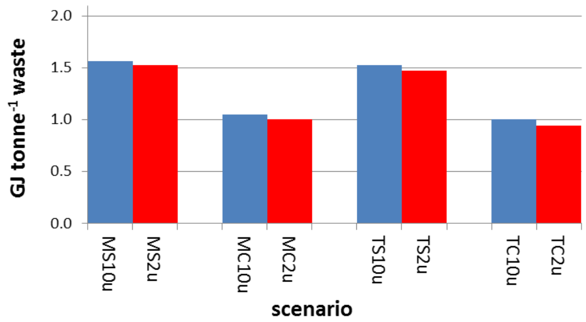
(a) electrical energy and heat



(b) biomethane and heat



(c) electrical energy only



(d) biomethane only

Figure 5. comparison of energy balances for electricity and biomethane production

5.4 GHG emissions

Emissions balances for the four scenarios with electricity production at 2,500 tonnes waste input are given in Table 27, while Figure 6 and Table 28 show the relative emissions savings from various sources at 2,500 and 10,000 tonnes waste input.

The values shown do not include emissions from combustion in the CHP unit since the biogas is produced from a waste source, rather than being a fossil fuel; it is therefore considered to be part of the short carbon cycle and not a net contributor to GHG emissions. Two potential sources of emissions savings are considered here: replacement of electricity generated from fossil and other fuels and replacement of heat generated from fossil fuels. As noted above, however, not all digesters will be located in situations in which the heat can be used.

The high GWP of the methane component means that process losses of biogas are the major component in GHG emissions, and thus an important issue in plant design and operation. They are equivalent to 7% of the emissions savings (Table 27) and their reduction would make a considerable contribution to the effectiveness of the plant in GHG terms.

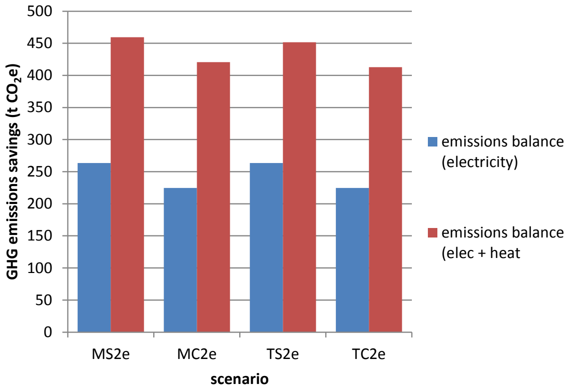
Emissions savings from the 10,000 tonnes scheme are much higher than from the 2,500 tonne (Figure 6), but the values per tonne of waste processed are very similar (Table 28) indicating that small-scale systems are not necessarily inefficient in this respect.

Table 27. Emissions inputs and outputs for electricity production in the 2,500 tonne scenarios

tonne CO_2eq	MS2e	MC2e	TS2e	TS2e
diesel for composting	0.00	12.14	0.00	12.14
embodied carbon ($year^{-1}$)				
digester embodied	3.72	3.72	3.72	3.72
pasteuriser embodied	0.05	0.05	0.05	0.05
CHP embodied	0.41	0.41	0.41	0.41
upgrading embodied	0.00	0.00	0.00	0.00
gas holder embodied	0.13	0.13	0.13	0.13
ABPR building embodied	2.06	2.06	2.06	2.06
digestate storage	1.69	1.69	1.69	1.69
separator embodied	0.00	0.01	0.00	0.01
feedtank embodied	0.03	0.03	0.03	0.03
total	**8.07**	**8.08**	**8.07**	**8.08**
process loss	44.6	44.6	44.6	44.6
exported electricity savings	316.1	289.4	316.1	289.4
exported heat savings	196.1	196.1	188.3	188.3
total emissions	52.7	64.8	52.7	64.8
emission savings (total)	652.4	625.7	644.5	617.8
emissions balance (electricity)	263.4	224.5	263.4	224.5
balance (elec + heat)	459.5	420.6	451.7	412.8

Table 28. emission balances for electricity production

(tonne CO_{2eq} $tonne^{-1}$ waste)	MS2e	MC2e	TS2e	TS2e	MS10e	MC10e	TS10e	TS10e
total emissions	0.021	0.026	0.021	0.026	0.020	0.024	0.020	0.024
emission savings (total)	0.261	0.250	0.258	0.247	0.262	0.251	0.260	0.249
emissions balance (electricity)	0.105	0.090	0.105	0.090	0.107	0.091	0.107	0.091
(electricity + heat)	0.184	0.168	0.181	0.165	0.186	0.171	0.184	0.169



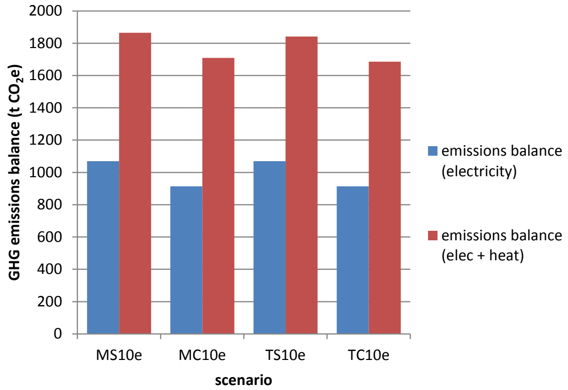


Figure 6. Potential emissions savings from electricity production scenarios

The emissions balances for biogas upgrading and compression options are shown in Table 29. As with the scenarios for electricity production, there is little difference on a per tonne waste basis between the scales of operation. The major difference is between the simple and complex scenarios, and is a result of the higher electricity demand in the complex scenario leading to reduced biogas availability for upgrading. Including the heat export reduces the difference between the simple and complex options, as the increased size of the CHP allows greater potential for heat to be exported.

