UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING AND THE ENVIRONMENT

Automating Bus Stop Dwell Time Measurements for London Buses Using iBus

by

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ABSTRACT

FACULTY OF ENGINEERING AND THE ENVIRONMENT

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iBus is Transport for London (TfL)'s GPS-enhanced Automatic Vehicle Location System, which has been rolled out to the entire contracted fleet of over 8,500 buses across London, and resulted in efficiencies in fleet management, improvements in bus waiting times, and provided improved real-time information for passengers. The System resides on board each vehicle, as well as in operators' bus garages and at the main TfL Control Centre, and records a number of on-street events relating to for example buses' entry and exit into stop zones, when their doors opened and closed, and their location and speed in real-time. This information, which is collected in the 'log' files of every vehicle, provided an opportunity to develop further uses for the System, including an alternative method for measuring bus stop dwell times. Historically, dwell times in London have been obtained using manual road-side surveys, which are relatively expensive, and therefore occur infrequently. However, dwell times and their variability are important to bus operations, network planning and traffic management, and they can affect the ability of urban traffic control systems such as SCOOT to provide buses with priority at traffic signals, which reduces their effectiveness. An alternative method for measuring dwell times using iBus therefore offers many benefits for TfL, provided a process could be determined and largely automated, as the dwell values are not recorded directly by the System, which is relatively complex. A knowledge base of the bus log files therefore had to be developed, and was tested to allow different algorithms, flow charts and programs to be produced for deriving dwell times, based on a sequence of different vehicle speed, stop zone and door events. An experiment was also conducted to validate the dwell times obtained through this method against video data obtained of vehicles stopping on street, which showed a close match between when the vehicle speeds are zero and roadside dwell, although another method, using the duration between when doors opened and closed, provided a close approximation, particularly when an offset value is accounted for. The dwell times obtained through the 'speed zero' method in the experiment were then analysed, and this showed wide variations between different bus stops and routes, which are consistent with previous surveys in London, and suggests that generalised values of dwell are inadequate for most applications. The analysis also showed that the dwell time variation by time-of-day is more complex than a traditional morning and afternoon peak, which may reflect changes in ticketing, vehicle modernisation, and the demand made by different types of bus passengers in recent years.

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DECLARATION OF AUTHORSHIP

I, Alan WONG, declare that the thesis entitled:

Automating Bus Stop Dwell Time Measurements for London Buses Using iBus

and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research. I confirm that:

- this work was done wholly or mainly while in candidature for a research degree at this University;
- 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;
- where I have consulted the published work of others, this is always clearly attributed;
- where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
- I have acknowledged all main sources of help;
- where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself; and
- none of this work has been published before submission.

Signed: …………………………………………………………………………..

Date:…………………………………………………..…………………….

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This work is dedicated to my Mother.

DEFINITIONS AND ABBREVIATIONS

AIMSUN	Advanced Interactive Microscopic Simulator for Urban and Non-urban Networks.
APC	Automatic Passenger Counting (technology).
AVL	Automatic Vehicle Location (system).
BVARY	The Bus Vary parameter used in SCOOT.
CentreComm	TfL's Transport (including bus network) Control Centre in London.
Control Centre	The operations room where bus fleet managers reside, and where bus services and vehicles are managed on a day-to-day basis.
CORSIM	CORnell Microsimulation Model.
Cv	Coefficient of Variation.
DDM	iBus Depot data Manager.
DfT	The Department for Transport.
DRACULA	Dynamic Route Assignment Combining User Learning and microsimulAtion.
EngD	The ENGineering Doctorate.
ETM	Electronic ticketing Machine.
EWT	Excess Waiting Time, a measure of bus service performance.
FTP	File Transfer Protocol.
GLA	Greater London Assembly.
GPS	Global Positioning System(s).
HCM	Highway Capacity Model.
IBIS (Plus) **Unit**	The iBus device that resides on board vehicles.
iBus	The intelligent AVL system used for London buses, which includes components on board vehicles, at bus garages, and at various TfL (and System hosting) locations.
IQR	Inter-Quartile Range.
ITS	Intelligent Transport Systems.
London Buses	London Bus Services Limited, a division of TfL (Transport Trading Limited), and the legal entity which regulates and controls bus services in London.
LRD	iBus London Reporting Database.
LTDS	London Travel Demand Survey.
MSE	Mean Squared Error.
OBU	On Board Unit.
Paramics	PARAllel MICroscopic simulation.
RTPI	Real-Time Passnger Information.
SCOOT	Split Cycle Offset Optimisation Technique.
SMARTEST	Simulation Modelling Applied to Road Transport European Scheme Tests.
SPRINT	Selective PRIority Network Technique.
SVD	Selective Vehicle Detection.
TCQSM	Transit Capacity and Quality of Service Manual.
TfL	Transport for London.
TRB	Transportation Research Board.
TRG	Transportation Research Group, at the University of Southampton.
TRL	Transport Research Laboratory Ltd.
TSG	The Technical Services Group (within TfL).
TVN	Technical Vehicle Number used in iBus.
UTC	Urban Traffic Control system.
VISSIM	Verkehr In Städten - SIMulationsmodell" (German for 'Traffic in cities - simulation model')
WLAN	Wireless Local Area Network.

Definitions and Abbreviations Used in This Study

Boarding Time	The time taken for passengers to board and alight, as distinct from separate board or alight times.
Bus Log File	The .saf or statistical analysis file recorded by every iBus vehicle for each block of trips outside the garage.
Data Item	General term for each item of data held in the bus log files (.saf).
Daytime	The main daytime period, as defined by TfL (7am-7pm).
Dead Time	The residual time for vehicles to remain stationary at bus stops, excluding the Boarding Time. Includes the period for doors to physically open and close, and other reasons why a vehicle may remain stationary at bus stopsm, i.e. not directly associated with the boarding/alighting of passengers.
DNS	Did Not Stop - cases where a vehicle did not stop at a bus stop.
Doors Opened / Closed	Operation of the door release / close button for an iBus vehicle.
Dwell Time	The time period that a bus spends stationary at a bus stop for the purpose of serving passengers.
Halt	Events generated in iBus when a vehicle has come to a stop below a certain speed threshold (2 km/h by default) for a period of 5 seconds or longer, and its speed then climbed above this threshold for 1s or more.
Inter-Peak	The period between the AM (morning) and the PM (evening) Peak hours.
Peak (or Rush Hour)	The busiest part(s) of weekdays in terms of passenger demand / numbers, which is characterises by commuters travelling to and/from work.
Region	Urban, Suburban or Rural Areas; with Urban subdivided into the West End or City of London (i.e. Central London) areas, and Suburban covering both Inner and Outer London.
Speed Zero	Cases where the vehicle speed, as used in the bus log file of iBus vehicles, is recorded as zero km/h.
Stop Zone	The bus stop area defined within iBus, cf. the bus stop cages to be found on-street.
Weekdays	Mondays to Fridays inclusive, apart from National Holidays and Bank Holidays in the U.K.

Chapter 1 Introduction

1.1 Background of the Research

Transport for London (TfL) is one of the largest public transport providers in Great Britain, accounting for almost half of all bus passenger journeys taken in England in 2010/11, and over 480 Million Vehicle Kilometres travelled annually (DfT, 2011). Through competitive contract tendering, and network oversight from operating divisions and subsidiaries such as London Bus Services Limited, TfL (2010a) manages over 8,000 buses, 700 routes and 19,500 bus stops throughout Greater London. TfL (Amaral et al., 2008) plans the routes, specifies the required frequencies and monitors the quality of service provided by franchised operators, which include Go-Ahead, Arriva (formerly T. Cowie), Stagecoach, Metroline, First, Abellio and Transdev. As owner of the franchise contracts, TfL can also dictate other features required for the operators' services, including characteristic red vehicle branding, and the use of specific Intelligent Transport Systems and technology, such as "iBus".
iBus is an enhanced Automated Vehicle Location (AVL) System, which was rolled out across the entire TfL-contracted fleet of vehicles between 2007 and 2009, and formed part of an £117 Million investment programme (TfL, 2010a) in vehicle-related systems and associated road-side infrastructure, which was required to help manage an expanding bus network, and enable more routes and services to be provided to meet a long-term predicted growth in passenger demand in London (TfL, 2006a).

The System is based on an AVL package originally supplied by Siemens VDO (now Trapeze ITS), which was customised and extended to suit TfL's wide-scale corporate needs, for example (TfL, 2008a) to improve the quality of service for bus passengers, by reducing delays through giving buses priority at traffic signals, and provide more timely vehicle arrivals information at bus stops, e.g. through the associated and enriched "Countdown" system. The System software and equipment (Wong and Hounsell, 2010) resides "on board" each vehicle, as well as in operators' bus garages and their Control Centres, and at CentreComm - TfL's overall bus network Control Centre in Southwark. The System components are connected through mobile and radio communication networks between vehicles and the Control Centres, and by dedicated electronic links between operators' garages, CentreComm and a separate "data centre", which houses the iBus databases that are used for information storage, historical data analysis, and management reporting.

The implementation of the System, along with other associated measures, has already resulted (ibid) in improvements to bus service operations, reduced waiting times and enhanced the real-time information being provided to passengers. For example, the System includes real-time graphical visualisation software, which enables TfL (and fleet managers in operator Control Centres) to determine the location of vehicles at all times, and take remedial action to maintain the required frequency between buses. The System also communicates with "SCOOT" and other signal control systems to enable buses to be given extra green time or other priority at traffic junctions, which has reduce the journey time delays while in transit. The challenge increasingly for TfL however is to develop further applications from iBus, which maximise on the use of real-time and historical statistics data captured through the System, that in turn may be used to enhance service performance management, reduce costs, provide additional returns on investment, and thereby further improve bus operations in London.

One area where the archived information stored by iBus, which is captured by vehicles on-street in real-time, could potentially be applied is in the derivation of bus stop dwell times. Dwell times form an important constituent in bus journey times, and are major determinants in bus scheduling, journey time planning and for public transport modelling (Fernandez and Burgos, 2004). More importantly, their variability has a profound effect on the reliability of bus service operations (Liu and Sinha, 2007) and the effective provision of bus priority at traffic signals (Hounsell et al., 2004), where delays from an intervening stop between the vehicle detector and the signal stop line could negate the benefit of any extra green time given to buses.

1.2 Statement of Problem

Dwell times have historically been measured in London using manual road-side surveys, which are relatively expensive as they involve large teams of surveyors, and therefore tend to occur infrequently and only for certain routes, e.g. in 1993 (York, 1993) and 2002 (London Buses, 2003). While other methods, for example video surveillance, could be used to measure dwell times, they tend to be labour intensive also, e.g. they require the bus stopping durations to be manually transposed from video. The development of an iBus-derived method, assuming this could be largely automated, therefore provides an on-street sourced alternative to expensive road-side surveys, and it creates the potential for London bus stop dwell times to be measured more widely, easily, and cheaply in future. However, at the time of instigation, the ability to measure, or extract and derive bus stop dwell times automatically from iBus is neither simple nor straightforward. While a vehicle may be "observed" to be stationary at a bus stop through iBus in real-time, dwell time duration values are not captured explicitly or stored by the System retrospectively, and a method for their derivation needs to be determined.

In addition, iBus is a large, technically complex, and widely distributed System, which is integrated with other TfL systems. While some proprietary specifications from the original System supplier are available, these do not provide a suggested method for automating dwell time measurements. The specifications also tend to be technical in nature, i.e. not aimed at business users in TfL bus operations, which leads to complications in understanding precisely what information is stored within the System relating to dwell time, its level of accuracy, and how the data could be usefully applied. Extensive data analysis and field testing is therefore required to build up a detailed knowledge framework of the System, and to evaluate the possible methods for deriving dwell times. In the absence of definitive guidelines, TfL (Robinson, 2009) have also started to explore separate "Running Time" reports from iBus, which take into account bus stop dwell times. However, these assume that the reporting method employed, which is largely based on vehicle door open and close times, provides reasonable estimate of dwell times, and the potential use of this method therefore also needs to be evaluated.

1.3 Benefits

A reliable method for measuring bus stop dwell times has direct benefits for the operation of bus priority at traffic signals in London. At present, the vehicle delay savings from priority can be limited where bus stops are close to the traffic signal stop line (Hounsell et al., 2004). This is because traffic signal control systems need to account for the average bus journey time from the point of vehicle detection to the signal stop line in order to optimise on the priority strategy being given to the bus, which can be in the form of a green time "extension" to allow the bus to pass the signal, or a "recall" of the other traffic stages to reduce the vehicle's waiting time at the junction (Bretherton et al., 1996). However, the extra dwell time incurred by buses due to an intervening stop adds further variation and unpredictability to the estimated journey time (Hounsell et al., 2008a), which disrupts the effectiveness of signal control systems to provide delay savings. While it is sometimes possible to relocate bus stops further upstream from the junctions, i.e. before the detectors, this is often not feasible due to the road layout, or it is not desirable for passengers, particularly given TfL (2006b)'s policy to improve accessibility by siting bus stops at 400 metres apart or less. The ability to provide on-street based estimates of dwell times and their variability, without the need to conduct expensive road-side surveys, would therefore allows traffic signal control systems to account for the extra delay due to bus stops, and improve the operation and benefits from bus priority at signals.

The measurement method could also be used to provide dwell times to improve other aspects of London public transport operations, and in traffic management, transportation planning and simulation modelling. For example, dwell times form an important component in bus journey times or average speeds (Hounsell, 2004). Estimates derived through this method could therefore provide an improved understanding of the expected delay of vehicles at bus stops, as well as their impact on other traffic, and therefore help predict more effectively the overall journey times for buses and other vehicles between two points, which is useful for bus scheduling, day-to-day traffic management and the planning of new transport schemes.

The variability in dwell times can also impact significantly on the "regularity" or headway between buses (Hounsell et al., 2012), which in turn affects "excess waiting time" (EWT), a key parameter used to measure London bus service performance. TfL's franchises are structured to reward operators for exceeding "standard" performance, as measured by EWT reliability, which according to one operator can add a further 20% to contract values, running into millions of pounds annually, while deductions are made for unreliability, as well as lost mileage. A method to provide consistent dwell time measurements would therefore help improve the analysis of service performance variations, to the benefit of TfL and bus operators. (See Section 2.4 for a more detailed discussion of how measured dwell times may be applied.)

1.4 Aims and Objectives

1.4.1 Aims

The aims of this research are:

- to provide an improved understanding of the iBus System, and how the statistical data captured by on-street vehicles can be used to derived bus stop dwell times;
- to apply the iBus data to develop a method for measuring bus stop dwell times, which can be used to improve the operation of bus priority, without the need to conduct manual road-side surveys;
- to provide guideline methods for obtaining bus stop dwell times, with indicative daytime values, that could be used to improve bus performance monitoring, service operations and traffic management.

1.4.2 Objectives of Research

To achieve these aims, the objectives of this research are:

- to provide a knowledge base framework for the iBus System, including descriptions of its statistical data structures and the functionality required to derive bus stop dwell times;
- to develop a new method for measuring bus stop dwell times, including algorithms that automate the extraction and processing of the required data from the System;
- to evaluate how this method compares to historic surveys conducted and the TfL Running Time reports in development;
- to provide guidelines for obtaining bus stop dwell time values, which can be used as inputs into traffic signal control systems for the optimisation of bus priority and improve bus stop/vehicle detector locations; and
- to derive indicative daytime estimates of dwell times, which along with the new method and guidelines, can be used to help improve bus scheduling, journey time reporting, traffic management and transport planning.

1.4.3 Scope

This research focuses on the dwell time information derived from TfL-franchised, high frequency, urban fixed-route services, i.e. London iBus vehicles that normally operate to a frequency of 12 minutes or less. Low frequency routes, or those that run to schedule (i.e. timetable), were also reviewed as part of this research, but the variations in their dwell times are less of an issue in traffic management or for bus priority, as there are fewer vehicles operating these services at any given time, and passenger demand tends to be relatively consistent (see Section 2.2 for how these factors can affect dwell times). This research documents the specific data items that may be used to derive dwell times, for example bus "halt", "door open/close", and "stop zone" events from vehicle "log" files, but other iBus information obtained through this research, for example that relate to the operation of traffic signal bus priority, have not been included in this Thesis. (They were provided separately to TfL.) It should also be noted that iBus does not capture information relating to passenger boarding and alighting at present, and therefore the potential to assess the impact of such factors on dwell times is difficult, except where ad hoc road-side surveys have been taken. (The potential for integrating iBus data with passenger counting technology is under consideration for the future - see Section 6.4.)

This research has tested the expectation that it is possible to develop a consistent iBus measurement method for bus stop dwell times, from which general indicative values across common time-of-day periods could be derived. However, it does not provide a "production" automated system (i.e. the hardware and database) for collecting and storing dwell time information over time, nor the direct electronic inputs for signal control systems such as SCOOT. (If required, TfL may pursue these options for industrial implementation separately.)

In the course of this research, it has been necessary to withhold certain information (including sources) from publication for commercially sensitive reasons. Nevertheless, this Thesis is published in good faith, and the assistance of TfL, individual bus operators, Trapeze ITS, and the Transport Research Laboratory (for SCOOT) is gratefully acknowledged.