Table 29. emission balances for biogas upgrading

(tonne CO_{2eq})	MS2u	MC2u	TS2u	TC2u	MS10u	MC10u	TS10u	TC10u
total emissions	54.4	66.5	54.4	66.5	197.4	245.8	197.4	245.8
emission savings (total)	447.3	409.1	439.5	401.2	1799.6	1646.6	1776.4	1623.5
emissions balance								
(biomethane)	358	283	358	283	1451	1152	1451	1152
(biomethane + heat)	393	343	385	335	1602	1401	1579	1378
(tonne CO_{2eq} tonne^{-1} waste)								
total emissions	0.022	0.027	0.022	0.027	0.020	0.025	0.020	0.025
emission savings (total)	0.179	0.164	0.176	0.160	0.180	0.165	0.178	0.162
emissions balance								
(biomethane)	0.143	0.113	0.143	0.113	0.145	0.115	0.145	0.115
(biomethane + heat)	0.157	0.137	0.154	0.134	0.160	0.140	0.158	0.138

5.5 Use of modelling tool to investigate effects of loading rate on energy balance

As an example of its potential applications, the modelling tool was used to investigate the effect of changing the loading rate and feedstock quantities at mesophilic and thermophilic temperatures.

The energy balance for mesophilic systems is slightly higher than for the equivalent thermophilic, for example at 1.98 GJ tonne^{-1} waste compared to 1.90 GJ tonne^{-1} waste for the simple configuration with electricity production and 10,000 tonnes waste input (Table 25). As the amount of waste is the same, this is a result of the increased heat requirement from the feedstock and digester. Increasing the specified loading rate reduces the size of the digester required, thus reducing the heat needed per tonne of waste input. The effect of increasing the loading rate from 4 kg VS m^3 day^{-1} up to 8 on the energy balance per tonne of waste is shown in Figure 7 (m = mesophilic, t = thermophilic).

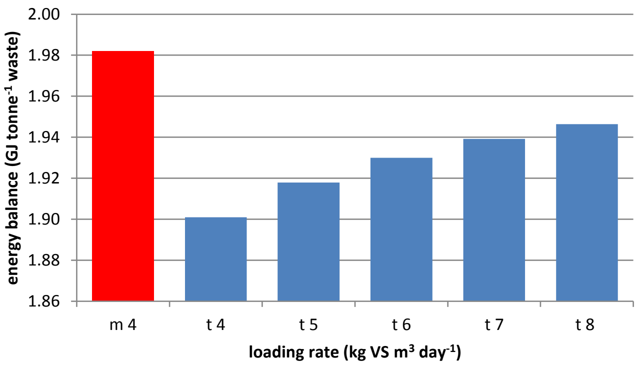


Figure 7. Effect of loading rate on overall energy balance

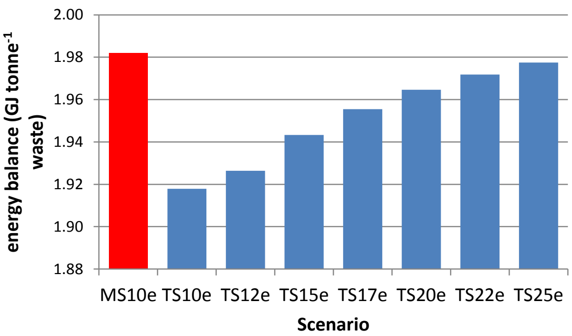
As the loading rate increases the energy balance per tonne of waste approaches that of the mesophilic system, but increasing the loading rate does not reduce the heat required to raise the temperature of the feedstock: this remains the same, depending only on ambient temperature and amount of waste. The degree to which the loading rate can be increased is also limited by the metabolic capacity of the digestion process.

An alternative approach to increase the specific efficiency would be to maintain the digester size and increase the amount of feedstock – thus also increasing the loading rate. An example of this approach to changing loading rates is outlined in Table 30. For this example the digester capacity is maintained at 1664 m^3 and the system assumed is a simple one (M is mesophilic, T thermophilic, MS10e and TS10e are the same as the scenarios above).

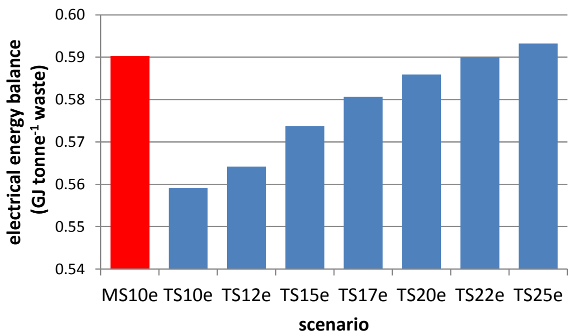
Table 30. Maintaining digester capacity, increasing amount of feedstock

Example	MS10e	TS10e	TS12e	TS15e	TS17e	TS20e	TS22e	TS25e
feedstock (10^3 tonnes $year^{-1}$)	10	10	12.5	15	17.5	20	22.5	25
loading rate (kg VS m^{-3} day^{-1})	4	4	5	6	7	8	9	10

The effect of increasing the amount of feedstock on the overall energy balance is shown in Figure 8a, and on the electrical energy only balance in Figure 8b.



(a) Overall energy balance



(b) Electrical output only energy balance

Figure 8. Overall and electrical energy balances for varying load scenarios

By increasing the amount of feedstock material and the rate of processing (by increasing the loading rate) it is possible for the thermophilic process to achieve similar energy balances per tonne of waste to the mesophilic.

The effect on emissions of changing the loading rate in the thermophilic digesters with the same amount of feedstock material is shown in Figure 9, and the effect on the emissions balance of changing the amount of feedstock but maintaining digester capacity is shown in Figure 10. Changing the loading rate has little effect on emissions, as the amount of energy and fertiliser produced is related to feedstock volume and so remains constant. In all cases, use of the heat as a fossil fuel replacement is required to offset the emissions produced.

While the example considered is relatively trivial, it illustrates the use of the modelling tool in exploring the energy and GHG emission implications of a change in operating conditions.

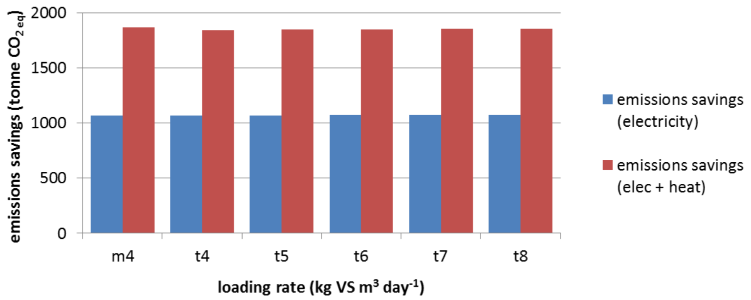


Figure 9. Effect of varying loading rate on emissions balances

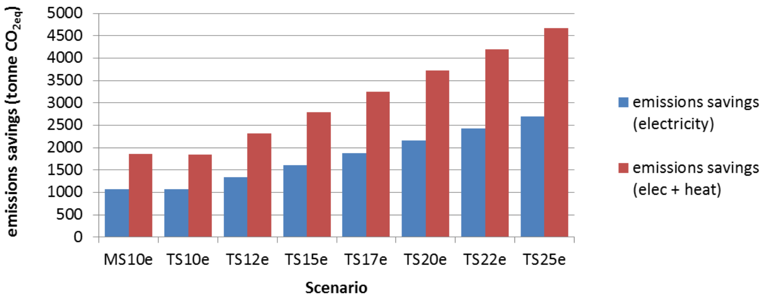


Figure 10. Effect of varying feedstock amount on emissions balances

5.6 Conclusions from scenario modelling

The results of the modelling confirmed that all of the scenarios considered showed a positive energy balance. Thermophilic and complex systems had a slightly lower net energy yield in all cases, and larger systems (higher waste input) had a marginally higher yield than smaller ones, but the differences were not large, due to the relatively high energy inputs available from the produced biogas in comparison with embodied and parasitic requirements in all cases. The main issue was the existence or otherwise of a use for the exportable heat. If the heat can be fully utilised then electricity production shows a marginally higher net energy output; if not then gas upgrading is the more effective option in terms of maximising utilisation of the available energy. GH emission savings are better for upgraded biomethane than CHP electricity production alone but less if the heat generated can be exported as a fossil fuel derived replacement. The values from the anaerobic digestion scenarios with 2,500 tonnes year^{-1} of waste input were taken forward for inclusion in the overall energy balance calculations in section 6.

6 Overall energy and GHG balances from waste to field

The AD model was used to estimate energy and emissions for digestate utilisation based on the values obtained in deliverable D6.2 (VALORGAS, 2013c). The results were combined with output from collections modelling in section 2 to establish overall balances for energy and emissions for the complete system of waste collection, processing and use of digester outputs, as shown in Figure 11.