1.5 Approach

1.5.1 Research Process

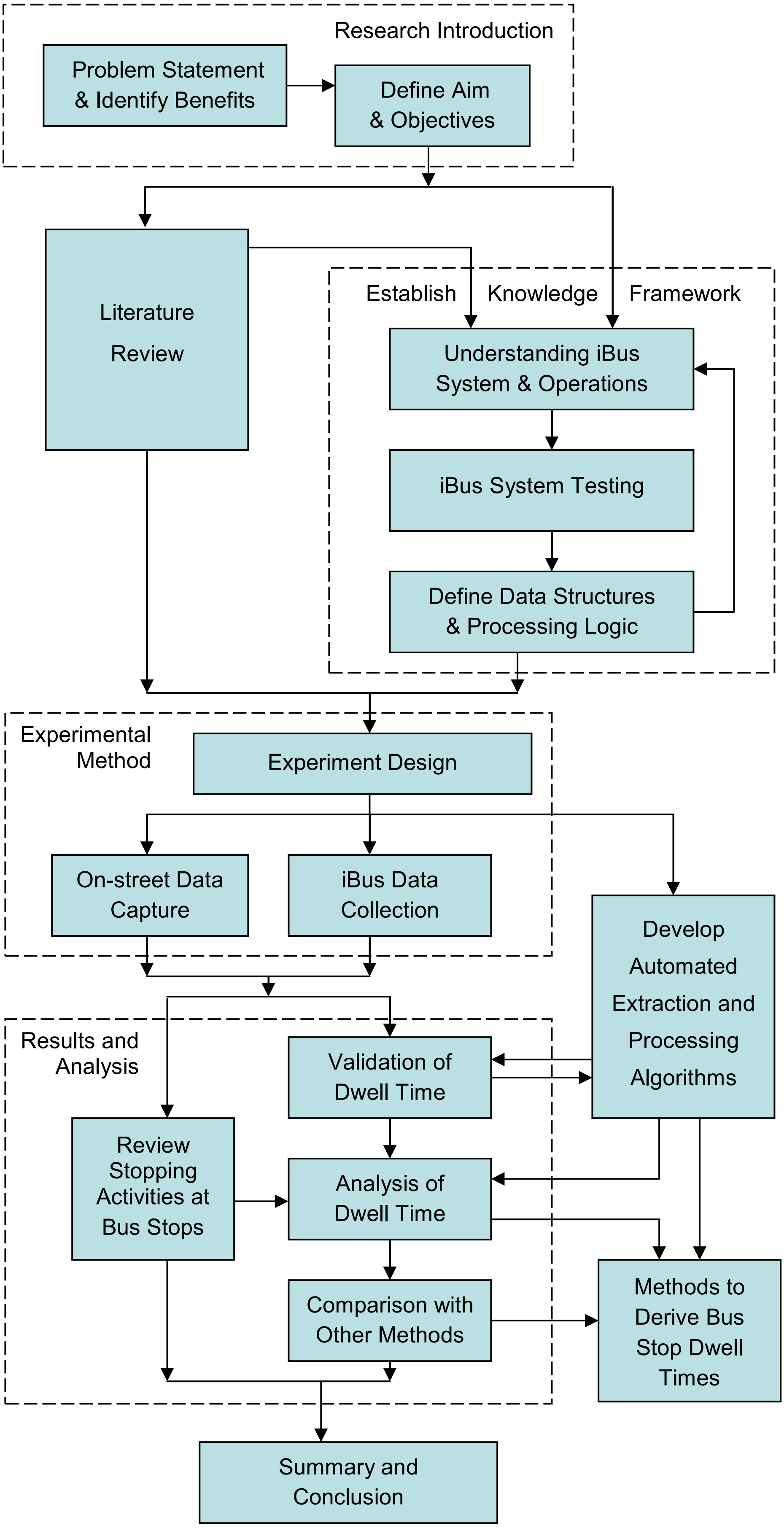
This Thesis forms part of the work conducted for the Engineering Doctorate (EngD) Programme sponsored originally by Transport for London's Bus Priority Team (now part of the Better Routes and Places Directorate). A flowchart of the research process and the structure of this Thesis is given in Figure 1.1.

1.5.2 Thesis Structure

The remainder of this Thesis is divided into the following Chapters:

- Chapter 2 provides a review of the literature on bus stop dwell times, including how they are measured and used;
- Chapter 3 provides a knowledge framework of iBus as it relates to dwell time, including the system components and data structures, as obtained through system testing and research;
- Chapter 4 describes the experimental method used to evaluate the different dwell time measurement methods;
- Chapter 5 describes the results and findings from the experiment; and
- Chapter 6 summarises the research conclusions, and offers suggestions for future research.

Figure 1.1 Research Process Flowchart



Chapter 2 Literature Review

This Chapter looks at the literature on bus stop dwell times, and evaluates what can be learnt about the meaning of dwell time, how values are derived and have been modelled, and their application and importance to bus priority, service operations, traffic management and transport planning.

2.1 What is Dwell Time?

There are currently numerous ways in which bus stop "dwell time" may be defined. A previous study in London (York, 1993) defined dwell as "bus stop time", which is a function of:

- the number of passengers boarding and/or alighting at the bus stop, and the time taken for each person to board or alight;
- plus other vehicle "dead" time.

According to York (1993), the passenger boarding/alighting time depends on whether the vehicle has one or two sets of doors, as the latter usually allows boarding and alighting to occur concurrently through the separate doors, whereas the former must be conducted in sequence, with passengers allowed off before others may board. For two-door vehicles therefore, dwell is the *greater* of passenger boarding *or* their alighting time, plus other dead time; whereas for one-door vehicles, dwell is the time for passengers to alight *and* board, plus dead time. The dead time accounts for other factors for the bus to remain at the stop, i.e. it is not associated with passenger boarding/alighting, and includes for example the time taken to open and close doors, which is dependent on the door mechanism, and any delays in the door opening and closing sequence, e.g. the entrance doors are not closed until after the exit doors have shut, and the driver's reaction time before pulling out to rejoin the traffic flow.

More recently, according to the Department for Transport (2006), dwell is defined simply as the period "that a bus spends *stationary* at a stop", and this definition has also been applied by TfL (Robinson, 2009), although another similar definition has been used historically: that of time between when the "wheels stop" and "start" again at a bus stop (London Buses, 2003). Under these definitions, dwell is differentiated from passenger "boarding time" (ASA, 2005), which is "the time during which people pass through the bus doors", i.e. *boarding* is a separate generic term for passengers getting on (and off) the bus, which can be several seconds less than the overall stationary or dwell time, due to for example the additional dead time (York, 1993).

At first sight, the definitions used by other countries appear similar to the U.K. In North America for example, the Highway Capacity Model (TRB, 2000) or HCM defines bus "dwell" as "the amount of time a bus spends while stopped to serve passengers" at a specific stop, and the Transit Capacity and Quality of Service Manual (Danaher, 2003; and Ryus, 2003), which is a specific revision of the HCM for public transport, defines it as "the time a vehicle spends stopped to load and unload passengers". However, these definitions can be interpreted in different ways, for example:

- as either a function of the *overall* boarding time for passengers, e.g. Guenthner and Sinha (1983a), which *excludes* the delays due to the vehicle stopping and starting at the bus stop, which are termed separately; or
- as the service time between when a vehicle opens and closes its doors, which includes the time taken for passengers to board, e.g. Levinson (1983).

These interpretations are different again to those used in previous London surveys by York (1993) and London Buses (2003), which measure the *total* vehicle stopping time, and the distinction between boarding time, door open and close duration, and the total stopping time can be critical for applications such as bus priority, where other dead time/delays at bus stops need to be accounted for, or where a higher level of precision is required.

Although in all cases, dwell is traditionally associated with buses stopping for passengers, the high-level definitions leave scope for interpretation, and for this reason, TfL have applied a working definition for iBus (Robinson, 2009) which inherently assumes that dwell is associated with the vehicle doors being opened and closed, i.e. it measures when the vehicle is stationary at the bus stop *and* its doors have opened for passengers. This definition therefore covers all *passenger-loading* associated reasons why a bus may be delayed at the bus stop, including hold-ups due to the interaction of consecutive vehicles (Fernandez and Tyler, 2005), as well as the dead time components described by York (1993). However, it excludes the *non*-passenger related delays that a bus may experience inside the bus stop zone (i.e. when the doors are not opened) due to the effects of congestion or queuing from a downstream signal or pedestrian crossing, which are considered to form part of the "normal" bus journey time.

Given there is no universally-agreed standard at the working level, it is important for users and researchers to consider what definition and context of dwell time they require, as this can result in different stopping duration measurements, and caution should be taken when comparing "dwell" values derived through different methods.

2.2 How are Dwell Times Derived?

Historically, the literature on bus stop dwell times has been scarce (Dueker et al., 2004), due to for example the cost and time required to collect data manually at the road-side. From the literature that exists, dwell times may be derived based on one or more of four methods generally, which consists of:

- road-side observations or measurement;
- use of data from AVL Systems, based on door opened and closed times, or the arrival and departure timings of vehicles at bus stops;
- calculation from predictive models, based on estimates of passenger boarding times, and/or other dead time; and
- an analysis of the data from Automatic Passenger Counter (APC) technologies, which monitor passenger loadings to derive boarding times.

The relevance of these methods for obtaining dwell times in London is described in Sections 2.2.1 to 2.2.4 below. In addition, where dwell cannot be estimated/measured through these methods, the U.S. Transit Capacity and Quality of Service Manual (TCQSM) (Ryus, 2003) for example has provided three static default values for use in future planning, although it is often the *variability* of dwell times which is the issue for bus operators and transport planners. The default values and the variability of dwell are described in Section 2.2.5 and 2.2.6, and Section 2.4 provides a brief discussion of how dwell times may be applied.

2.2.1 Road-side Measurement

A few attempts have been made in the past for deriving bus stop dwell times for large conurbations in the U.K. using direct road-side measurement, e.g. York (1993) for London. Seddon and Day (1974) also conducted some work in Manchester, but these were geared towards measuring and developing models for passenger waiting times. A more recent survey was conducted in 2002 for London Buses (2003), but this was intended for a different purpose, and the measured dwell times were limited to a few routes, as a consequence of which, the different factors that influence dwell were not discussed. According to York (1993), dwell time at the road-side depends on:

- the type of vehicle employed;
- the number of boarding/alighting passengers, and the payment option they used;
- the time of travel (e.g. peak or off-peak); and
- the service frequency.

The vehicle type was viewed as important (ibid), as larger buses allowed more passengers to board and alight, and the type of bodywork or chassis dictated the number of doors, which determined whether passengers could board and alight independently (as sequential boarding and alighting took longer), and the number of steps that passengers had to navigate, which all impacted the boarding time. Boarding times also depended on the payment options that existed at the time, i.e. whether passengers had travel "passes", or needed to pay, and/or receive change, as well as the number of people waiting to board (i.e. passenger demand), which varies according to the time of day and the service frequency. The remaining component of dwell, i.e. dead time, was not determined explicitly, other than to include door opening and closing delays and the driver's reaction time for example, i.e. where a bus is delayed at the stop for other reasons, it is inferred that surveyors could make a judgement as to whether these delays were included in the dwell time.

Although York's study was very useful, many of the parameters used in his determination of dwell time, such as the composition of vehicle fleets, London's population density/demand, ticketing arrangements, and the degree of traffic congestion, have all since changed in the intervening period (TfL, 2006a). Indeed, vehicle and bus operations are now almost unrecognisable from those that were described previously, with:

- the retirement of old Routemaster buses;
- the use of Mercedes-Benz Citaro "bendy buses" on heavy usage routes, although these are being phased out and replaced with "rigid" body Citaro's or other double-decked buses;
- accessibility changes, that require vehicles to possess low floors and no steps;
- the move to widespread one-person operations;
- the introduction of the "Oyster" card and other cashless boarding initiatives, such as ticket machines by bus stops.

York (1993) also assumed that unusual boarding or alighting activities were relatively rare, and could therefore be treated as singularities, and ignored manually. However, this assumption may not always be true. According to Ryus (2003), at least in the U.S., the occurrence of specific passengers or events, such as boarding by tourists, bicycles, or wheelchair passengers, can affected dwell time. The impact of these passengers or activities may be even more significant outside the peak periods, as the proportion of trips being made for leisure, shopping and education purposes increases (TfL, 2009). Since the introduction of the Public Service Vehicles Accessibility Regulations and other similar legislation in the U.K. (Butcher, 2009), all London's 8,000+ standard buses are now low-floored and wheelchair accessible; this compares to less than 70 vehicles operating with no steps and low floors in 1994 (Hansard, 1994), so an increase in bus use by wheelchair passengers from latent demand is possible, particularly if London follows the ageing population trend occurring for the U.K. (ONS, 2011). On most buses (TfL, 2010b), wheelchair passengers board using the central (or exit) doors via an extension ramp, and the front doors are kept shut to ensure other people do not cause obstruction. Hence, if the number of wheelchair passengers boarding at a particularly stop is material, as may be the case near hospitals or care homes, there is likely to be a corresponding increase in dwell times. Indeed, as free bus travel for disabled users and pensioners in London has been extended to 24 hours (London Councils, 2011)**,** the assumption that different types of boarding passengers do not impact on dwell times is unlikely, and such differing passenger activity should be accounted for in measurement.

In addition, under current London operations, bus stop dwell times may be complicated by many other factors *not* associated with boarding (Fernandez and Tyler, 2005), such as the interaction of buses with other vehicles, and increased traffic congestion which delays buses from stopping and/or pulling out from the stop. York (1993)'s analysis makes no reference to the frequency of such occurrences, or how they are treated, and many of the routes studied appear to have been chosen where such effects would be minimised. For example, route no. 65 is largely a single service, suburban route along the edge of South West London, and no. 31 is a semi circular route around the northern periphery of Central London (whereas most urban routes tend to radiate from the centre). Road-side surveys are also a relatively time consuming and expensive manual process, which is neither practical nor realistically achievable for the many bus stops, routes and operating circumstances that apply in London. For example, York only sampled 10 routes in his study, or less than 1.5 % of the 700 routes currently operating in London - yet this was considered to be comprehensive at the time. For all these reasons therefore, York's method and estimates may no longer be reliable or applicable to London, and while manual surveys are known to provide good measurements of dwell times, no similar published surveys have been performed since, apart from a limited trial in 2002 (London Buses, 2003), and the individual sampling of bus stops that is performed as part of day-to-day operations. Although more recent field studies have been conducted in other countries, these have either used different definitions and measurement methodologies to London, e.g. Li et al. (2006) in Florida, Kim (2007) in Houston, and Estrada et al. (2011) in Barcelona, or engaged other technologies that are not available to London, e.g. Shalaby and Farhan (2004) with APC in Toronto. An alternative, cost-effective method for deriving dwell times for London Buses is therefore required, to provide updated measurements, and enable further research into the factors that affect dwell times.

2.2.2 Use of Data from AVL Systems

AVL systems and their associated technologies have been deployed in many cities around the world for some time (Furth et al., 2003). Dueker et al. (2004) had suggest that bus dwell time data at individual stops can be derived using such systems, as an alternative to labour intensive road-side surveys. Historic information collected in this way can be analysed to provide useful indicators for the determinants of dwell time, which include time of day, vehicle type and the route type. However (El-Geneidy et al., 2007), the focus of these systems has traditionally been to improve fleet management, to address scheduling issues, and provide improved travel information to increase customer satisfaction, and few efforts were made to use this data for analysing the different aspects of bus service performance, or specifically to measure bus stop dwell times. Where archived data has been used, the analysis has concentrated on the measurement and delays in bus running or journey time, e.g. Chakroborty and Kikuchi (2004), Shalaby and Farhan (2004), Camus et al. (2005), Berkow et al. (2007), Pangilinan et al. (2008), Mazloumi et al. (2010), and Tétreault and El-Geneidy (2010), as distinct from the causes and effects of dwell time. There are also concerns (El-Geneidy et al., 2007) over how the archived data from AVL systems could be analysed and used to derive the information necessary for measuring dwell times. For example, dwell is typically not stored as a separate variable in these systems, e.g. London Buses (2008) and El-Geneidy and Vijayakumar (2011), and needs to be calculated. However, there may be limitations over what real-time data is archived to enable the *total* stationary time to be derived. While door open and close events are tracked by most AVL systems (Furth et al., 2003), and therefore the duration difference between these events is easily calculated, e.g. as shown by Berkow et al. (2007) and Feng and Figliozzi (2011), the measurement of *other* dwell time components, such as delays by a blocking vehicle in front or before drivers can pull out into traffic after the doors have closed, may not be available.
In addition, where dwell is calculated using the difference between the departure and arrival times of vehicles at a bus stop, such timings may be subject to the location accuracy of the AVL system used to determine when the bus has reached the stop (Greenfield, 2000), particularly in urban areas. For these reasons, since this study's inception, although a few attempts have been made to *measure* dwell times through archived data from AVL systems e.g. Milkovits (2008), Feng and Figliozzi (2011) and El-Geneidy and Vijayakumar (2011), the number of working examples gathered from major cities remains limited. The implementation of iBus therefore provides an opportunity to develop an alternative method for measuring dwell times, using the archived data collected from on-road vehicles in London in real-time.

However, such a method is not without its drawbacks. For example, York (2003)'s on-road survey was conducted with the assumption that dwell times varied with the elasticity of passenger demand at bus stops, and at present boarding numbers would only be measurable if London adopted further technologies, e.g. to supplement the AVL data with automated passenger counting systems (see Section 2.2.4) or to integrate part of the Oyster card system. In addition, on-road observations (London Buses, 2003) allow manual judgements to be made on what negative road-side interactions could be ignored, e.g. where a bus stops much longer than usual due to reasons other than for passenger boarding, and only those that fit a certain definition of dwell selected for inclusion in measurement and analysis - which may not be possible with AVL systems, where more empirical means are required to exclude extreme or unusual values. Finally, although data from AVL systems could allow the dwell times of many more bus stops and routes to be measured, the information extraction, consolidation, and dwell time calculation process would need to be automated to a large degree, if it is not to prove equally labour intensive.

2.2.3 Calculation from Predictive Models

Despite the lack of copious data from road-side measurement, the literature suggests many models have been developed for estimating vehicle dwell times at bus stops, and "standard" ones have even been defined for the U.S., e.g. Ryus (2003). Some of these models are derived based on road-side measurements, e.g. Levinson (1983), Guenthner and Sinha (1983b), York (1993), Aashtiani and Iravani (2002) and Kim and Rilett (2005), while others have applied data from AVL systems and related technologies, e.g. Dueker et al. (2004) and El-Geneidy and Vijayakumar (2011). Generally, they assume dwell at a stop level is based on a linear function of passenger demand (or the number of people arriving at bus stops), plus a constant for the opening of doors or a dead time:

$$t_d = n * t_b + t_{oc} \qquad \text{(from Cundill and Watts, 1973)} \qquad (2.1)$$

where:

t_d is the average dwell time (in seconds, *s*);
n is the number of passengers (*p*) waiting at the stop;
t_b is the boarding time per passenger (*s*), and includes e.g. buying a ticket; and
t_{oc} is the time taken for the doors to open and close and/or other dead time (*s*).

The values of t_b and t_{oc} vary by model, depending on the dwell time definition used, i.e. what is included in boarding or dead time, and the models typically assume that passenger demand is random and follow a normal distribution, with a corresponding effect on dwell (Ryus, 2003).

The total boarding time, i.e. nt_b in these models can be split into separate terms, i.e. as multivariate models, to distinguish between the passengers getting on and those coming off, which can depend on whether there is a door entry / exit choice (Li et al., 2006), as well as on the number of doors as suggested by York (1993), i.e. whether independent boarding / alighting can occur. If historical values are not available, the board time is then calculated based a combination of passenger counts (obtained either manually or using APC systems) and estimates of the average service time (Ryus, 2003), which accounts for the different payment / ticketing method employed, and the other factors previously described by York (1993). The alight time can also be derived from historical values, or it can be taken as a percentage of the number of passengers already on-board (Fernández and Burgos, 2004), or calculated using average alighting times and passenger counts. According to TRB (2000) and Ryus (2003), Equation (2.1) can therefore be rewritten as:

$$t_d = n_a{*}\, t_a + n_b{*}\, t_b + t_{oc} \qquad \text{(from TRB, 2000; and Ryus, 2003)} \qquad (2.2)$$

where:

t_d is average dwell time (s);
n_a is alighting passengers per bus through the busiest door (p);
t_a is average passenger alighting time (s/p);
n_b is boarding passengers per bus through the busiest door (p);
t_b is average passenger boarding time (s/p); and
t_{oc} is door opening and closing or dead time (s).