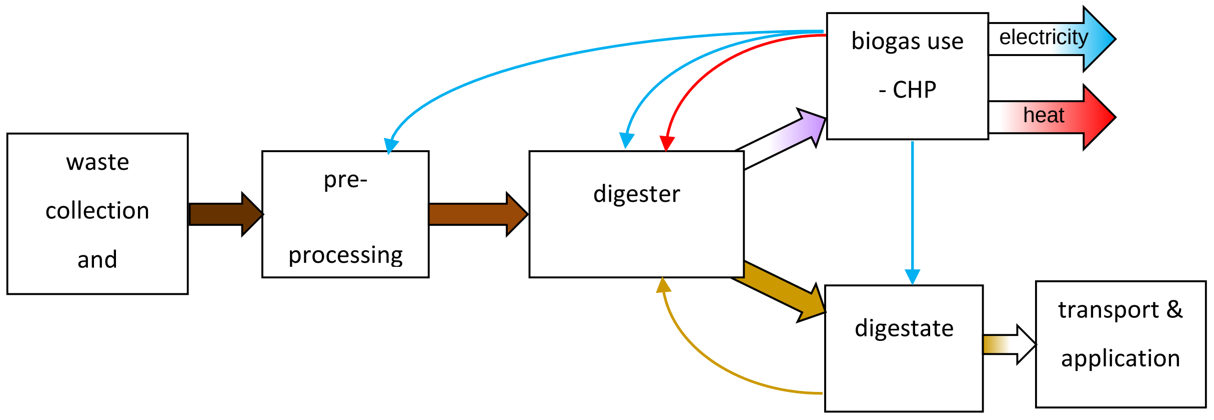


Figure 11. Schematic of overall food waste collection, digestion, gas and digestate utilisation system

6.1 Energy and emissions in digestate transport and utilisation

Energy and emissions factors used for digestate and mineral fertiliser application are shown in Table 31. For the purposes of this study, the farm was assumed to be 30 km away from the site of the digester, with digestate transported to the farm by lorry.

The area required for digestate application is defined by the maximum application rate, which was set at 170 kg N ha^{-1} based on limits for Nitrate Vulnerable Zones (NVZ) in the EU Nitrates directive (91/676/EEC). The nutrient composition of the digestate is based on that the digester feedstock (section 3.1), but the nutrients become more concentrated during the digestion process as the amount of digestate produced is smaller than the original amount of feedstock. The nutrient content of the digestate reported by the model is 9.9 g N kg^{-1} FM, 3.7 g P_2O_5 kg^{-1} FM and 4.9 g K_2O kg^{-1} FM.

Table 31. Energy and emissions in digestate transport and application

	diesel use	emissions (CO_2eq)	embodied energy
mineral fertiliser application	2.9 l ha^{-1} (a)	7.78 kg ha^{-1} (b)	8.5 MJ ha^{-1} (c)
digestate transport	2.07 MJ $tonne^{-1}$ km^{-1} (d)	0.155 kg $tonne^{-1}$ km^{-1} (b)	36.27 GJ $year^{-1}$ (d)
whole digestate/liquor application	3.8 l ha^{-1} (a)	10.2 kg ha^{-1} (b)	42.8 MJ ha^{-1} (c)
fibre fraction application	9.5 l ha^{-1} (c)	25.5 kg ha^{-1} (b)	47 MJ ha^{-1} (c)

(a) VALORGAS (2013c), (b) 0.075 kg CO_2e MJ^{-1} diesel (AEA, 2010), (c) Salter (2011) (d) Section 2

When applied to a field the digestate was assumed to replace fossil fuel based mineral nitrogen fertiliser which would require 42.9 MJ kg^{-1} to produce and deliver to site with an emission value of 6.81 kg CO_{2eq} kg^{-1} N (Mortimer et al., 2010). For the purposes of the current study energy and GHG emissions savings were based on N fertiliser substitution only, as this is the most significant component in terms of fossil fuel replacement and was used as the limiting factor for land application.

6.2 Overall balances

The energy and emission balances presented in this section are based on 2,500 tonnes year^{-1} of waste incurring an additional collection energy of 1500 GJ year^{-1} and 70 tonnes CO_{2eq} year^{-1}, as derived in section 2. This is combined with the results of the scenarios for 2,500 tonnes of waste input from section 5. The resulting whole system scenarios are summarised in Table 32, where M and T represent mesophilic and thermophilic, S and C simple and complex, and e and u electricity production and gas upgrading options, as before..

Table 32. Whole system scenarios

	WMSe / WMSu	WMCe / WMCu	WTSe / WTSu	WTCe / WTCu
collection	yes (including transport from waste transfer station)			
pretreatment	no	yes	no	yes
digestion	mesophilic	mesophilic	thermophilic	thermophilic
digestate treatment	simple (none)	complex (separation, composting)	simple (none)	complex (separation, composting)
digestate application	single	separate fibre and liquor applications	single	separate fibre and liquor applications

In all cases the 2030 tonnes of digestate produced is enough to provide the nitrogen requirement for 118 ha of crop. In the simple case this is just transported and applied. In the complex case it is separated and the fibre fraction is composted, leading to a further reduction in mass; both fractions are then returned to land in separate applications. The energy requirements for transport and application in this case are shown in Table 33.

The digestate is assumed to replace 20,060 kg of fossil fuel based nitrogen which would require 860 GJ to produce and deliver with an emission value of 136.6 tonnes CO_{2eq} kg^{-1}.

Table 33. Digestate transport and application

	amount (tonnes)	transport (GJ)	transport (tonne CO_{2eq})	application (GJ)	application (tonne CO_{2eq})	embodied energy (GJ)
simple	2030	126.1	9.44	16.1	1.20	41.3
complex - liquor	1441	89.5	6.70	16.1	1.20	41.3
complex - fibre	294.5	18.2	1.37	40.1	3.01	41.3

6.2.1 Energy balances

The results for production of electricity/biomethane only, electricity/biomethane and heat, electricity/biomethane and fertiliser replacement, and electricity/biomethane, heat and fertiliser are shown in Table 34 and Figure 12. In each of the scenarios considered production of electricity only would lead to a negative energy balance (more energy consumed in collection, processing and transport than is available for export as electricity). In these cases, however, export of between 10 and 33% of the available heat would be sufficient to reach a neutral balance. In the complex scenarios, production of electricity and fertiliser also shows a slight negative balance. The balances for biomethane production are positive in all cases. As before, increased complexity or digestion temperature reduces the overall energy balance; while if all of the heat can be utilised production of electricity gives a marginally higher balance than gas upgrading for biomethane under the conditions assumed.

Separation of digestate into liquid and solid fractions incurs higher energy costs for processing, transport and application, despite the mass reduction in the solid component. This may partly reflect the fact that in food waste digestion the solids breakdown is high, and the residual mass reduction in composting is relatively small. Digestate separation may, however, be necessary for certain application techniques to be used.

Table 34. Whole system energy results based on 2500 tonnes waste year^{-1}

(GJ)	WMSe	WMCe	WTSe	WTCe	WMSu	WMCu	WTSu	WTCu
collection inc. embodied	1500	1500	1500	1500	1500	1500	1500	1500
digestion inc. embodied	1131	1507	1269	1644	1695	2154	1832	2314
digestate transport & application inc. embodied	184	247	184	247	184	247	184	247
exported electricity / biomethane	2518	2305	2518	2305	5509	4674	5509	4674
exported heat	3434	3434	3296	3296	619	1044	481	906
mineral N fertiliser replaced	860	860	860	860	860	860	860	860
Total energy balance	3997	3345	3721	3070	3609	2677	3334	2379

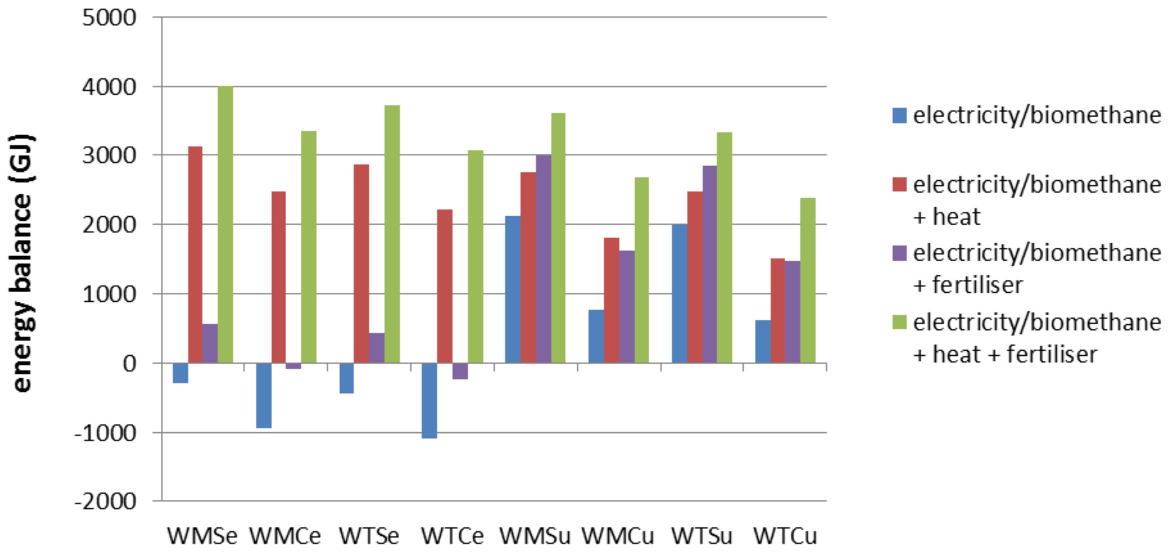


Figure 12. Whole system energy balances.

6.2.2 GHG emissions

The results for GHG emissions are shown in Table 35. In all cases the emissions saved through replacement of electricity, heat and mineral fertiliser are greater than those created by the collection of the waste, construction and operation of the digester, digestate use and from combustion of the biogas in the CHP unit. Effectively this means that the process may have a value in terms of GHG abatement, even without net energy production: if other disposal routes such as landfill may lead to uncontrolled methane losses the benefit will be correspondingly higher.

Process losses of biogas (losses in the digestion plant before combustion) make up 31% of the emissions and their reduction would make the scenarios even more beneficial in terms of emissions savings. The relative emissions savings resulting from the replacement of electricity, heat and fertilisers produced from fossil fuels are shown in Figure 13.