Where there are two sets of doors for passengers to board and alight through different channels, the dwell time is determined by the larger value of the total board and alight times, plus the door opening and closing or dead time, i.e.:

$$t_d = \max\{n_a{*}\, t_a,\ n_b{*}\, t_b\} + t_{oc} \qquad (2.3)$$

This is similar to the work of Pretty and Russell (1988), where dwell time is determined by:

$$t_d = t_{oc} + \max\left\{\sum_{i=1}^{m} t_{ai}; \sum_{j=1}^{n} t_{bj}\right\} \qquad (2.4)$$

where:

t_a and t_b are the time that each passenger takes for alighting and boarding (s); and
m and n are the numbers of passengers alighting and boarding respectively.

Dwell time can also be represented by a more complex function, e.g. (Kim and Rilett, 2005) of passenger loads, bus headways, schedule adherence and other parameters:

$$t_d = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \varepsilon \quad \text{(from Kim and Rilett, 2005)} \qquad (2.5)$$

where:

t_d is the average dwell time (s);
β_k are parameters, $k = 0,\ldots 3$;
x_1 is the schedule adherence (s);
x_2 is passenger loads (p);
x_3 is bus headway (s); and
ε is random error, $N(0, \sigma)$.

York (1993) and Ryus (2003) also suggest that the calculated boarding time values in models are adjusted to account for different time-of-day periods, to reflect expected changes in passenger demand and service times between e.g. (Dueker et al., 2004) the morning peak, midday, afternoon, and evening peak time bands. Some models also suggest that boarding time should be adjusted to account for certain specific events (Ryus, 2003), e.g. the additional time required for cyclists and wheelchair users to board, or that the average vehicle lift operation time should be included where the bus is not low-floored (Dueker et al., 2004). Boarding time could also be affected by crowding factors, such as the contention time due to standing passengers when the bus is fully loaded (Ryus, 2003). Models can therefore include further parameters that account for the friction (Dueker et al., 2004), impact (Milkovits, 2008), or the level of vehicle occupancy and/or the number of passengers on-board prior to the fare collection point (Fernandez et al., 2010). They may also include other passenger-bus interface factors (Jaiswal et al., 2008) that impact on dwell prior to boarding, such as the crowd density on the bus stop platform, particularly at peak times, and the walking distance required from the waiting area to the entry door, particularly where the platform is large.

While the constant t_{oc} can simply include the time taken for doors to open and close, models can also follow York (1993)'s wider definition and include other parameters for the non-boarding related dead time, for example a clearance time (Ryus, 2003) for the vehicle to leave the stop and re-enter the main traffic flow. Indeed, according to Fernandez and Tyler (2005), the dead time of buses in London depends on further delay factors than those suggested by York, as the capacity of bus stops and the frequency of bus arrivals give rise to many interactions between vehicles at the stop. This results in buses queuing to enter, or being obstructed by previous vehicles or other buses from leaving the stop for example, and such delays can form a significant component of dwell times. For these reasons, calculations based on the difference between the arrival and departure time of vehicles at stops, irrespective of the factors involved, could provide better estimates of dwell time, e.g. as per El-Geneidy and Vijayakumar (2011).

Instead of a linear function associated with passengers boarding and alighting at each stop, dwell can also be affected by the nature or type of route (Dueker et al., 2004), and the dwell at one stop can influence those preceding or following it. Dwell can depend on factors such as:

- bus stop spacing (Ryus, 2003), as the greater the spacing, the higher the demand expected at each stop (assuming normal and random passenger arrivals at each stop), and the greater the dwell time; and
- the service interval or bus headways (Shalaby and Farhan, 2004), as the longer the headway, the higher the expected number of passengers at each stop (assuming passenger arrival rate is linearly related to the time of waiting), and therefore dwell time.

Dwell can therefore be modelled as higher-level service and/or vehicle behaviour across many stops along a route, i.e. as a function of the stop spacing (or number of stops per unit link), headway, and running (or journey) time of vehicles (e.g. as calculated from the bus speed and distance between stops), and the frequency of service. For example, Shalaby and Farhan (2004) described dwell by the actual arrival time of vehicles at bus stops which is sensitive to stop-based control strategies, i.e. the dwell time of the n_{th} bus at the $(i+1)_{th}$ bus stop is predicted by:

$$t_{d\,(n,\,i+1)} = r_{(i+1)} * [AT_{n\,(i+1)} - AT_{n-1\,(i+1)}] * t_{b\,(i+1)} \quad \text{(Shalaby and Farhan, 2004)} \quad (2.6)$$

where:

$t_{d\,(n,\,i+1)}$ is the predicted dwell time for bus n at stop $i+1$;
$r_{(i+1)}$ represents the predicted passenger arrival rate at stop $i+1$;
$AT_{n-1\,(i+1)}$ is the actual arrival time of the previous bus $n-1$ at stop $i+1$;
$[AT_{n\,(i+1)} - AT_{n-1\,(i+1)}]$ is therefore the predicted headway for bus n (from bus $n-1$) at stop $i+1$;
$t_{b\,(i+1)}$ represents average passenger boarding time at stop $i+1$, assumed to be 2.5s/passenger.

Practically, dwell can also be extracted from theoretical and actually journey time and vehicle speed. According to Guenthner and Sinha (1983b) for example, the actually operating speed is a function of bus average running speed, the cost of dwell time and the start/stop penalty, i.e.:

$$\begin{pmatrix} operating \\ speed \end{pmatrix} = \begin{pmatrix} running \\ speed \end{pmatrix} - \begin{pmatrix} dwell\ time \\ \cos t \end{pmatrix} - \begin{pmatrix} starting - stopping \\ \cos t \end{pmatrix}$$

(from Guenthner and Sinha, 1983b) (2.7)

Therefore, on a given a route (i.e. specific length) dwell time can be derived by:

$$t_d = t_a - t_v - t_c \qquad (2.8)$$

where:

t_d is the average dwell time;

t_a is actual operational journey time on this route;

t_c is the time cost on vehicle start and stop (and other delays); and

t_v is the "ideal" journey time calculated by the distance and the vehicle running speed by:

$t_v = d / v$; *where*,

d is the distance travelled, i.e. the length of the route, and

v is the vehicle speed.

The parameters used to predict bus stop dwell times can therefore vary widely by model, and while these are very usefully in helping to understand the different constituents that contribute to dwell times, the relevance and application of various parameters or constituents to current London bus operations remains to be tested. In addition, many of the models still require data collection at the road-side, e.g. to obtain estimates of passenger numbers, and/or the average boarding time per customer, which can be equally labour-intensive. It may therefore be more cost-effective to measure dwell times directly, based on the stationary or departure and arrival time of vehicles at bus stops, if an accurate and automated method could be developed from iBus, which in turn could lead to more precise or sophisticated predictive models to be developed for London Buses.

Note: In addition to mathematical models, there are many software tools available to automate and/or simulate public transport operations and their impact on general traffic flow - these are discussed briefly in Section 2.3 further below.

2.2.4 Using Automatic Passenger Counters

APC technologies are not new. (Indeed, according to one bus operator in London, the iBus System has the capability to apply them, although the associated sensing technology has not been implemented.). They can be used (Rajbhandari et al, 2003) to provide more accurate estimates of passenger demand, and therefore act as useful inputs or help to improve existing prediction models, e.g. the multivariate linear models described in the previous subsection, which separating boarding and alighting times (TRB, 2000) - see Equation 2.2. However, while the technology is very useful for monitoring and reporting on large scale ridership changes, measurement errors are also known to exist (Kimpel et al, 2003), although the general overestimates can be adjusted by a correction factor. The errors depend on where the counting sensors are located, and are affected by crowding, passengers near the doors, and their exiting behaviour, which can vary significantly between different vehicles, i.e. they depend on the vehicles' configurations. A more recent study (Fernández et al., 2010) suggests that passenger counting technology is gaining maturity, but there is still further room for development in the optimisation of detection and configuration geometry, and given iBus is not deploying this technology at present, its accuracy, relevance and benefit to London is yet to be determined. While it has also been shown that passenger counts could be derived from video footage for cameras mounted on-board vehicles (Fricker, 2011), this study was also supported by APC technology, and the video counts still needed to be transcribed manually, which is not practical for London buses, given the high number of vehicles and passengers involved.

2.2.5 Default Dwell Time Values and Their Variability

Where dwell times cannot be derived from on-road measurements, using AVL data, or from predictive models and/or passenger counts, some indicative values have been provided in the literature for future planning purposes, e.g. Ryus (2003). This suggest, at least in the U.S., that a "default" value of 60s (seconds) could be assigned to a busy downtown or interchange stop, 30s to a "major" outlying stop, or 15s to an otherwise "typical" outlying stop (Levinson, 1982). However, others e.g. Fernández (2010) suggest that dwell times are specific to individual stops, due to the variety of conditions that may arise (as discussed in the previous Sections), and therefore the use of such default values is too generalised and should be avoided, particularly as predictive and simulation models improve, which will allow a wider variety of factors to be simulated. It may be for these reasons that York (1993) did not provide a similarly small set of default values for his dwell time measurements in London, as there is much scope for variation across routes (e.g. due to the frequency of the service, and the average bus stop spacing), as well as in individual bus stops, and across different time-of-day periods. Therefore, another important parameter to describe dwell time is introduced: dwell time *variability*. It was suggested by Hounsell (2004) that long and variable bus-stop dwell times are more likely to affect the regularity of bus service. Dwell times with higher variances are likely to cause irregular headways, e.g. longer (or shorter) than scheduled, which in turn increases (or decreases) passenger boarding numbers, and therefore result in buses getting delayed (or running ahead) even further. In extreme cases, this can result in severe delays and/or bus 'bunching'. In the TCQSM (Ryus, 2003), a *coefficient of variation* (*Cv*) is commonly used to describe the variability of dwell time for a bus stop or route. *Cv* (St. Jacques and Levinson, 1997) is the *standard deviation* of dwell times *divided* by the *average dwell time*. The lower the *Cv* is at a given stop or route, the more consistent the dwell times, and therefore the lower the risk of fluctuation in headways and irregularity.

Cv is affected by the same factors as for the values of dwell time, e.g. the arrival patterns of buses and passengers (Trompet, Liu and Graham, 2010). Therefore, higher regularity of these two factors results in lower *Cv*, and vice versa. However, while *Cv* was recommended to be 0.6s (St. Jacques and Levinson, 1997), and is quoted as such in the TCQSM (Ryus, 2003), reported values were found to be as high as 1.0s (St. Jacques and Levinson, 1997).

Indicative values for dwell, boarding and alighting, *Cv* and dead times from the literature are summarised in Table 2.1, although it is uncertain how these could be applied generally to bus stops in London.

Table 2.1 Indicative Times and Variability

Dwell Time Component	**Values** (in second)**	**Source**
Average boarding time	1.6 - 8.4 / person	Fernández et al. (2010), from York (1993)
Average alighting time	1.1 - 2.0 / person	Fernández et al. (2010), from York (1993)
Dead time	2.8 - 8.3	Fernández et al. (2010), from York (1993)
Dwell for busy bus stops*	60	Levinson (1982)
Dwell for major outlying stops	30	Levinson (1982)
Dwell for typical outlying stops	15	Levinson (1982)
Boarding (pre-payment)	2.25 - 2.75 (2.5)	TCQSM (Ryus, 2003)
Boarding (buying single ticket)	3.4 - 3.6 (3.5)	TCQSM (Ryus, 2003)
Boarding (require extra change)	3.6 - 4.3 (4.0)	TCQSM (Ryus, 2003)
Boarding (using swipe or dip card)	4.2	TCQSM (Ryus, 2003)
Boarding (using smart card)	3.0 - 3.7 (3.5)	TCQSM (Ryus, 2003)
Alighting (by front door)	2.6 - 3.7 (3.3)	TCQSM (Ryus, 2003)
Alighting (by rear door)	1.4 - 2.7 (2.1)	TCQSM (Ryus, 2003)
Coefficient of variation (Cv)	0.4 - 0.8 (0.6)	TCQSM (Ryus, 2003)

* Busy bus stops represent downtown stops, major interchange points, or major park-and-ride stops.
** Where given, the numbers in brackets are recommended values from the literature.

In order to apply these values, it is essential to understand the scenarios under which they are valid and what they represent, although unfortunately this is not always apparent. For example, the first three values could potentially be applied directly to several models, where dwell time is calculated from the numbers of passengers and dead time. However, these values were based on data collected from bus stops on specific routes and vehicle types in London (York, 1993), which may not be applicable to other areas or cities. Also, the data used to derive them were for the main weekday time period from 7:30am to 6:30pm (although the sample counted after 5:30pm was limited), and a wider variation exists for other time periods, which are provided separately by York (1993), e.g. to distinguish between “peak” and “off-peak” times.

The "standardised" range of values given by York (1993) suggests a range of dwell times from 15.7s to 22.2s, but this assumes an average of 3 people both boarding and alighting, and there is a weighted average of the serving times for the different payment methods used in boarding. However, these average passenger numbers may not be representative of the bus stop for which dwell times are now sought, and more importantly, the payment methods used in York's measurements may no longer be applicable for many parts of London, for example.

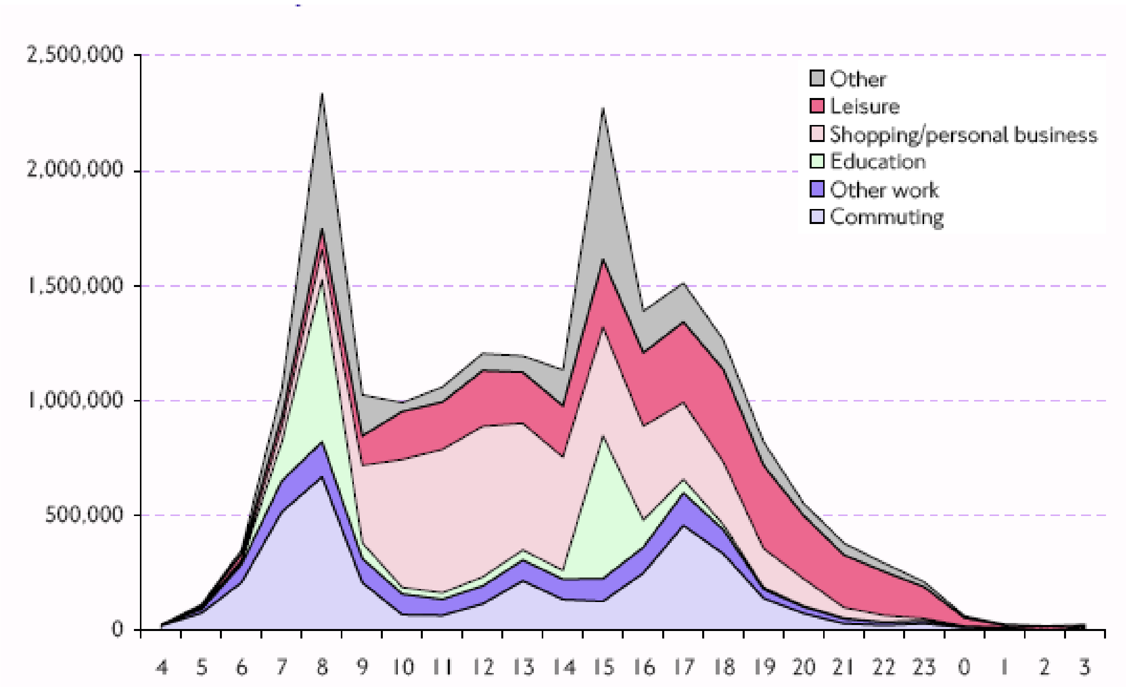
2.2.6 Demand Variation by Time-of-day

Bus stop dwell times can also vary depending on many other factors, including the passenger demand by time-of-day. The literature suggests that dwell times are typically normally distributed, e.g. in TCQSM (Ryus, 2003), Paramics (SIAS, 2007a) and VISSIM (PTV, 2008), as one of the principally components is the number of passengers arriving at the bus stop to board, which is assumed to be random (e.g. Furth and Muller (2006), and Csikos and Currie (2008). This is supported by the work of others, e.g. Cundill and Watts (1973), York (1993), Ryus (2003), Shalaby and Farhan (2004), and Kim and Rilett (2005), where bus stopping times are said to be principally a function of the number of passengers boarding and alighting, plus a dead time to account the time for the doors to open and close, and for e.g. the vehicle to pull out into traffic, as discussed previously. While TfL operate bus services throughout the 24-hour period, the dwell times of interest are typically "day" time, covering the morning or AM peak, the evening or PM peak, and the inter-peak period. This is the period when traffic is at its heaviest, e.g. due to the addition of commuters and shopping traffic in London, and when for example bus priority at traffic signals needs to be operational, and are of the greatest benefit. Previous research (York (1993), and London Buses (2003) therefore focuses only on this period, but provided breakdowns of dwell times according to the three different time periods. Both York (1993) and London Buses (2003) suggest that trips during the daytime are broadly divided into three principal daytime periods: a morning peak, an evening peak and an off (or inter-) peak. This is supported by work in other countries, such as U.S.A. (Ryus, 2003) and Australia (Jaiswal et al., 2008), which suggest dwell times are at their highest normally during the peak hours, that reflects the corresponding increase in passenger demand during these periods.

However, more recent work by TfL (2009), based on the London Travel Demand Survey (LTDS), suggests that the spread of trips by London residents during weekdays is more complex than has been traditionally suggested - see Figure 2.1.