Table 35. Whole system GHG emissions

(tonnes CO_2eq)	WMSe	WMCe	WTSe	WTCe	WMSu	WMCu	WTSu	WTCu
collection inc. embodied	70	70	70	70	70	70	70	70
digestion inc. embodied	52.7	64.8	52.7	64.8	54.4	66.5	54.4	68.1
digestate transport & application inc. embodied	9.64	12.28	9.64	12.28	9.64	12.28	9.64	12.28
process losses	44.6	44.6	44.6	44.6	44.6	44.6	44.6	44.6
replaced grid-produced electricity / diesel fuel	316.1	289.4	316.1	289.4	412	349.5	412	349.5
replaced fossil fuel based heat	196.1	196.1	188.3	188.3	35.3	59.6	27.5	51.7
replaced mineral N fertiliser	140.2	140.2	140.2	140.2	140.2	140.2	140.2	140.2
Total emissions savings	475.5	434.0	467.7	426.2	408.9	355.9	401.1	346.4

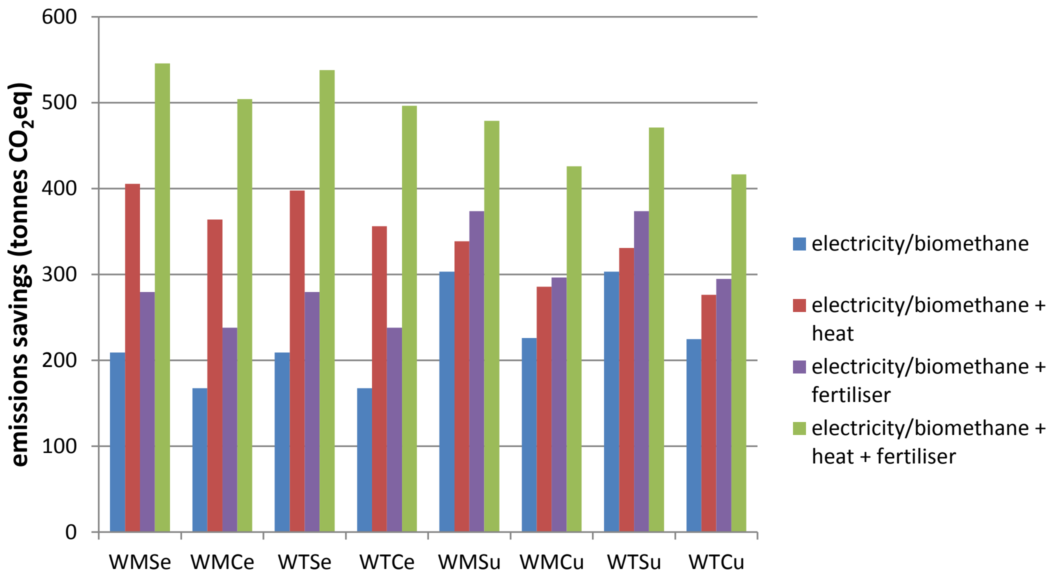


Figure 13. Whole system emissions savings

Mineral fertiliser replacement makes up between 28 and 40% of the net savings in GHG emissions (Figure 14). The emission savings in the case of the complex digester processes are lower, due to the extra processing of waste input and digestate output for production of the same amount of fertiliser; so fertiliser replacement makes up a larger part of the savings in these cases. There is little difference between thermophilic and mesophilic operation in these scenarios.

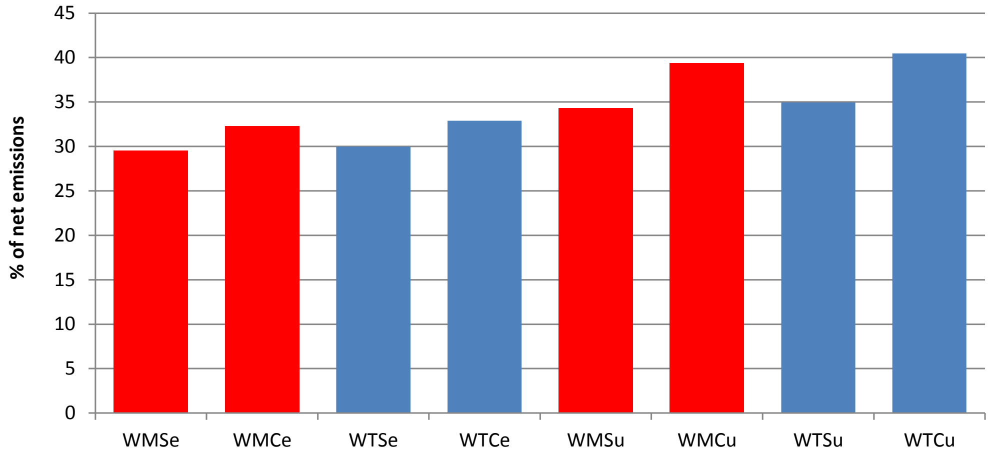


Figure 14. Mineral fertiliser replacement as % of net GHG emission savings

6.2.3 Operation without digestate re-use

In some cases it is not possible to return the digestate to land, for example due to local farming practice; soil or hydrological conditions; regulatory requirements; or unacceptable levels of contamination. The digestate therefore cannot be credited as a mineral fertiliser replacement in the energy and emissions balances. In this situation it is assumed that the digestate is separated into solid and liquid fractions (complex case) and the liquid fraction is treated to an acceptable standard for recycling or discharge to sewer at an assumed energy cost of 48 MJ $tonne^{-1}$ liquor (VALORGAS, 2012a). The fibre fraction of the digestate is assumed to be transported 30 km to a landfill site for disposal, with no further processing requirements.