Figure 2.1 Number of Trips by Journey Purpose by Hour of Departure (Weekdays, 2007/8)

(TfL, 2009)



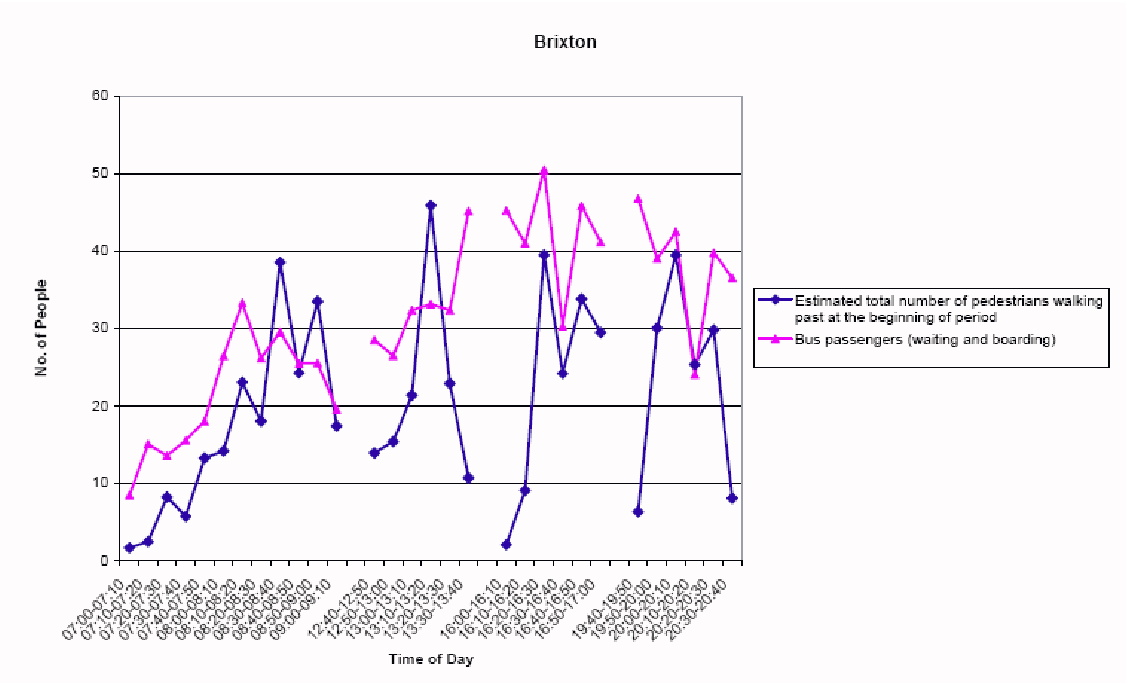
The derived "Trips Profile" shown in Figure 2.1 (TfL, 2009) shows that, while there is still a sharp morning peak, the afternoon/evening "rush hour" is actually comprised of two separate and distinct demand peaks, with a smaller, later peak occurring between 4 and 7pm for the traditional home commuting trips, while there is a higher peak of over 2 million journeys around 3pm due to shopping, leisure, education-related and other purposes. In addition, the LTDS survey (ibid) shows that the bulk of journeys made by Londoners prior to the 3pm peak is for shopping and leisure purposes, which gives rise to another, smaller peak during the middle part of the day, around 12 noon, although the impact of such daytime demand variations on bus stop dwell times has not been researched previously.

This profile also supports previous work carried out nationally (Balcombe et al., 2004), which suggests that the public transport trips made by pensioners using passes during the day are nearly as high as those that are made by other adults for travelling to and from work. It was also claimed in the same research that trips made by child pass holders are half as many again as work-related trips, and given that schools finish during the mid-afternoon period, which along with the introduction of the free Oyster card for children up to 16 in London, it is likely that high numbers of education-related trips would contributed to the mid-afternoon demand peak as shown in Figure 2.1

In the rare cases where passengers counts has been conducted by time-of-day periods at a bus stop in London and published in the literature, e.g. as at Brixton Town Centre (Hall et al., 2006), the demand curve suggests the number of people waiting and boarding can be even higher during the inter-peak period than the peaks - see Figure 2.2.

Figure 2.2 Passenger Demand by Time-of-day for a Bus Stop in Brixton

(Hall et al, 2006)



However, it should be noted that Brixton is known as a busy city centre stop throughout the day, which serves a mixture of commuters and leisure/education-related travellers (ibid). Nevertheless, the variation in demand by time-of-day shown in these more recent surveys suggest that the traditional association of higher dwell times in the morning and evening peaks may no longer be valid. Indeed, this is reflected in the findings by Dueker et al. (2004), which showed that boarding times during the morning peak is actually lower than the midday, mid-afternoon and evening peak periods, and this was attributed to a higher proportion of regular commuters, who used passes (and were less likely to ask questions), and to bus trips that were more directional during the AM peak period.

Such variations and values of dwell times have implications not only for bus network operations and planning, but they can also impact the overall traffic network. (See Section 2.4 further below for a summary of some of the transport applications that are affected by dwell time.)

2.3 Simulation Modelling

Modern bus and transport planning is usually aided by computer simulation models and other software tools. Historically, the models for new schemes and tools to simulate traffic flows tend not to take account for the separate behaviour of buses, and particularly their flow and impact on other traffic at bus stops. However, it was suggested that the behaviour of public vehicles is significantly different with others and should be considered separately (SMARTEST, 1999). Also, micro-simulation models may make assumptions about bus stop dwell times that are not reflected through practical on-street experience and the findings suggested previously by the literature. They assume that dwell times:

- are either fixed, or fluctuate according to a random distribution (e.g. CORSIM)
- follow a Normal distribution (e.g. AIMSUN), and can be accounted for by merely specifying a mean and standard deviation, or follow a user-defined distribution (e.g. as can be defined in VISSIM); or
- are a function of the average boarding time, and the number of passengers boarding, plus a fixed constant dead time (e.g. PARAMICS).

This Section provides a review of some of the major commercial software that provides both simulations for public transport and other vehicles, although they are representative of how dwell time is simulated generally. In essence, there are three concepts used in these models that can impact on the calculation of dwell time, and these need to be understood first:

- the *generation of buses*: i.e. how buses are generated in a model determines the vehicle headways, and the variations of headways. It is related to dwell time because in some models dwell time is calculated by the number of passengers, and the boarding time for each passenger; and the passenger demand is in turn a function of the headway or time gap between buses and the passenger arrival rate;
- the *passenger model* that governs demand: some software do not include a passenger (arrival) model, while others generate passengers by following certain distributions (e.g. Poisson and Normal distribution), or they use a fixed arrival rate (i.e. constant passenger demand per hour);
- the *capacity or design of bus stop*, where there are more than one route operating on a given link: for example, whether a bus stop is used exclusively for one bus route, or whether it can accommodate different buses from separate routes, thereby reducing the potential for bus-to-bus and bus-to-other traffic interactions and obstacles that can affect dwell.

2.3.1 Paramics (S-Paramics 2007)

As part of its bus modelling, Paramics (SIAS, 2007b) recognises that the dwell time of buses at stops affects the flow of traffic, particularly where the stops are placed on the carriageways, as is standard now for London, with the removal of bus bays (TfL, 2006b). In the version of Paramics reviewed (S-Paramics 2007), the bus "stopping time" may be modelled in two ways (SIAS, 2007a), either as:

- (i) a fixed time (in seconds); or
- (ii) using a built-in "passenger model", which derives the time it takes (in seconds) for the bus to load passengers, subject to the bus capacity, from:
  - passenger demand;
  - the average "pay" time per passenger (in seconds); and
  - the percentage exit (or alighting) rate from the bus.

In this model (Fernandez and Burgos, 2004), buses are generated by a predefined fixed frequency per line (or route), while passenger demand is calculated by a fixed arrival rate, which can be applied to a single stop, several stops, or indeed every stop on route for the service. Bus stops are defined to be able to accommodate more than one bus, depending on the length of the stop (as defined by the user), but each stop was is assigned to one line only. Assumptions are therefore made to simplify the calculation of dwell, for example, by using either a fixed time/frequency and/or fixed passenger arriving rate, which can not be assumed in reality. Similarly, other assumptions are also made in Paramics:

- the average alighting time is half the average of boarding time; and
- the percentage exit (or alighting) rate is a percentage of the occupancy of each vehicle.

A summary of the impact of these assumptions is given later in Section 2.3.4.

2.3.2 VISSIM (v5.1)

In the version of VISSIM reviewed (v5.1), the user may choose to derive dwell times (in seconds) by one of two methods (PTV, 2008):

- (A) either using sampling from a dwell time distribution; or
- (B) using an "advanced passenger model" calculation (which is not dissimilar to Paramics), based on the average boarding and/or alighting times per passenger, and taking into account the passenger demand (or flow) at the bus stop, the percentage of passengers alighting, the clearance time for the vehicle to stop and open/close its doors, and its capacity, which are parameters specified by the user.

For option (A), two types of dwell time distributions may be specified, as part of setting up the "Base Data" for the model (which may then be selected for use in individual stops):

- (i) Normal distributions, with means and standard deviations as defined by the user, e.g. N(15, 2), and a zero second cut-off where negative; or
- (ii) "empirical" distributions, which are defined by the user, from a maximum and minimum value, with intermediate points in-between.

In VISSIM (Fernandez and Burgos, 2004), buses are again generated by a fixed frequency; and when the "advanced passenger model" is applied to calculate dwell time (for Option B), the passenger demand is determined by a fixed passenger arrival rate. However, stops are not assigned for each line, and therefore, in a multi-laned bus stop, buses can overtake each other to leave or enter the stop area, again reducing possible interaction effects or delays. VISSIM also has an additional function to set the "departure" time (in seconds) for each bus stop, which effectively holds a bus to schedule, if its derived dwell time at that stop is less than this value (thereby effectively reducing its variability artificially).

2.3.3 AIMSUN (v6.1)

AIMSUN can model public transport operations. However, in the version reviewed (version 6.1), bus stop dwell times are simply sampled from a Normal distribution, with the user having to specify a mean and standard deviation, which may be applied to one stop, or can be set for all stops on a given service (TSS, 2010). In AIMSUN, buses are generated either by following constant headways, or following a timetable for each line with a standard deviation around the expected arrival time. Buses are defined to run only on an exclusive lane, and stops are able to take more than one bus (depending on its length), but again, each bus stop was assigned to one bus line only. Like VISSIM, AIMSUN also has the capability for the user to define an "offset" for each stop, which sets the minimum time (in seconds) before a vehicle is allowed to arrive at the stop from its previous departure point. However, at the time of writing, this version of AIMSUN (v 6.1 base) has no e.g. passenger generation model implemented that would allow the various different bus stop factors to be simulated, although it is understood that a later version, as part of the "Micro-simulator" module, will contain this function, using for example an enhanced "Legion" module to model specific passenger boarding movements and other dwell time factors.

2.3.4 Summary on Simulation Modelling

As discussed previously, in most micro-simulation models, dwell time is considered to be a fix time or a function of passenger arrival rate. However, there are many issues associated with these simplified assumptions (Fernandez and Burgos, 2004), for example the assumption of fixed frequency of buses, as well as the fixed arrival rate of passengers may not reflect the reality. Moreover, dwell time is not necessarily related only to passenger demand, or its variation during the simulation period, and cannot be an arbitrary value, irrespective to different traffic patterns (Fernandez and Burgos, 2004). The models also may not reflect passenger behaviour, for example in DRACULA, where all passengers are loaded onto the first arriving bus, regardless of their intended destination. Therefore, the modelling of bus stop dwell times based principally on numbers of passengers boarding and/alighting or their arrival rates, the frequency of arrival of buses and the capacity of bus stops, may not provide a realistic simulation of on-street behaviour, as it would miss other effects that could affect bus stop dwell times, such as the crowding factors that will further delay the bus. These models as stands may therefore not be able to simulate an accurate representation of bus stop behaviour and dwell times in London. However, by enabling an alternative method to measure dwell times through iBus, improved on-street values can be obtained to providing typical values for specific routes or bus stop for modelling comparison purpose, and help to refine and develop the use of these simulation models.

2.4 Applications of Dwell Time

In addition to bus priority, dwell times are useful to many aspects of transport management, including traffic and public transport operations, network planning and scheduling, and transport planning and simulation modelling. However, dwell times and their variability can also cause many problems for traffic engineers, bus operators and transport planners. As indicated earlier for example, in the case of bus priority at traffic signals, where detectors are located upstream of a stop, the delay of vehicles at the stop affects the ability of the signal control system to provide priority and reduces its benefits, if the bus dwell time and its variation cannot be predicted or measured with a degree of accuracy. On a day-to-day basis, dwell times (along with other journey time delays) can also affect the ability of bus operators to provide effective services to meet their contracted performance obligations, as the regularity or frequency between buses needs to be managed pro-actively, e.g. to reduce Excess Waiting Times, a key indicator used to measure the service performance of buses in London. Dwell times also have relevance in bus network and/or transportation planning, for example to optimise routes and traffic flows, as a balance needs to be struck between servicing passenger demand by improving journey times, and the impact that buses have on other traffic. Improved dwell time values, and an improved understanding of their variability, could therefore help improve day-to-day service management, future bus network planning or service scheduling. These, and other applications of dwell time are discussed further below.

Bus Priority at Traffic Signals

Historically (Hounsell et al., 2005), bus priority in London has been achieved using infrastructure-based systems, which engage road-side beacons or inductive loops and associated vehicle transponders to identify buses on approach, and select them for a green time extension or recall at the signal, i.e. Selective Vehicle Detection (SVD). This priority (Hounsell and McLeod, 1998) can be given locally through vehicle actuated control at isolated junctions, or coordinated centrally through Urban Traffic Control systems like SPRINT and SCOOT, i.e. Split Cycle and Offset Optimisation Technique (Bretherton et al., 1996) In the case of London (e.g. Hounsell and McLeod, 1998), experience shows that bus stop dwell time is an important parameter in the operation of systems such as SCOOT, which affects the effectiveness of traffic signals in providing bus priority, and usually dictates where detectors are sited e.g. for SVD.

The journey time forecasts in SCOOT do not explicitly account for traffic and other delays for individual buses between the detector (which is sited upstream of the junction) and the stop line to the signal, and it has been TfL's policy traditionally (ibid) to site bus priority detectors at 60 metres *upstream* of the signal stop line, to provide the maximum benefits in time or bus delay savings. Where a bus stop lies close to the traffic signal however, detectors have been sited *downstream* of the bus stop, i.e. short of 60 metres upstream to the stop line, to avoid the need to account for the unpredictability (both duration and variability) in the bus stop dwell time. As a consequence (Hounsell et al., 2004), bus delay savings from signal priority are limited where stops are closed to signals, and although there is the option to relocate bus stops further upstream to the junction, this is not always feasible (e.g. due to road layout) or desirable for passengers. While SCOOT has the capability to support detectors sited *upstream* of bus stops, its effectiveness is limited by the ability to accurately predict "BUS VARY" (or BVARY), or the variability in the bus stop dwell time due to various factors, such as the type of stop (e.g. where passenger loading is high) or the time of day. In the past, this has required the use of *additional* detectors, e.g. downstream of the bus stop or near the signal stop line, to compensate for inaccurate journey time predictions derived from the upstream detector.

The effectiveness of SCOOT to implement bus priority using detectors *upstream* of bus stops can therefore be significantly improved by providing BVARY values which are obtained from live data at each site. The development of a measurement method for dwell times from iBus therefore provides an opportunity to supply SCOOT with these values.

Bus Network Planning and Performance Management

Dwell times can also be used to help estimate the bus stop capacity required in network planning and scheduling. Stop capacity is the maximum number of buses per hour that can be scheduled to arrive at a bus stop without causing queues and delays. It is a function of the mean and variation of dwell time, the effective green time of a downstream traffic signal (if there is no downstream signal, the effective green time = 1), the clearance time between successive buses (as discussed previously), the number of effective berths, and the possibility that upstream queuing of vehicles may form (TRB, 2000). Therefore, more accurate dwell times help to provide improved estimates of stop capacity, which can in turn reduce the chances of when a bus arrives at a stop and finding the loading area being occupied, which is known as *failure rate* in TCQSM (Ryus, 2003), which in turn causes extra delay.

As dwell times (Hounsell, 2004) also form a critical component in the link journey times for buses, their variability can impact significantly on Excess Waiting Times (EWT), which is used to measure service or bus operator performance, and therefore impacts on their potential revenues. However, traditional TfL journey time performance measurements have been patchy, as they focus only on certain timing points and subsume dwell times within the travel time for a link - i.e. they do not account for the potential variation in bus stop dwell times, and therefore their impact on bus journey times, and the regularity of services. While it is the headway or journey time measurement which is important, an improved understanding of the variation of bus stop dwell times could help to highlight route sections or bus stops where performance improvement actions need to be taken.

Public Transport and Traffic Management

For some time, dwell time is considered an important factor in urban bus and traffic operations. In the US for example (Guenthner and Sinha, 1983b), it has long been considered as one of two significant “in-vehicle delays” which, along with tortuous routing, deter people from using public transport over motor cars. Bus stop dwell time is therefore an important parameter in managing public transport operations. However, in transport research, it was suggested (Younan and Wilson, 2010) that operational planning models should consider not only the time savings for bus passengers, but also the impact on the whole traffic network. In London (Fernandez and Tyler, 2005), buses tend to operate in tandem with other traffic, and are therefore subject to the effects of traffic congestion, and their delays have a corresponding impact on their flow. For example, along with the removal of bus bays (TfL, 2006b), a stopped bus can cause a temporal blockage for the rest of the traffic (Fernandez and Burgos, 2004). Therefore the effect of varying bus stop dwell times can be significant for traffic management, as well as in managing bus operations, especially when buses can make up 10% of the whole

traffic flow, particularly in the nearside lane (Gibson et al., 1989). Even where buses can be insulated through the use of dedicated lanes and/or bus bays, they still have to merge or interact with other traffic, and their flow or delay must also be accounted for in traffic management.
As buses can also interact with each other at bus stops (Fernandez and Tyler, 2005), giving rise to further delays, it is important to develop a good understanding of the dwell times at bus stops, and some of the factors that influence them, when considering traffic flow and in managing public transport operations.

<u>Real-Time Prediction of Vehicle Arrivals at Bus Stops</u>

The variability of bus stop dwell times is also cited (Kim, 2007) as a key issue in estimating bus arrival times in Real-time Passenger Information systems. Dwell time variability (Hounsell, 2004) affects the performance of the Countdown system, which must account for the dwell and other delays en route, as well as the travel time between stops. The ability to derive dwell times from AVL systems (Shalaby and Farhan, 2004) allows the development of models which can account for the effect of buses arriving early or late at bus stops, thereby leading to more accurate predictions of their arrivals (as well as the subsequent effect on journey time and dwell time) at bus stops further downstream.

<u>"Before and After" Effectiveness Measures</u>

In the past, there has even been an argument in New York (Nelson, 2009), to introduce free bus travel for everyone, as this local government investment can be compensated by reduced delays from fare collection, and therefore bus stop dwell times, leading to a corresponding benefit for all passengers in time savings. However, the cost / benefit of these new initiatives are hard to quantify, without benchmark (or indicative) values based on historical data for comparison, which can only come with improved measurements of dwell times, that do not require manual survey data collection. Measurements at different time periods could also provide "before" and "after" performance indicators to assess the impact of boarding, ticketing and other innovative or technology measures aimed at reducing dwell (and overall bus journey) times. For example, dwell times could have been useful in assessing:

- the impacts of new bus stop designs (TfL, 2006b);
- the wider move to cashless operations;
- the use of different floor designs to buses; and
- the impact of moving bus stop sites.

Other Uses

Information on bus stop dwell time has other commercial applications not associated with transport management. For example (ASA, 2005), dwell times for various types of vehicles at bus stops are useful in determining advertising revenue, and can influence the type of adverts displayed on vehicles and at bus stops.

In addition, a method to derive dwell time for each specific bus stop provides typical values for modelling purposes, and to validating existing models, as discussed in Section 2.3. The derived dwell times can also be used to test the existing Running Time reports that are being developed by TfL, to determine whether this alternative approach is practical over the long term.

2.5 Conclusions from Literature Review

From the literature, (and following discussions with TfL and bus operators), it is apparent that an improved measurement of bus stop dwell times could have many uses, not just for bus priority, but also in bus operations, traffic management, transport planning and simulation modelling. However, relatively little work has been conducted to provide an alternative method to manual road-side surveys for measuring dwell times in London, which could also help to improve and validate existing predictive and computer simulation models. Given the wide-scale changes to vehicles and the payment methods that are now being deployed in London compared to 20 years' ago, some of the traditional factors that impact on dwell, as explored previously by York (1993), may no longer be valid, and these could have a corresponding effect on dwell times and their variability, especially given the time-of-day trip demand changes as highlighted by the last major London Travel Demand Survey. The literature also suggests dwell times depend on a wide range of factors and parameters, and generalised or default values should not be used unless no alternative method is available. The implementation of iBus therefore provides a good opportunity to use the archived data captured by the System from on-street vehicles to develop an alternative measurement method, and thereby enable more recent bus stop dwell times for London to be derived. However, as there is no universally agreed practical definition of dwell time, the various possible methods for calculating dwell time durations from iBus needs to be explored. The next Chapter (3) will therefore look at what has been learnt about the iBus System, and Chapter 4 will discuss the possible methods for deriving and automating bus stop dwell time measurements.

Chapter 3 iBus Dwell Time Knowledge Framework

In order to establish whether dwell time information could be derived from iBus, it was first important to determine what data is recorded by the System and how it is stored, especially since this was not always reflected in the technical documentation provided. While "functional specifications" were available, these were not "user friendly", and few operating manuals existed, which lead to complications for the business teams in understanding exactly what data is collected, and how this could be applied. For example, according to the documentation, the System holds records of when buses opened and closed their doors in the statistical "log" files of individual vehicles. However, in practice, it only recorded when the *first* door opens, and the *last* door closes, where vehicles have more than one set of doors, i.e. there is only *one* open *and* one door close event, and therefore it was not possible to distinguish *which* doors have opened, or their opening and closing sequence, without other corroborating evidence (or unless a significant change was made to the System). In addition, the capture of certain items of information was sometimes dependent on the particular way that the System is used, or they are stored only upon the deployment of compatible technology, neither of which were stated explicitly in the specifications. For example, the software is capable of recording the number of passengers entering and exiting a vehicle's doors, but according to operators, the storage of this variable was dependent on the installation of counting sensors on each bus, and this technology had yet to be deployed widely across London (although it could be a future enhancement), and this data item therefore always appears as zero. Also, the System allows users to configure data attributes in many cases, and these default parameters needed to be tested for applicability to London (and changed where necessary) before the data is relied on.

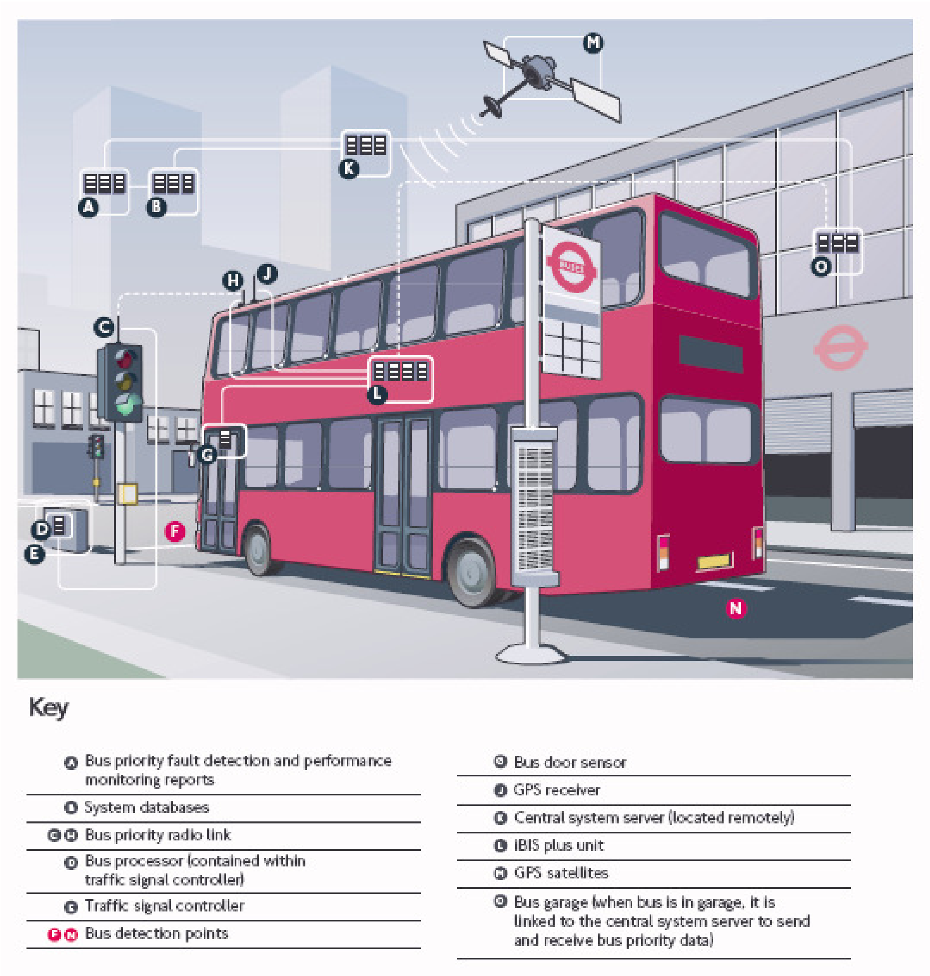
For these reasons, in addition to a literature review, rigorous field tests were conducted in conjunction with TfL, including meetings with various bus operators, to establish a detailed knowledge framework of the System, which helped to determine whether it was feasible to derive bus stop dwell times. This research provided essential information and experience relating to the functionality of the iBus System, the structure and format of the data generated, its quality and quantity, and how this information may be collected, particularly in terms of the archived statistical log files of individual vehicles that capture on-street events in real-time. This knowledge was used to develop a framework or information base, which can also be used by TfL for further development of the System and other research and applications into the iBus data. The main findings are summarised in Sections 3.1 to 3.3 below.

3.1 What are the Main Components of iBus?

In essence, iBus is made up of four inter-connected components - see Figure 3.1 (TfL, 2006c):

- an "*IBIS Plus*" unit on board each bus (Item L in Figure 3.1);
- a "*data server*" (or large personal computer) at individual bus garages (Item O);
- a central "*system server*" (or powerful computer) located away from Central London (Item K), which holds master records of bus routes, their timing points and operating frequencies, as well as the location of detectors for giving buses priority at signals; and
- associated local "*databases*" (Items A and B) and a "*Control Centre*" application (or core system for fleet managers), which are used for bus network management and reporting.

Figure 3.1 Components of the iBus System
(TfL, 2006c)



The *IBIS Plus* unit is essentially an on-board computer chip (OBU), with iBus software loaded, which is connected to the vehicle's door sensors (Item G) and a Global Positioning System (GPS) receiver mounted on the roof (Item J). The unit logs the real-time (second-by-second) GPS location of the vehicle, as well as the occurrence of certain statistical "events", e.g. it timestamps when the doors are opened or closed. In addition to GPS, each vehicle is supported by a traditional odometer and gyroscope (or dead reckoning) system, with optimisation and "map matching" software, which are used to improve the detection of the bus' absolute and relative longitude and latitude positions.

The unit also sends regular location updates (approximately every 30 seconds) via mobile telecommunication messages to the *Control Centre* application (not shown in Figure 3.1), which can be viewed by bus fleet managers in operators' garages, as well as in CentreComm, TfL's overall bus Network Operations Centre. The location of every vehicle is displayed against a map in the Control Centre application, along with their performance relative to the service frequency for that route. The IBIS Plus unit is also connected to a transmitter mounted on the roof of each vehicle (Item H), which can send radio "telegrams" to request bus priority from individual traffic signal "controllers" (Item E) via their aerials (Item C).

When buses return to their garages (typically at the end of each "block" of trips), their IBIS Plus units are connected to the garage's *data server* through a Wireless Local Area Network (WLAN). This in turn, provides a link to the remote central *system server* for the purpose of downloading new route and/or detector locations into the units, and to upload their individual event log files for that period. These real-time event log files are then consolidated and stored centrally in local *databases*, which can then be analysed to provide a chronology of vehicles trips and a number of operational reports, including bus journey times between stops. These can be used, for example, to identify where problems persist on the bus network, e.g. links where buses are frequently delayed, and/or where priority at signals could potentially help to reduce bus delays. The file and data transfer process between vehicles and the local database is described in further detail below.

3.2 The Data / File Transfer Process

The bus log files are uploaded onto data servers at garages using FTP (File Transfer Protocol) whenever vehicles return home to depot. The files are consolidated in each server or Depot Data Manager (DDM), and then "*parsed*" into a central Staging Server, which is essentially a holding database. "Parsing" is a process which takes the individual bus log file records, and separates the data contained within them, which are held *linearly*, into predefined sizes, and processes and stores these as distinct fields in the Staging Server database. (A "Parser Logic" program was built into the System specifically for this purpose.) Data from the Staging Server is then transferred on a regular basis into the London Reporting Database (or LRD), which is the main local data repository for management and other statistical analysis information collected through iBus. (Technically, iBus actually uses many databases for information storage. Aside from the LRD and Staging Server for example, "master" system records are also stored in the VLD, another central database located at the remote system server.)

Business users in TfL have "read" access to the LRD for the purpose of running a list of pre-defined reports, e.g. "Report 240" for Running Time analysis, or to perform certain "ad hoc" type queries, although historically there has been a two day lag typically between when files are recorded by vehicles, to when they are uploaded into the DDMs and transferred to the LRD, although this process could sometimes take up to a week (and longer in extreme cases, for example, when there is a fault in the logging or communications equipment of a vehicle, which then causes a delay in the record capture or log file transfer process). There is therefore a potential to derive bus stop dwell times through the development of reports from the LRD, or alternatively, to use the consolidated bus log files, e.g. from either the DDMs or the Staging Server. Both methods are under investigation by TfL, and a description of the data source, or the bus log file data that could be used, is given below.

3.3 Bus Log File Data Structures

The bus log file, technically Statistical Analysis File or ".saf", consists of a number of different record types, which are "stacked" to form a record of the vehicle's various events and activities during a block of trips. Looking at the files, the data layout and formats are not straightforward to interpret, largely because each record is stored as a "flat" text file, comprising 14 standard "header fields" (or data items), which are then "concatenated" with data specific to a "record ID" or type, i.e. the format of each record type is different, but the records are all contained in one sequential bus log file. According to the System supplier (London Buses, 2008), the header fields include the record ID, a date and timestamp, vehicle speed, and longitude and latitude - see Appendix I, and there are over 35 different record types or events that could be recorded in the bus log file in real time, although research suggests only some of these are useful in deriving dwell time or are used for bus priority purposes - see Figure 3.2 for examples of bus log file records.

The record types that could potential be used to derive dwell times are:

- ID 21 - vehicle "Halt" events;
- ID 31 - bus "Stop Zone" events;
- ID 41 - "Doors" (opened and closed) events; and
- ID 82 - "Detailed GPS" location events.

Figure 3.2 Example Bus Log File Records

Record ID	Date	Time	Speed [km/h]	Longitude	Latitude	Shortname								
Bus Stop Zone Event:							Event Type	Geo Index	Schedule Dev					
31	15/09/2009	14:54:16	29	-604450	1.86E+08	StopZone	1	272	32767	*Vehicle Inside Stop Zone*				
31	15/09/2009	14:55:36	21	-607653	1.86E+08	StopZone	2	272	32767	*Vehicle Outside Stop Zone*				
Halt Event:							Event Type	Schedule Dev						
21	15/09/2009	14:54:31	0	-606186	1.86E+08	Halt	1	32767	*Halt Inside Zone of Stop*					
21	15/09/2009	14:55:18	11	-606458	1.86E+08	Halt	2	32767	*Vehicle Halt Ended*					
Door Event:							Event Type	Schedule Dev						
41	15/09/2009	14:54:27	0	-606186	1.86E+08	Door	1	32767	*Front Door Released*					
41	15/09/2009	14:54:32	0	-606186	1.86E+08	Door	2	32767	*Front Door Closed*					
RTIG TSP Message:							Task	Junct ID	Movement	Telegram	Acknowledgement			
84	15/09/2009	14:55:15	0	-606165	1.86E+08	RTIGTSP	0	9	4	1091004C2500F080FF0F00007080000C	0	*Priority Requested*		
84	15/09/2009	14:55:15	1	-606167	1.86E+08	RTIGTSP	1	9	4	107091004C2500	1	*Acknowledged*		
VDP Coordinates Based Action:							Trigger Index	Trig Long	Trig Lat	Text	Capture Zone	Point Type	Sub Type	
103	15/09/2009	14:55:16	1	-606167	1.86E+08	GeoAct	28485	-606662	1.86E+08	SVD on stop (N/b) - outside 5 Rosslyn Hi	20	GEOPOINT	SVD_Detect	*VDP triggered record*

***Note:** Only data shaded (in green and yellow) are from the bus "log" file. Data shaded in green (dark shade) are "header" items; those in yellow (light shade) are record specific items.*

All other text has been added manually to aid reading and interpretation. (Some of the data has also been edited or formatted for this purpose.)

Some data items are NOT shown here for simplicity. (E.g. "milliseconds", "meters", "navigation state", "driving direction", "coordinate quality", "number of satellites" and "odometer reading" for the "header".)

GPS longitude and latitudes in log files must be divided by 3,600,000 to obtain "normal" GPS coordinates in decimal degrees.

Records are shown separated here for illustration. In practice, records are stacked one on top of another (in record ID and time order), and there can be tens of thousands of records generated in one single afternoon.

In addition, the individual data items are concatenated with each other in one continuous text record (i.e. not split into cells, as shown here).

In detail, the ID 21 vehicle Halt event records are generated when a vehicle has come to a stop below a certain speed threshold (set at 2 km/h by default) for a period of 5 seconds or longer, and its speed then climbed above this threshold for 1s or more, i.e. these criteria cause a halt "beginning", and an associated halt "end" record to be generated, which essentially smooth out the stopping and starting times for when a vehicle comes to a halt. The speed is taken from the vehicle odometer, and is recorded in the header field of these records. The Halt Begin records are distinguished from the End ones using data item "event type" (Begin = 1, and End = 2).

The ID 31 Stop Zone records log when a vehicle "enters" or "exits" the designated stop zone of a bus stop. The entry and exit points are determined based on a comparison of the vehicle's "enhanced" location, as determined by the IBIS Plus unit through GPS and/or the other location technology used, and a zone located typically 30 to 50 metres in length around the bus stop coordinates (as defined in the central iBus database beforehand), although this size could be adjusted if required to suit the particular bus stop geometry. See Figure 3.3 for an example of an on-street bus stop "cage" or zone. The cage typically runs for 30m along the road, but can be longer when required, subject to road layout. Note the bus stop "flag" or pole to the right.

Figure 3.3 Example Bus Stop Zone

The bus stop coordinates are typically defined as being at the site of the bus stop flag, but in practice could be located in effect at any point along a "snap" line between the flag and the geographical centre (line) of the road. Like Halt events, the Stop Zone Entry and Exit records are differentiated using event types 1 (Entry) and 2 (Exit).

The ID 41 Doors records log when a vehicle's doors have opened or closed (event type 1 = Door Released and type 2 = Doors Locked), and the ID 82 records log the vehicle's enhanced location on a second-by-second basis. See Figure 3.2 for examples of the ID 21, 31 and 41 records. The ID 82 location records are too numerous to show in this Figure, even for one bus stop transition, but they essentially record time, longitude, latitude, and the vehicle's speed readings using GPS and/or dead reckoning every second. A detailed layout of the four different record types or IDs is given in Appendix II. Although knowing the structure of this data is helpful, the content of the records needed to be validated and tested before they can be relied on. This was achieved through on-road user testing with TfL and research conducted as part of this study. Further aspects relating to the content and operation of bus log files are discussed in Chapters 4 and 5 below.

Chapter 4 Experimental Method

4.1 Introduction

As discussed previously, there are many definitions and measures of dwell time, which traditionally have been associated with vehicles serving passengers at bus stops. However, in addition to the time taken for passengers to board and alight (which can be included within the door opening and closing times), dwell may also be defined, e.g. by York (1993) and TfL (London Buses, 2003), to include other associated vehicle dead times, when the bus remains stationary at the bus stop, e.g. while it is waiting to re-join the traffic flow. Through field testing and meetings with operators, it was established that these different definitions of dwell could potentially be derived using one or more combinations of the various event records registered in the bus log files (or .saf) of individual iBus vehicles.

4.1.1 Methods for Deriving Dwell Times from iBus

In iBus, dwell times are not recorded directly as a data item by vehicles stopping at bus stops. However, there are four bus log file record types (as discussed in Chapter 3) that provide information which could be used to calculate a range of stationary durations associated with a given stop. These are:

- Doors Opened and Closed events, which are usually "paired";
- Halt Begin and End events (again paired);
- Stop Zone Entry and Exit events (also paired); and
- Detailed GPS events which record vehicle speed, and therefore register when the vehicle's speed has reduced to, or increased from, zero.

As these events are time-stamped, an elapsed duration in seconds can be calculated from each pair of events, e.g. (Doors Closed time - Doors Opened time), which in turn can provide an estimator for dwell time. In the case of the Detailed GPS events, a duration could be calculated from when the first record reached Speed = 0 and when the last record was zero. While TfL were aware of the existence of the Doors, Halt and Stop Zone events, they have not been used to measure dwell times, and none of these methods had been tested for validity or accuracy previously; and the possibility of using the "Speed Zero" method only arose after several rounds of field testing, as the associated Detailed GPS records are used principally for determining real-time vehicle location only.

At the time of project instigation (Robinson, 2009), TfL were exploring the possibility of measuring dwell time durations in Running Time reports using the difference between the "departure" and "arrival" times of vehicles at bus stops. However, as these times are not recorded by the iBus vehicles directly, it was down to the "Parser Logic" program to determine how these values could be derived from the bus log files, and it was decided that the bus stop departure and arrival times could be based on the sequence of Doors Opened and Closed events (ibid), and where these are absent for whatever reason, on the Stop Zone Entry and/or Exit events, which in effect is adopting a similar definition used in the U.S., i.e. to cover the passenger service time between when a vehicle opens and closes its doors (see Chapter 2). The measurement of Stop Zone Entry and Exit durations was also considered in this study, due to their possible inclusion in the TfL Running Time reports, although it was considered likely these would maximise the estimates of dwell, given they measured the large distance between when a vehicle enters and exits the detection area of a bus stop.