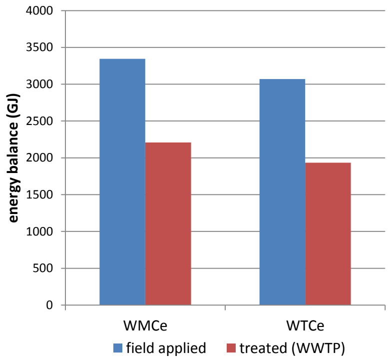
The energy input and outputs for these scenarios are shown in Table 36, and the emission balances in Table 37. These only apply to the complex digestion scenarios; in the simple scenarios the digestate receives no post-treatment. It can be seen that the total energy balance, while lower than with digestate utilisation, is still positive. Figure 15 shows the comparative energy and emission balances for the whole systems with either application of the liquor and fibre fractions of the digestate to field, or separation and treatment and disposal of the two fractions.

Table 36. Input and output energy for separated digestate without utilisation

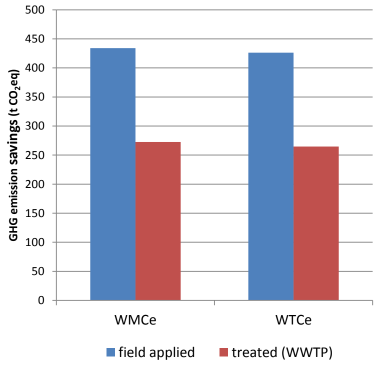
(GJ)	WMCe no digestate use	WTCe no digestate use
collection (including embodied)	1500	1500
digestion (including embodied)	1743	1881
digestate transport & application (inc embodied)	49.3	49.3
exported electricity	2068	2068
exported heat	3434	3296
mineral N fertiliser replaced	0	0
Total energy balance	2210	1934

Table 37. Emission balances for separated digestate without utilisation

(tonne CO_2eq)	WMCe no digestate use	WTCe no digestate use
collection inc. embodied	70	70
digestion inc. embodied	64.8	64.8
digestate transport & application (inc. embodied)	3.68	3.68
process losses	44.6	44.6
replaced grid produced electricity	259.6	259.6
replaced fossil fuel based heat	196.1	188.3
mineral N fertiliser replaced	0	0
Total emissions savings	272.6	264.8



(a) energy balances



(b) emission savings

Figure 15. Energy and emission balances

Treating the liquor rather than using it as a nutrient source for crop production reduces the energy balance by 25% (through increased use in the plant reducing the exportable electricity fraction) and the emissions savings by 30% through reduced electricity for export and non-substitution of fossil fuel based fertiliser.

6.3 Discussion and conclusions for whole system assessment

In almost all of the cases considered in this section the net energy production is positive, i.e. the energy derived from the collection, transport and anaerobic digestion of food waste including pre and post-processing and utilisation of the digestate and energy products is greater than the fossil fuel derived energy consumed. The only exceptions to this are where the biogas is used to produce electricity via CHP with no potential to export the heat. This is due to the relatively low energy conversion efficiency for electricity (35%), and can be compensated for by the use of approximately 30% of the heat generated. All of the scenarios involving upgrading of biogas to methane show a positive energy balance, indicating this is a rational means of valorisation especially for small-scale distributed sources of waste.

In all cases considered there is a net savings in terms of GHG emissions through replacement of fossil fuel generated energy. This is to be expected, as relatively small amounts of fossil fuel energy are being consumed compared to the amount of energy generated as electricity, heat or biomethane.

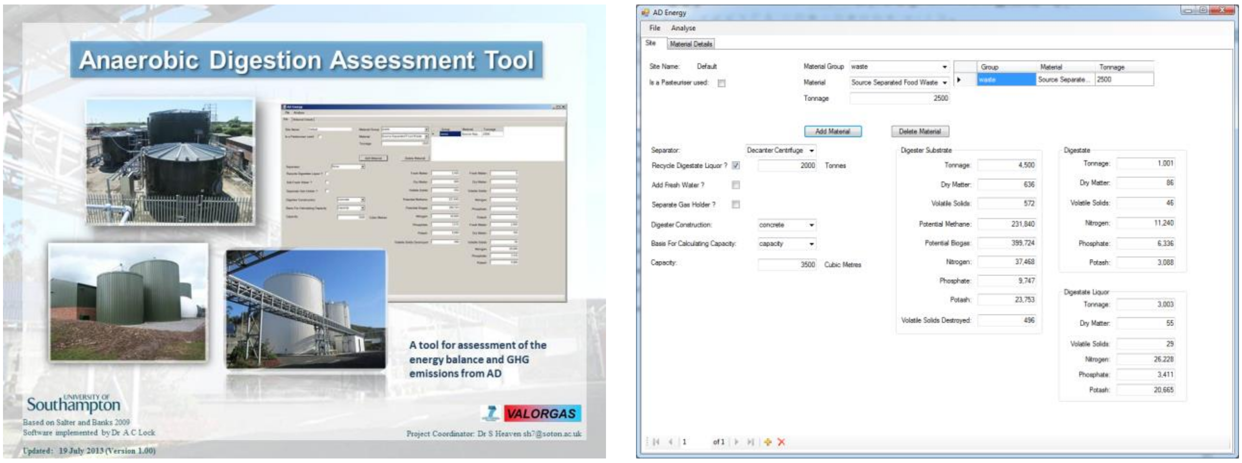
The current scenarios considered small-scale plants with an input of 2,500 tonnes year^{-1} of source segregated domestic food waste. Larger schemes processing more waste may show energy balances that are slightly higher, due to minor increases in efficiency with scale. Further modelling would be needed, however, to consider the effect of any increase in the transport distances required for collection and transfer of the extra waste to a single, centralised digester compared to a distributed digester system (see deliverable D2.5, VALORGAS 2012).