The times from paired Halt event durations were suggested by the system supplier as a potential source for the statistically reporting of dwell times at bus stops, with a "productive" stop being defined in the System (London Buses, 2008) as being halt events occurring within the stop zone, where the doors were released. The Halt events in the System were designed to smooth out the stopping, deceleration and acceleration profile of buses at very low speeds, with the aim of providing a more consistent measure of stopping times. However, they are *not* associated with Stop Zone events in the bus log files, and can occur at locations other than at bus stops, e.g. due to queuing from a downstream traffic signal or pedestrian crossing. Therefore, it would be necessary to associate these Halt durations with the Stop Zone events in order to measure dwell, and preclude other stopping activities. Halt events are also not being used by TfL at present for reporting purposes, and their durations have not been compared to other possible measurements for dwell, including the period when the vehicle's speed is zero. Historically, the second-by-second Detailed GPS records used to determine speed were also not used by TfL for statistical reporting purposes, as the number of such records generated on a daily basis is very large, and they are not used actively apart from in real-time fleet management operations and for retrospective bus monitoring, e.g. to locate a vehicle at a certain point in time. (There are typically ten's, if not hundreds of thousands of such records generated within one log file for a given vehicle on a single day alone, and hence for storage limitation reasons, they are usually retained in the System only for a period of around two months before being deleted.) However, research from field testing suggests these records could provide a realistic measure of bus stop dwell times, as according to TfL, the speed values stored in these records are taken directly from the vehicle's odometer readings, and they should therefore reflect on-street observed times for when a bus is stopped, i.e. its Speed is zero.

Extracting the dwell time-related data for the four different methods from the bus log files was neither automatic nor straightforward at first. The process was laborious and time consuming - the log files were relatively large (they are stored in compressed form), and the contained records are not "relational", i.e. it is not possible to "index" from when a vehicle had entered the stop zone of a bus stop (from the ID 31 records), to determine when its doors opened and closed (to select the ID 41 records), or the associated halt times (for the ID 21 records). As the three types of events are independently recorded in the bus log files, separate logic therefore had to be developed to *associate* these records, based on the relative sequence of these different events, and computer algorithms had to be designed and developed to process the files more efficiency, to provide an alternative method to manual surveys for measuring dwell times. (Note that the developmental process went through several iterations, before an acceptable method could be used - see Section 5.1 for details of the final logic, flow chart and computer algorithms applied).

4.1.2 Research Methodology

Having obtained a good understanding of the information contained in the bus log files, and the four possible event types which could be used to derive dwell times, the next stage in the research process involved:

- designing an experiment which could be used to validate the stationary times derived from the four different iBus events against real (i.e. video) data of buses stopping on-street, including sampling from different regions of London, and defining how the video and iBus log file data is collected;
- conducting an "on-street" trial using video to validate the different iBus measurement methods and provide a preliminary analysis of some of the factors that could affect dwell times - the results from which was used to improve the subsequent analysis of all iBus-derived dwell time measurements;
- developing a method for the volume processing and automatic extraction and association of different iBus records from the collected vehicle log files, and converting this data to a readable format (with the aim of automating part of the dwell time measurement and reporting process);
- using the results from the on-street trial to compare and validate the stationary times derived from the four different iBus measurement methods against those from video data as observed on street;
- conducting a more detailed analysis of all the collected iBus dwell time measurements, including comparisons against values obtained historically through surveys, and (where it was possible) some of the factors that influence dwell and cause its variability, such as the time-of-day; and

- defining the expected results for the experiment, i.e. for the validation of different iBus measurements against video, and the subsequent detailed analysis of all iBus-derived dwell times.

These research steps are discussed separately in Sections 4.2 to 4.5 below, and the results and analysis are given in Chapter 5.

4.2 Experiment Set-up and Design

A controlled on-street trial was set up in order to compare and evaluate the four different methods for deriving and measuring bus stop dwell times from the iBus vehicle log file records. A preliminary analysis was also conducted on the video and iBus data collected through this trial, which was used to define (and refine) the process and methods applied in the next stage of the experiment, i.e. the subsequent analysis of all iBus-derived dwell time measurements.

4.2.1 Identifying Stops of Interest

The first stage involved identifying and selecting a sample of representative routes and bus stops, which enables the *four* iBus-derived measurement methods to be compared against observed on-street dwell times and associated events, as captured manually on video (the *fifth* measurement method). Routes known to have some problems with the operation of the System (e.g. due to location/map matching problems or poor GPS signal coverage) were deliberately screened, although these were said to be only a handful at the time.

4.2.1.1 Regions and Location Types

The routes were chosen to provide a broad coverage of different bus stops, and to give exposure to different areas of London, including the follow *Regions*:

- Central London or the "West End";
- the "City of London" (or Central) Business District;
- the suburban areas, i.e. Greater London; and
- rural stops outside the Greater London boundary, where TfL still had jurisdiction and the buses operated regularly, but with less frequent (schedule-based) services.

Central London or West End stops were defined as those included in the area covered by TfL's Central London bus map (TfL, 2008b), encompassing essentially the equivalent of London Underground Zone 1, while the City or Central Business District included only those stops within the City of London Corporation's administrative boundaries (City of London, 2008). Both the City and West End were defined as *Urban* regions generally for the purpose of detailed analysis of dwell times, while those outside the Central London map but falling within the Greater London boundary (TfL, 2008c), as determined by the Greater London Assembly (GLA), were defined as an Inner/Outer London *Suburban* region. Routes and bus stops falling outside the GLA boundary were defined to be in a *Rural* region generally.

It was expected that passenger demand would vary on average across these different regions (due to population density), and therefore if passenger demand was a significant factor driving dwell time variability, this would be reflected in the subsequent analysis of the derived dwell distributions. In addition, bus stops were also separated into different *location types*, for example *Interchanges* or *Shopping Area* stops, which is also used to distinguish between the demands from different stops. (Historically, bus stops were classified into "Compulsory" or "Request" stops, which were used to distinguish between those stops that attracted a higher passenger demand, such as the ones at major interchanges or shopping centres, and those where demand was lighter, and a signal/bell had to be given to the driver in order for the bus to stop. However, these classifications are no longer in use for London Buses, and the use of stop location type provides a similar alternative.)

4.2.1.2 Routes

The routes selected for the experiment are shown in Table 4.1 and illustrated graphically in Figures 4.1 and 4.2 further below. As can be seen from Table 4.1, they routes cover a range of bus operators, service frequencies (routes), as well as regions and bus stop locations.

Table 4.1 Routes Used in Experiment

Route	Terminus	Principal Stops	Route Region	General Direction	Service Frequency*	Vehicle type	Operator
14	Putney Heath and Warren Street Station	Putney - Fulham - South Kensington - Green Park - Tottenham Court Road Station - University College	Urban / Suburban	South West - North East	High (3-6 mins)	Double-Decked	London General (Go-Ahead)
31	Camden Town Station and White City Bus Station	Chalk Farm - Swiss Cottage - Kilburn - Westbourne Park - Notting Hill Gate - Shepherd's Bush	Urban	Orbital	High (5-6 mins)	Double-Decked	First Centrewest
65	Ealing Broadway and Kingston	South Ealing - Brentford - Kew - Richmond - Petersham	Suburban	North - South	High (6-8mins)	Double-Decked	London United (TransDev)
74	Putney and Baker Street Station	Earl's Court - South Kensington - Knightsbridge - Marble Arch	Urban / Suburban	Orbital	High (7-8mins)	Double-Decked	First Centrewest
85	Kingston and Putney Bridge Station	Kingston Hill - Roehampton Vale - Roehampton - Putney Heath - Putney	Suburban	South West - North East	High (7-8mins)	Double-Decked	London General (Go-Ahead)
134	Tottenham Court Road and North Finchley Bus Station	Warren Street Station - Camden Town - Highgate - Muswell Hill - Friern Barnet	Urban / Suburban	South - North	High (5-6mins)	Double-Decked	Metroline
168	Old Kent Road and Hampstead Heath	Elephant and Castle - Waterloo - Aldwych - Holborn - Euston - Camden Town - Haverstock Hill	Urban	North - South	High (6-7mins)	Double-Decked	Arriva (London)
521	Waterloo and London Bridge Stations	Aldwych - Holborn - Holborn Circus - Cannon Street ("Red Arrow" Commuter Route)	Urban	East - West, City (CBD)	High (2-6 mins)	Single-Decked	London General (Go-Ahead)
507	Waterloo Station and Victoria Bus Station	Horseferry Road - Lamberth Bridge ("Red Arrow" Commuter and Shopping Route)	Urban	East - West, West End	High (2-6 mins)	Single-Decked	London General (Go-Ahead)
K3	Esher and Roehampton Vale	Hinchley Wood - Long Ditton - Surbiton - Kingston - Norbiton - Robin Hood Lane	Suburban / Rural	South West - North East	Low (15 mins)	Single-Decked	London United (TransDev)

Note: - "High" frequency services are those with five or more buses an hour, whereas "low" frequency routes typically operate with four buses an hour or less.
* The typical weekday daytime frequency is shown in brackets, e.g. a bus operates every 5-6 minutes.

As can be seen from Table 4.1 and Figures 4.1 and 4.2, the selected routes, and therefore bus stops, comprise a mixture of East-West, North-South and Orbital services through Central and Greater London. Three of the routes were also chosen to enable a direct comparison with previous manual surveys, i.e. York (1993) and London Buses (2003). They include two "Red Arrow" routes through the City and West End, which operate principally for commuters on a "limited stop" basis, where passengers are known to use season tickets or "Travelcards" (i.e. passes) and the Oyster pre-paid card predominantly. Passengers are also allowed to board and/or alight from either sets of doors (i.e. front or rear), and therefore average boarding times per passenger are relatively consistent compared to other routes (London Buses, 2003).

Figure 4.1 Routes Covering Central London

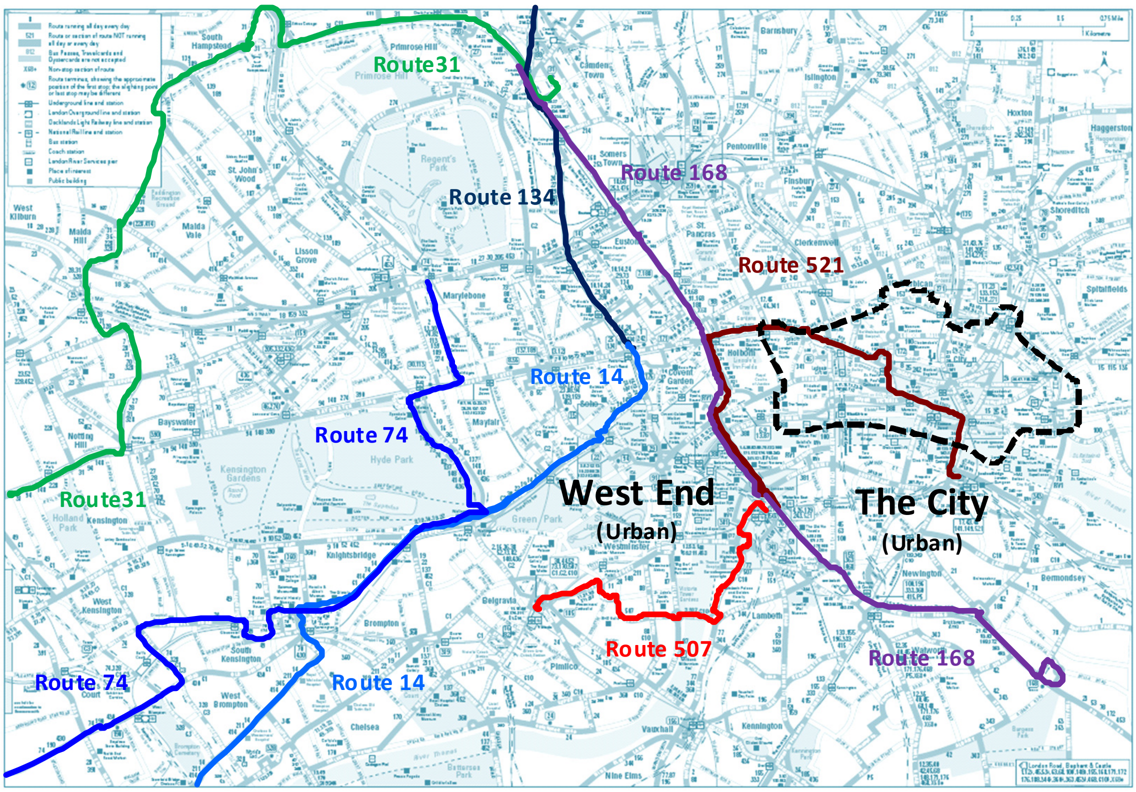
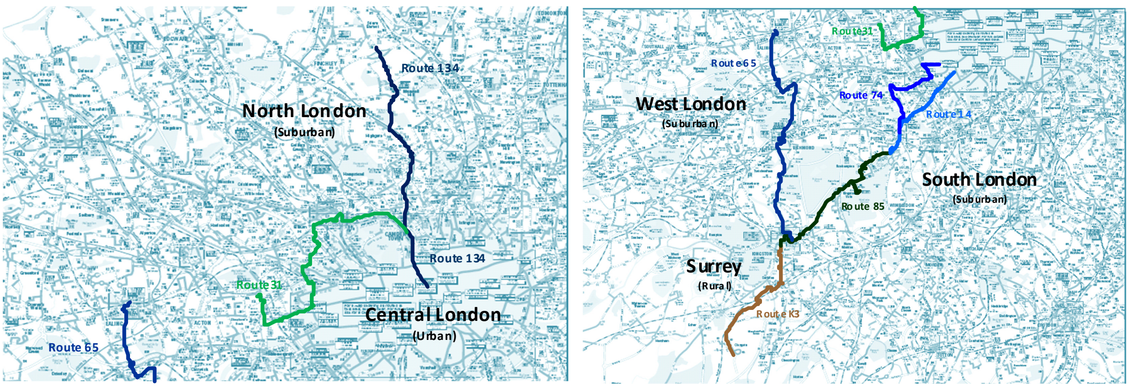


Figure 4.2 Routes Covering Outer London



All the routes are high frequency services, with an average weekday frequency of between 2 and 8 minutes, apart from one (rural) route, which has an frequency of every 15 minutes.

4.2.1.3 Vehicle Types

The literature (see Chapter 2) suggests that dwell times can be affected by different vehicle types, for example between single and double deckers, due to different levels of occupancy or capacity, and the scope for crowding on board the bus. The routes were therefore selected also to provide a mixture of single (e.g. routes K3, 507, 521) and double-decked operated buses (e.g. routes 31, 65, 85 and 134), to enable a comparison between these two different vehicle types.

4.2.2 The On-street Trial

The on-street trial was conducted over two separate weekdays in 2010, principally over the inter-peak period from 12pm to 5pm, as it was not possible to conduct the experiment during much of the peak periods. On occasions when this was tried, buses were seen to be over-crowded, particularly in Central London, which made the videoing of vehicle, as well as passenger boarding and alighting movements through the front and rear doors impossible. This was similar to the situation experienced by York (1993), although it should be noted that the subsequent iBus log file data collection (see Section 4.2.2.2 below) occurred for a longer period than the two days of the trial (and the inter-peak times). This wider iBus data collection enabled a more detailed analysis of measured dwell times across different "time-of-day" periods, i.e. to including the morning and evening peaks, as well as other intra-daytime periods. (The evening and night time periods from 7pm to 7am was generally ignored, although this data was also collected as part of the experiment.)

For the purpose of the trial, both the start and end stops for the routes (i.e. at the terminus) were excluded, as these are known to exhibit behaviours that are not representative of bus stops. Each bus stop was also assigned unique reference number for identification purposes.

4.2.2.1 Video Data Collection

The dwell times derived from the four possible iBus methods were evaluated by comparison with observed video data, comprising footages of on-board bus journeys conducted over the two days, covering the routes, bus stop locations/regions, and vehicle types given previously. The video data recorded is shown in Table 4.2 further below. A minor proportion (24%, or approximately 36 minutes) of the video data had to be discarded, because the corresponding iBus .saf files could not be collected, e.g. because the files for the vehicles involved were in use or had not yet been uploaded from the garages. Only those that did enable direct comparisons between video and iBus stopping times are shown in Table 4.2, which covered 7 of the 10 routes originally planned. The videos were recorded using a Canon handheld 8mm camera and "Hi-8" resolution tapes. The tapes were time stamped, and synchonised at the start of each day of the trial with a stop-watch provided by the Transportation Research Group (which was synchronised with the Speaking Clock). In total, over five hours of video data was recorded, and subsequently analysed, during the two days.

Table 4.2 Video Data Collected for Comparison with iBus Data

Videos Captured:

On 09/07/2010

vid_tape_no	dig_vid_name	rec_date	route	bearing	rec_start_time	rec_end_time	rec_duration
Tape A	DT0001	09/07/2010	K3	SW-NE	12:24:02	12:44:38	00:20:36
Tape A	DT0002	09/07/2010	85	SW-NE	12:57:34	13:19:00	00:21:26
Tape B	DT0004a	09/07/2010	134	S-N	14:45:56	15:21:27	00:35:31
Tape B	DT0004b	09/07/2010	134	S-N	15:21:27	15:51:39	00:30:12
						TOTAL:	01:05:43

On 16/08/2010

vid_tape_no	dig_vid_name	rec_date	route	bearing	rec_start_time	rec_end_time	rec_duration
Tape 1	DT0007	16/08/2010	521	E-W	13:02:07	13:22:21	00:20:14
Tape 1	DT0008	16/08/2010	507	E-W	13:30:14	13:44:57	00:14:43
Tape 1	DT0011a	16/08/2010	31	Orbital	14:55:09	15:15:36	00:20:27
Tape 1	DT0011b	16/08/2010	31	Orbital	15:15:37	15:36:41	00:21:04
Tape 2	DT0011c	16/08/2010	31	Orbital	15:37:23	15:44:09	00:06:46
						TOTAL:	00:48:17
Tape 2	DT0012a	16/08/2010	65	N-S	16:13:30	16:35:51	00:22:21
Tape 2	DT0012b	16/08/2010	65	N-S	16:35:52	16:59:05	00:23:13
Tape 2	DT0012c	16/08/2010	65	N-S	16:59:06	17:02:18	00:03:12
						TOTAL:	00:48:46

In addition to the video-derived data, the start and end times of when the bus was physically stationary, as well as when its doors open and closed, were also recorded manually using the stop-watch by the experimenter sitting on the bus. The number of passengers boarding and alighting at each stop, along with any unusual boarding activities, such as the delays caused by passengers asking questions, or elderly and disabled passengers, were also recorded manually. All these events were reviewed with the video evidence later for confirmation.

At the start of each bus journey, the vehicle's bonnet number and registration mark was noted, and this information used to determine (subsequently from the iBus database), the vehicle's unique "Technical Vehicle Number" (TVN) in the System, from which all its associated bus log or .saf files could be identified and extracted.

4.2.2.2 iBus Data Collection

The "raw" (i.e. unmodified) iBus .saf files were extracted using a remote "FTP" file transfer utility from Trinity Park, TfL's second data centre in Walthamstow in London. The .saf file records for the seven vehicle journeys (as determined by their TVNs) were downloaded from the remote server (which holds the .saf file records uploaded from every vehicle over a two-month period), to a local TfL networked PC at Trinity Park. Due to technical constraints at the time, downloading each file was a time and labour-intensive process, taking approximately half-an-hour to forty minutes each with manual intervention. (This issue has since been addressed.) In addition, as well as the seven routes used in the trial, the data for the three other routes (as originally planned) were also collected around this period, as their associated vehicle IDs or TVN's had been made available (i.e. the total collected iBus data was not specific to the two days or seven routes used in the trial). A much larger dataset was therefore used in the subsequent detailed analysis of iBus dwell times, compared to that used in the validation of the four different iBus dwell time measurements (for which video data was available).

With the permission of TfL, the individual .saf files corresponding to the different vehicles and routes were copied onto a portable drive, and transferred to Southampton for further analysis. The iBus file downloads and copying was carried out over two separate days, each following a week or two after the day of the video-recording, as the upload of the .saf file data from individual vehicles to bus garages, and ultimately to the central and remote system servers, typically takes 2 days to one week to complete (at the time of the experiment).

4.3 Automatic Record/Data Extraction from Bus Log Files

As the dwell-time related data are not structured or stored in the .saf files in an easily accessible way, a method needed to be developed to extract this information from the records for further processing and analysis. Due to the high volumes of records involved, it was also necessary to (at least) automate this process. "middleware" programs were therefore developed in C++ to convert the raw bus .saf file data into decipherable terms, to capture, parse and compare the recorded timestamps of when vehicles entered/exited the bus Stop Zone, Halted, Opened and Closed Doors, and when the Speed is zero, and to use these times to calculate the stationary durations. C++ was chosen as the language for the middleware programs, as it was widely used by commercial developers, and is openly available to TfL (unlike e.g. Matlab). The final program listing for this "saf processor" can be found in Appendix III.

The program extracted and reported on the following event records from the vehicle saf files (see Appendix IV for example):

- 21 - Halt Begin and End;
- 31 - Stop Zone Entry and Exit;

- 41 - Doors Opened and Closed; and
- the second-by-second 82 Detailed GPS records.

As well as the duration between the Halt Begin/End, Doors Opened/Closed, and the Stop Zone Entry/Exit Events, the program compares the “Speed” field of the ID 82 records to determine when the vehicle’s speed reduced to zero and increased from zero, and calculated the duration between the intermediate events. Initially, this encompassed all instances of when the speed was reduced to zero, but it became apparent that this included all instances of when the vehicle stopped in the vicinity of the bus stop, e.g. where the stop is close to a pedestrian signal or zebra crossing, and the bus had to stop. The output (report) of derived stationary durations was therefore refined manually (by comparing to the video data) to remove records where these durations were not relevant, i.e. not associated with the bus stopping for passengers.

4.4 Validation of Measurements and Dwell Times Analysis

<u>Validation against Video</u>

The “cleaned” iBus records (which could be compared to video) were then transposed and consolidated into tables in Microsoft Excel, to enable the validation comparison between different dwell time measurement methods and the video data captured during the trial.
The techniques employed for this validation, include exploratory data analysis and correlation, are described in more detail in the next Chapter, along with the findings.

<u>Preliminary Analysis of Trial Data</u>

In addition to the validation, a preliminary analysis was conducted using the video-related data obtained from the on-street trial. This included a brief analysis of some of the factors that could affect bus stopping times, such as passenger types and numbers. While this information is not stored by iBus, the importance of passenger numbers on dwell times is well recognised in the Literature, and therefore the findings from this preliminary analysis was used to inform and improve the methods deployed in the subsequent detailed analysis of the iBus-derived dwell times. For example, it could be used to define the sub-classifications of stops that would provide some meaningful comparisons of iBus dwell times with previous research.

<u>Detailed Analysis of iBus-derived Dwell Times</u>

The preliminary analysis also helped to refine the automated iBus dwell time extraction process, as described in Section 4.3 above. In validating the four different iBus measurements against road-side video data, it became apparent that the detailed analysis needed to extract and analyse a much larger sample of dwell times (outside of those corresponding to the video data) to enable comparisons with previous studies. The method to determine how dwell (i.e. the stationary times at bus stops) could be measured was therefore refined, and plotted on flowcharts. These were then used to modify and improve the C++ extraction program logic, and the subsequent improved algorithm used to perform both the volume data extraction from the log files, and to automate (in so far as it is possible) the addition data reduction and cleansing required - see Appendix II and V for listings of the software used. Although the validation and analysis of dwell times appeared simple, it was in fact far more complicated than at first thought. For example (as will be seen in the next Chapter), the validation process threw up the existence of more complex stops, where buses stopped for multiple times and for lots of different reasons, in addition to the clean durations, which needed to be dealt with as part of the automation process. Further logic also had to be developed to link up other data items required in order to report on dwell times, such as the route number and bus stop name, and this required several iterations of testing as well as programming. (See Chapter 5 for further details of the final algorithm used to measure dwell time, and the flowchart logic.)

4.5 Expected Results

4.5.1 Difference Between Measurement Methods

Intuitively, the durations derived from Stop Zones Entry and Exit timings should produce a much *higher* estimation of dwell than is observed road side, since a stop zone can be defined as up to 50 metres (m) before the bus stop flag (and up to 30m after), and vehicles are typically around 10m long, and drivers tend to stop close by the flag itself, i.e. these durations would include the extra time for vehicles to travel across the bus stop zone. The durations between Doors Opened and Closed Events could provide a more accurate measurement of observed dwell, assuming the principal cause of bus stop delays is attributable to passengers, i.e. there is a constant stream of people boarding and alighting while the doors are opened, as some linear models suggest. However, this estimator of dwell would not factor in other causes of dead time or why buses may remain stationary at the stop, such as delays caused by the interaction of buses, or the vehicle being delayed from pulling out, which depends on road and traffic conditions. It is therefore likely that Doors durations would *under*-estimate dwell for bus priority purposes, although it *may* suffice if the definition of dwell adopted is taken solely as the service time required for passengers to board and/or alight, as discussed previously in Chapter 2. The use of iBus Halt events has also been suggested by the supplier, and it is understood that the speed smoothing method applied in their generation is based on previous experience. However, how well the Halt Begin/End durations reflect observed dwell times is untested yet, and the same is said for the Speed = 0 method using Detailed GPS records, although this latter method is expected to mirror closely the time when the vehicle *wheels* are stationary.

4.5.2 Dwell Time Analysis Results Expected

Assuming at least one of the four proposed iBus methods provides an accurate measurement for bus stop dwell times (compared to those observed road side), it should be possible to conduct some comparisons with the values obtained previously in London using manual surveys, e.g. by York (1993) and London Buses (2003). It should also be possible to assess how dwell times vary now compare to those previously, e.g. in terms of any change in the standard deviations of their values, although it should also be possible to calculate a coefficient of variation, as is suggested in the literature.

While it has been suggested that many of the factors that affected dwell time have changed since the previous surveys, such as the passenger demand and the vehicles employed , it will not be possible to compare directly the impact of these changes, as passenger boarding counts are not collected by iBus for example. However, it may still be possible to indicate how *some* factors could influence dwell, through reference to other information published in the literature or by TfL. For example, the effect of different vehicle types on dwell times may not be so great now, e.g. compared to York, as the relatively modern buses used in London's fleet are now all low floored (i.e. no steps for passengers to negotiate), and their acceleration/deceleration performances have improved. Similarly, the encouragement of Oyster card use and cashless payments in London should have reduced the impact of various payment types used in boarding that were found in York's day, which in turn may affect the variation in dwell times now.
In addition, dwell times are known historically to vary according to the time-of-day (see Chapter 2), and an analysis of the dwell times obtained through the iBus measurements should provide indicative trends of how they vary, which in turn may help guide any future research required in this area.

Chapter 5 Analysis and Results

As discussed in Chapter 4, the iBus vehicle log files provide four potential methods for deriving bus stop dwell times. The first step in the analysis was to determine which method provided the best match to stationary dwell time as required by TfL. This was performed by comparing the durations derived from each of these methods against the dwell time data captured by video during the two days of the experiment - see Section 5.1 for details. As well as the validation, a preliminary analysis of the video-related data from the on-street trial was also conducted, and this is also described in Section 5.1 below. Having decided on the one iBus method which provided close alignment to video, further detailed analysis was then performed (see Section 5.2) on the durations derived using this method from all the log file records collected during the experiment, and the results used to provide indicative "dwell time" values which could be used to improve bus operations, network scheduling, transport planning and simulation modelling. This analysis should also demonstrate the validity of using the iBus method to measure dwell times for individual bus routes or stops in London, which in turn can used to improve the operation of SCOOT and similar systems for bus priority purposes. As TfL are also developing Running Time reports based on door durations, i.e. the Doors Opened and Closed times of vehicles at bus stops, the dwell time values derived through the best chosen method were also compared to those generated in this way. The results of this analysis are given in Section 5.3, which also provides guidance to TfL on the ongoing validity of using this alternative method.

5.1 Preliminary Analysis and Validation of Dwell Time

An automatic extraction program was developed (see Section 4.3) to estimate dwell time from the log file event records for each of the four possible methods, i.e.:

- the Stop Zone "Entry" (Record ID = 31, "Event Type" = 1) and "Exit" records (ID = 31, "Event Type" = 2);
- the Halt "Beginning" (ID = 21, "Type" = 1) and "End" records (ID = 21, "Type" = 2);
- the Doors "Opened" (ID = 41, "Type" = 1) and "Closed" records ("Type" = 2); and
- the Detailed GPS (ID = 82) records, where the value of the "Speed" data item is zero, i.e. the "Speed Zero" (or "Sp = 0") records.

The Stop Zone, Halt and Door records were typically paired, and an elapsed duration was calculated from the time difference between the Entry/Beginning/Opened and Exit/End/Closed events, as each record is time-stamped. Exception handling was included in the program for the rare cases where the events were not paired due to technical reasons. In the case of Speed Zero records, the extraction program was written to compare the Speed value of the current record with that of the previous, and where this had decelerated to zero within the Stop Zone (i.e. the previous was not), this record was designated as the Speed Zero "Start" event; and after this record, when the Speed value increased above zero, the *previous* zero record was designated as the Speed Zero "End" event, and a stationary duration between the Start and End was calculated as the dwell time. The Detailed GPS records were chosen for the Speed Zero calculations as they are captured on a second-by-second basis in the log files, with the speed taken directly from vehicle instruments, i.e. odometer/speedometer. This gives the added advantage that Speeds are independent of the GPS signal, as the System reverts to using dead reckoning, i.e. location determination based on the odometer and gyroscope, to produce the Detailed GPS records when there is limited or no GPS signal.

The use of Stop Zone Entry and Exit events for estimating dwell times may seem inappropriate, as the stopping area or "cage" around the bus stop flag appears to bear no direct relationship to the purpose of a bus stopping to pick up and drop off passengers. However, these durations derived from Stop Zone Entry and Exit events could be used by TfL to provide other dwell and Running Time reports (as discussed in Section 4.1.1), and these records were therefore included in the analysis to compare their appropriateness for estimating dwell times. In addition, it was important to know when a vehicle had entered and exited the bus Stop Zone in the analysis and validation for the other three potential measurement methods. For example, while Doors Opened/Closed records typically (but not necessarily) occurred within a Stop Zone, both the Halt and Speed Zero records could be generated outside of Stop Zones, e.g. because the vehicle stopped at a traffic signal. The program therefore only extracted Halt, Doors and Speed Zero records which were contained (or started) within a bus Stop Zone, i.e. within a pair of Stop Zone Entry/Exit records. Conversely, within a given Stop Zone, the log file may contain more than one pair of Halt and/or Doors and/or Speed Zero records, and the extraction program needed to account for these situations also (see Section 5.1.2 below).

Section 5.1.1 describes in detail how the log file records are processed by the extraction program. After processing, the program produced an output report, which was initially designed to show all events comprehensively, i.e. listing all the Stop Zone/Halt/Doors/Speed Zero events at a bus stop, which provided an indication of all the activities related to vehicles stopping, that could be compared to the stationary durations as captured on video. However, on analysis of the output reports, it became apparent that the data derived from the Stop Zone/Halt/Doors/ Speed Zero durations had to be further processed, before a like-for-like comparison could be made between the different measurement methods. This "Pre-processing" logic is described in Section 5.1.2, which is followed by the preliminary results from the video/on-street trial data in 5.1.3, the Validation comparison results in 5.1.4, and a conclusion to these findings in 5.1.5.

5.1.1 Bus Log File Processing

The individual vehicle log files were processed as follows:

- The records were first sorted to ensure they were in "Date" and "Time" order, as a given log file can cover more than one day, e.g. when the vehicle operates a 24-hour service.
- The program then accounted for the different event and record types, and selected those used to calculate the time durations by the four measurement methods referred to above, including the separate logic for Speed Zero records. Detailed flow charts showing the processing logic in the final version of the extraction program are given in Section 5.2.1.
- The Time stamps for the records, which are contained in the record "Header", were then converted from a format of hours/minutes/seconds (or hh:mm:ss) to derive an absolute durations in seconds.
- Each relevant event record, including the calculated duration on Stop Zone Exit/Halt End/Doors Closed/Speed Zero End was then written to an output report, in Excel format (see Appendix IV for an example page).

Although the log files captured a high volume of data which could be useful for operational reporting, there are challenges to interpreting the information that requires a degree of manual intervention and expert interpretation. For example, the log file records do not hold the unique bus Stop ID, and each stop is identified in the log file records as a set of GPS coordinates as stored in the iBus "Master" Files. These coordinates were translated from their equivalent U.K. Ordinance Survey map coordinates, or the "Eastings" and "Northings" of the Stop IDs as held on TfL's BusNet System. Further logic therefore had to be developed, and included in the extraction program, to identify the stop name from the "Announcement" or ID 117 records. This included extracting the Stop Name text from the "Next Stop" announcements, as there can be more than one Announcement record for each stop, e.g. which provide passengers with the Service Destination (e.g. Bus 85 "to PUTNEY BRIDGE"), the Current Stop Name (e.g. this stop is "HAYWARD GARDENS"), as well as the Next Stop Name (e.g. "PUTNEY HEATH / GREEN MAN"). The Current Stop Name could not be used for this purpose, as the vehicle would have entered the Stop Zone (and/or opened its doors) prior to this announcement being given (and therefore could not be included in any output already written, without considerable processing overhead in the program). The reported Stop Names were reviewed manually after each run of the program to ensure they were consistent and unique (as the text did not have to be). Similarly, the Route Number for the vehicle (which is helpful to identify the stops served along the route) had to be extracted from the ID 116 Electronic Ticketing Machine (ETM) records, and the required "Service Route" data item written to the output report, along with the vehicle's iBus Technical Vehicle Number (TVN) to aid identification of the record source.

5.1.2 Data Pre-processing

The initial data output by the extraction program was further "reduced" and "cleaned". These two techniques are used in data mining (Han and Kamber, 2000) to remove incomplete and/or inconsistent records prior to analysis, in this case to ensure that the durations derived through the four measurement methods could be compared directly with the video data. This "pre-processing" involved removing:

- records where the bus did not stop, i.e. where a Stop Zone duration could be calculated from the paired Entry and Exit records, but no associated Halt, Doors and/or Speed Zero records could be found; and
- records where there were multiple Halt/Doors/Speed Zero events in the same Stop Zone.

For the multiple events or "complex" stops, it was not possible to discern a single stopping duration based on the log file data alone. From an analysis of the accompanying video data, it was noted that these complex stop records could be caused by many different reasons. Typically, they involve multiple passenger boarding and/or alighting occurrences, which could be due to, for example, a stop having several boarding/alighting points for passengers, e.g. as at Richmond Bus Station, where the bus stop cage is over 60m long, and buses were observed to queue up behind each other in moving upstream along the cage, dropping off and picking up passengers at different points as they proceeded. These drop-off/pick-up points were dynamic along the cage and could not be pre-determined beforehand. Alternatively, multiple boarding/alighting events also occurred when there are "late" passengers wanting to get on/off the bus, e.g. as at Goodge Street Station, where the driver had already made a "normal" stop and closed the vehicle's doors and driven off, but had to stop again and re-open doors for late passengers. Such complex stopping events could also occur when there are other, non-passenger related reasons for the vehicle to stop within the Stop Zone, such as queuing due to congestion or a traffic signal, or where there is a zebra or pedestrian crossing forcing the bus additionally to stop within the Zone, but these should not be counted as part of dwell time (see Section 2.1), particularly for use in bus priority, as they form part of the link journey time.

While it was possible to use the video data to separate out the different types of complex stop records, the objective of this research was to automate (in so far as it is possible) the derivation of bus stop dwell times based on the vehicle log files alone. Even with the video data, it was found that manual judgement still had to be applied to determine which complex records should be combined, and which ignored, to form a single duration record for deriving the bus stop dwell time. As these complex stop records formed a relatively small proportion of the total bus stopping records, or less than 20% of those available for the Validation analysis, they were excluded from the validation comparison, and only "clean" or normal stops were used, i.e. where vehicles stopped only once within the bus Stop Zone and opened and closed its doors for passengers. This approach is in line with TfL's definition for a "productive" stop (London Buses, 2008), as discussed in Section 4.1.1 previously. A more detailed analysis and discussion of the different types of stopping activities at bus stops is provided separately in Section 5.4. The overall pre-processing method used in this study is therefore consistent with that applied previously by TfL (London Buses, 2003), where "inaccurate" stopping times were excluded from manual survey counts, including cases where the stopping values were either indiscernible or the buses did not stop.

5.1.3 Preliminary Analysis of Video/Trial Data

To reduce the degree of manual data entry, the start and end times of the recorded video data (as described in Section 4.2.2) were used to filter out the corresponding iBus stopping records from the processed vehicle log files as captured for the on-street trial (see Section 5.1.1 above). This eliminated the need for keying in details such as the bus stop name when transcribing the on-street stopping times from video to an electronic "Preliminary Analysis" dataset for the trial. For each stopping record in the dataset, the video-related information transcribed included:

- the bus stop name (from iBus, but checked against the bus stop announcements on video),
- an assigned stop number,
- the stopping "activity type" (see below);
- the stopping duration (in seconds);
- the number of passengers boarding and/or alighting;
- any boarding activity notes, e.g. use by elderly/disabled passengers or those paying cash;
- the service route; and
- the region of a bus stop and its location type (as defined previously in Section 4.2.1.1).

As discussed in Section 5.1.2 above, the observations from video suggest that bus stopping activities may be divided into two types, i.e. clean (type 1) or complex (type 2) stops, and the proportion of these records in the initial preliminary analysis dataset is shown in Table 5.1.