As noted in section 2, energy and emissions in collection and transport depend on a wide range of factors, including ones such as population density and terrain that are specific to the location and cannot easily be 'optimised'. The indications from the current whole system assessment, however, are that the energy potential of food waste as a feedstock for anaerobic digestion is sufficient to give positive energy and GHG emissions balance in any of a variety of typical scenarios. The value of the modelling approach is that it allows assessment of the consequences of choosing options such as mesophilic or thermophilic temperatures, and simple or complex operation with or without export of heat and utilisation of digestate as a fertiliser replacement.

The VALORGAS project is funded under the EU FP7 Energy programme and its main focus is thus on food waste as a substrate for energy production. As noted in the EC's Communication on biowaste management (COM(2010)235), however, appropriate treatment of organic wastes can contribute to meeting other environmental objectives, and often offers one of the most cost-effective solutions. Fertiliser substitution provides an example of this, and is the reason that nutirents were included in the assessment carried out for the VALORGAS project. Nutrients from the soil are incorporated into crops, which are used either directly for human consumption or as feed for livestock: in either case a proportion is exported from the farm. Wastes are generated along the food supply chain, and if the nutrients in these are not captured and returned to the fields then they must be must be replaced from finite resources and/or through the use of fossil fuels. Collection, treatment and application of digestate is a means of returning the nutrients and completing the cycle, and is thus of value in its own right provided that the resulting energy requirements and GHG emissions are lower than those produced from the use of fossil fuels.

6.4 AD assessment tool

As part of the VALORGAS project, the modelling tool has also been encoded as a C# program to facilitate rapid testing of multiple scenarios. When used as a companion software package to the WasteCAT tool, this allows modelling of a very wide range of waste collection and anaerobic digestion scenarios. Figure 16 shows some screenshots from the Anaerobic Digestion Assessment Tool, while tables showing the main user-specified inputs, default values and constants are presented in Appendix 1. The software version of the model is embargoed from general release until January 2014 to allow beta testing by 'external' users (i.e. users not directly involved in creation of the tool); but together with the original tool as described in Salter (2013) it forms an important component in the project's exploitation strategy (deliverable D1.8, VALORGAS 2013d).



(a) Cover page

(b) Screenshot of opening screen

Figure 16. AD assessment modelling tool

As with the WasteCAT model, the outputs from the WasteAD modelling tool can be used to estimate economic costs and payback periods. In the earliest planning stages of the project, however, a deliberate decision was taken not to include this as an output or deliverable: VALORGAS is a pan-European project and it is clear that amongst the member states (or even the project partner countries) there are too many different tariffs, subsidies, local regulations and variations in exchange rate etc to make cost-based outputs useful or reliable. The tool has therefore been specifically developed to present the results in terms of readily quantifiable components such as energy, GHG emissions and nutrients, and thus to provide a robust and durable basis for both economic and life cycle assessment. Examples of how modelling tools of this type can be used for these purposes, and even as a basis for the estimation of marginal abatement costs of GHG emissions, are given e.g. in Jain et al. (2012) and Jain (2013).

7 Conclusions

The model makes it possible to examine a range of scenarios for the same waste inputs, in order to determine which option may provide the most energy or GHG efficient system. Modelling based on literature and reported values gave similar results to those for both of the full-scale plants monitored in the VALORGAs project, indicating the modelling tool is robust and reliable.

The majority of the typical scenarios considered showed positive energy and GHG emissions balances. Scenarios based on electricity production alone without utilisation of heat or digestate are likely to be energy negative. Collection systems operating in very sparsely populated areas with large transport distances may also show reduced or even negative energy balances, while digesters with larger throughput may benefit from improved efficiency. Systems based on production of biomethane showed a positive balance under all the conditions considered, providing further justification for the focus on small-scale gas upgrading and utilisation within the current project. The work reported here focusses mainly on the energy balance, as this is the main goal of the VALORGAS project; but the approaches adopted can be used to support decisions based on a wide range of factors in terms of cost, resources and environmental impact. The output from scenario modelling is not a single answer that will be correct in all cases: the optimum solution for a given scheme is dependent on its specific features, and in practice selection will be strongly influenced by cost and acceptability. The combined modelling tools provide a means of exploring the consequences of different choices in terms of energy, GHG emissions and nutrient, and thus offers support to the decision-making process.

In conclusion it appears that valorisation of food waste to biogas is an effective means of both energy production and environmental benefit. The current work has delivered two tools that can be used in conjunction to make a rational assessment of the energy and environmental benefits of alternative schemes.

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