Table 5.1 Video/On-street Trial Data Used in Preliminary Analysis

	N	% of Total	Mean (s)	s.d. (s)
Total type 1 (Clean) Stops:	120	88.9%	15.30	7.55
Type 2 (Complex) Stops:	15	11.1%	-	-
Total Video'ed:	135	100%		

In the case of complex stops, it was not always possible to determine an exact or single stopping duration visually, due to occurrence of multiple stopping incidences and/or door opening and closing sequences. However, it can be seen from Table 5.1 that the proportion of these stops is relatively small (or less than 12% of the total observed) and, in common with previous practice (London Buses, 2003), the preliminary analysis of video-related data from the on-street trial was therefore conducted using only the clean stops, i.e. N=120. (See Section 5.4.1 for further discussion of clean and complex stops.)

As observed through the on-street trial, there was a wide variation in the bus stopping times between different stops, e.g. min. = 4s, and max. = 51s. The preliminary analysis also suggests that there was a wide variation in stopping times between different routes - see Table 5.2.

Table 5.2 Stopping Times by Route during On-street Trial (Clean Stops Only)

		Bus stopping times:		Average no. of passengers:			s.d. of no. of passengers:		
Route	N	Mean (s)	s.d. (s)	Boarding	Alighting	Total*	Boarding	Alighting	Total*
31	29	16.1	7.03	2.5	2.9	3.9	2.5	3.0	3.5
65	24	12.5	6.66	2.8	1.6	2.8	3.2	0.7	3.0
85	14	17.4	10.29	2.5	2.3	3.5	2.8	2.1	4.2
134	23	15.2	5.19	2.5	2.8	3.4	2.2	2.5	2.7
507	7	15.7	7.30	2.5	3.8	5.4	3.8	5.0	5.6
521	11	12.0	4.86	2.0	1.5	2.2	1.4	1.3	1.5
K3	12	19.0	10.37	3.6	2.3	3.8	2.0	1.2	2.5
Total	120	15.3	7.55	2.6	2.5	3.5	2.6	2.5	3.3

* Total Passengers Boarding and Alighting

From Table 5.2, it can be sent that the clean bus stopping times as captured during the on-street trial varied between the seven different routes used, e.g. the mean times varied from 12 to 19s. Similar variations were also observed in the average number of passengers boarding and/or alighting for these routes, which is perhaps not surprising, given the importance of passenger numbers on dwell time (as discussed previously in the Literature in Section 2.2). However, the passenger relationship may be more complex than is suggested in previous research, as higher average passenger numbers (either in boarding, alighting, or both) do not necessarily always result in longer mean stopping times (although it should be noted that the on-street trial excludes the evening peak period, where passenger numbers could be higher still). There are likely to be other factors that impact on bus stopping times, which may account also for the variation in passenger numbers across the different bus routes and stops. Table 5.3 shows the variation of bus stopping times and passenger numbers by the region in which a bus stop is located.

Table 5.3 Stopping Times by Region during On-street Trial (Clean Stops Only)

		Bus stopping times:		Average no. of passengers:			s.d. of no. of passengers:		
Region	N	Mean (s)	s.d. (s)	Boarding	Alighting	Total*	Boarding	Alighting	Total*
1 (Central)	43	15.9	6.51	2.6	2.8	4.0	2.6	3.0	3.6
2 (City)	7	10.3	3.73	2.0	0.8	1.9	1.6	0.5	1.6
3 (Suburban)	65	15.1	7.69	2.8	2.4	3.3	2.8	2.1	3.3
4 (Rural)	5	20.0	14.40	2.8	-	2.8	1.8	-	1.8
Total	120	15.3	7.55	2.6	2.5	3.5	2.6	2.5	3.3

* Total Passengers Boarding and Alighting

Table 5.3 suggests there are also variations in passenger numbers and stopping times between stops in different regions, cf. Region 1 (Central Zone) with 2 (City) or 3 (Suburban). Similar variations were observed for bus stops located close to interchanges (location type 1) and in shopping areas (type 2) compared to regular stops (type 4) - see Table 5.4.

Table 5.4 Stopping Times by Stop Location during On-street Trial (Clean Stops Only)

Stop Location Type	N	Bus stopping times: Mean (s)	Bus stopping times: s.d. (s)	Average no. of passengers: Boarding	Average no. of passengers: Alighting	Average no. of passengers: Total*	s.d. of no. of passengers: Boarding	s.d. of no. of passengers: Alighting	s.d. of no. of passengers: Total*
1 (Interchange stops)	29	16.9	6.62	3.3	3.9	4.8	2.5	3.6	3.8
2 (Shopping Area stops)	10	18.4	7.88	4.0	3.6	6.1	3.8	3.7	4.7
3 (Hospital stops)	2	10.5	-	1.0	1.0	2.0	-	-	-
4 (Regular stops)	79	14.4	7.77	2.3	1.9	2.7	2.3	1.5	2.6
Total	120	15.3	7.55	2.6	2.5	3.5	2.6	2.5	3.3

* Total Passengers Boarding and Alighting

In addition to overall numbers, it was also observed that the occurrence of certain types of passengers resulted in longer stopping times. These include, for example, use by elderly and disable passengers, or those with pushchairs and young children - see Table 5.5.

Table 5.5 Stopping Times by Passenger Type during On-street Trial (Clean Stops Only)

Passenger Type	N	Bus stopping times: Mean (s)	Bus stopping times: s.d. (s)	Average no. of passengers: Boarding	Average no. of passengers: Alighting	Average no. of passengers: Total	s.d. of no. of passengers: Boarding	s.d. of no. of passengers: Alighting	s.d. of no. of passengers: Total
"Typical"	83	12.9	5.60	2.5	2.7	3.5	2.4	2.8	3.3
"Non-typical"*	37	20.6	8.65	2.9	2.1	3.4	2.9	1.6	3.2

* Involving passengers such as the elderly/disabled, or those with pushchairs/young children, luggage/shopping bags or paying cash.

From Table 5.5, it can be seen that the occurrence of such "non-typical" types of passengers resulted in a higher mean and standard deviation of bus stopping times compared to "typical" or able-bodied passengers. (See Section 5.4.1 for further discussion of the different types of passengers and activities that were observed during the on-street trial.) The stopping times for these two groups of passengers (typical and non-typical) were also compared using a two-sample Kolmogorov-Smirnov (K-S) test in SPSS, and the result suggests that their dwell times are significantly different ($p < 0.05$). Therefore, assuming the number of passengers boarding and alighting at each stop is random and independent of the different types of passengers, the results from the on-street trial suggest that the occurrences of certain types of passengers (i.e. the elderly/disabled or those with pushchairs/young children, luggage/shopping bags or paying cash) leads to longer than average bus stopping times. (Unfortunately the sample sizes for individual specific groups, e.g. the elderly/disabled, were too small to provide further meaningful analysis, with N<10 in each case.) While this preliminary analysis provided some useful understandings which could be taken forward to the later analysis of iBus-derived stop dwell times (in Section 5.2), no further statistical analysis was conducted on the video-related passenger data derived from the on-street trial due to the small sample sizes involved.

(The analysis of different types of passengers and their numbers is not an objective of this research in any case, as this information cannot be obtained directly through iBus currently.)

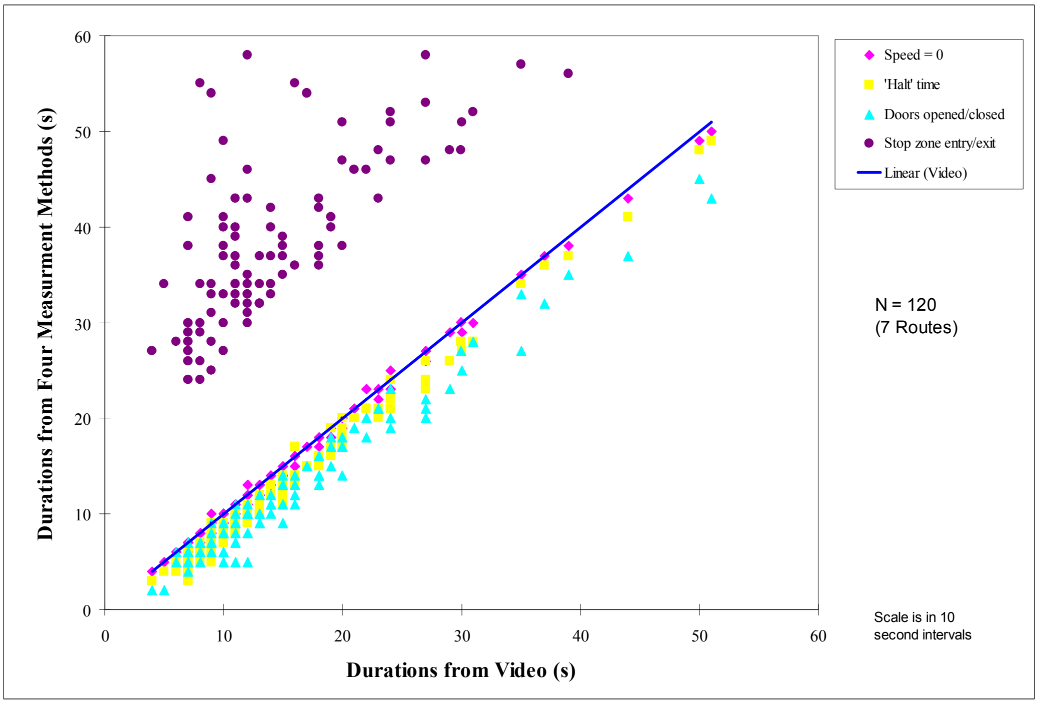
5.1.4 Validation of Dwell Time by Different Measurement Methods

Having conducted the preliminary analysis, the duration records derived using the four potential iBus methods were then compared against the bus stopping times as captured by video from the trial, which acted as a fifth measure for control purposes. The start and end times from the recorded video data (see Section 4.2.2) were again used to filter out the associated iBus Stop Zone/Halt/Doors/Speed Zero duration records for each vehicle/route. These duration records were then pre-processed and consolidated into a single clean "Validation" dataset as before and compared against the transcribed durations as captured on video. A same sized dataset was therefore used for the validation of different iBus dwell time measurements as in the preliminary analysis conducted previously, i.e. N=120 (see Table 5.1 above), although the records in this Validation dataset now contained extra data items to account for the four different stopping duration measurements from iBus as well as for video.

5.1.4.1 Exploratory Data Analysis

The Validation dataset covered a broad range of different routes, stops, regions and vehicles. Figure 5.1 shows a comparison of the duration accuracy between the four measurement methods and video, across the seven routes for which both the video and iBus data was available for comparison (N=120).

Figure 5.1 Dwell Time Durations as Measured by Different Methods in Seconds (Clean Stops Only)



In Figure 5.1, the durations derived from the four iBus measurement methods are plotted on the y-axis against those from video on the x-axis (representing the "true" dwell values) for an excerpt of stops. The blue 45 degree line suggests an "ideal measurement" which contains exactly the same values as the video data. It can be seen from Figure 5.1 that, apart from the durations based on the Stop Zone Entry/Exit events (in purple), the others three duration measurements of stationary dwell time are relatively consistent with the true video data. The Speed Zero durations (in pink) most closely match the 45 degree line, i.e. they are the closest to the true values amongst all four measurement methods, while the Stop Zone durations are distinctively larger than those from video. These Stop Zone durations are based on when vehicles enter and exit the stopping area, which are a function of the size of the capture zone, and the different stopping events that occur within this area, including any passenger-related stopping activities by the stop flag itself. Given the capture zone is typically 30 and 50m either side of the bus stop flag, the Stop Zone durations therefore include the time it takes for a bus to traverse the capture zone, as well as all manner of other causes which may require buses to stop, including obstructions due to parked cars and other vehicles e.g. in loading and unloading, traffic signals and pedestrians crossings, and delays due to the interaction of buses before, during and after the stop flag. The Stop Zone durations are therefore considerably longer than the other measurements methods, which can also be seen from their relative frequency distributions (N=120) - see Figure 5.2.

Figure 5.2 Frequency Distributions between Different Measurement Methods (Clean Stops Only)

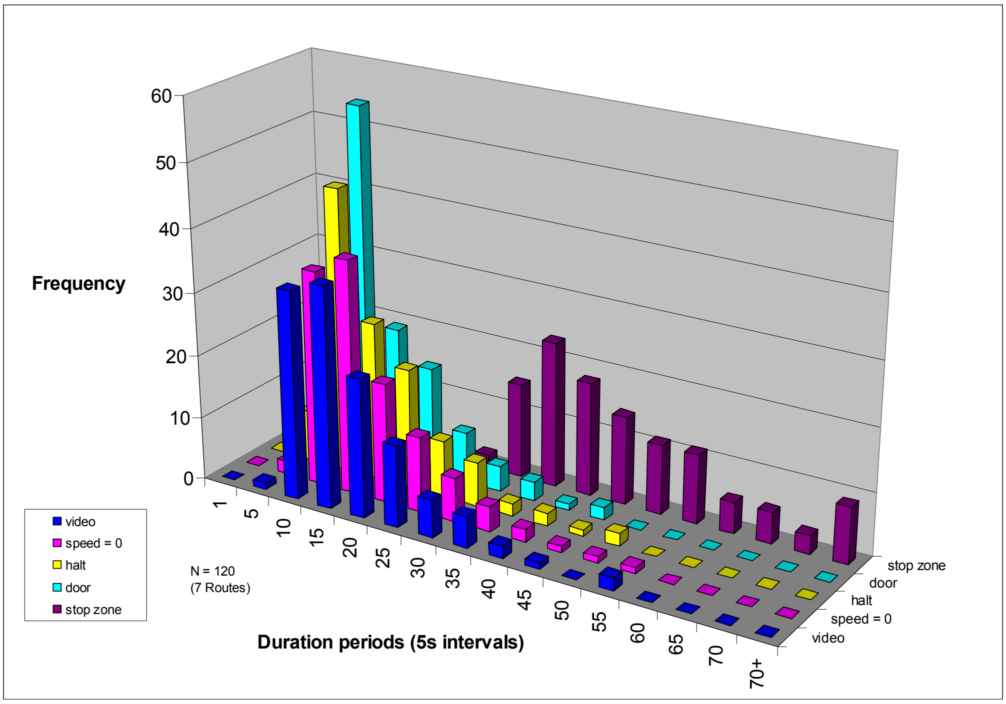
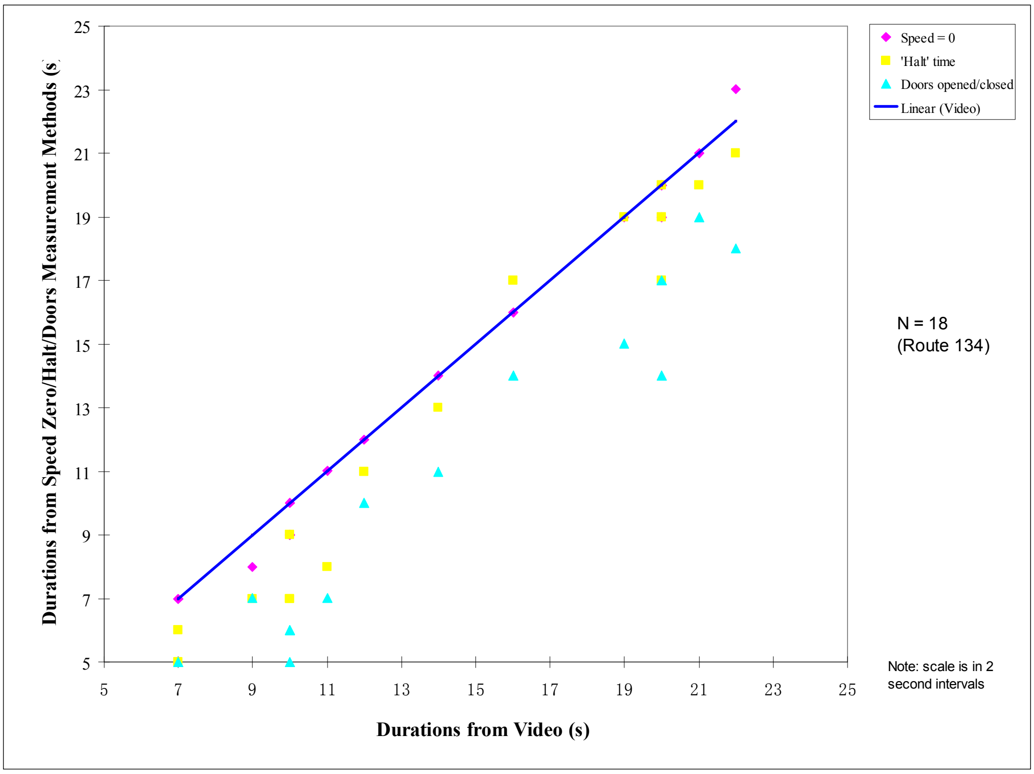


Figure 5.3 shows a smaller and more detailed excerpt of the graph from Figure 5.1, and compares the durations from the three remaining possible dwell time measurement methods to

video for one Route, Number 134 (N=18). (Note that a smaller scale is used in Figure 5.3 to highlight the differences between the three different iBus measurement methods and video.)

Figure 5.3 Durations from Video/Halt/Doors/Speed Zero Measurement Methods in Seconds (Route 134)



It can be seen from Figure 5.3 that, while the duration profiles between the different measurement methods are relatively consistent, those from Doors Opened/Closed events (points in light blue) tend to fall a few seconds below those derived from video footage (shown again by the 45 degree blue line). This is not surprising, given they cover only the period when the doors are open, and therefore exclude other vehicle dead times, e.g. for the door mechanisms to open and close, which is another important constituent of dwell time (York, 1993). The Halt events (yellow points) provide a closer match to the video times, but are generally less accurate than the Speed Zero measurements (in pink). This is because the Halt events are recorded by averaging out the stopping duration of vehicles, whereas the Speed Zero events in effect record when the vehicle's wheels are stationary, and therefore they are very consistent with those derived from the on-street video data.

Mean Squared Error

Table 5.6 below shows the Mean Squared Error (MSE) values between the Speed Zero, Halt and Doors durations compared to those from Video. These mean square errors are a measure of the errors between the Speed Zero, Halt and Door durations and those derive from video (i.e. the "true" values), and were calculated by taking the expected value of the square of the difference between the three measured values and the true values from video, i.e. (Lebanon, 2010):

$$MSE = E(\hat{\theta} - \theta)^2 = E(\sum_{i=1}^{n} \left(\hat{\theta}_i - \theta_i\right)^2) \qquad (5.1)$$

For a Normal distribution, this is the best unbiased estimator, but for a non-normal distribution, the unbiased estimate is:

$$MSE = \sum_{i=1}^{n} \left(\hat{\theta}_i - \theta_i\right)^2 \Big/ (n-1) \qquad (5.2)$$

Table 5.6 Mean Squared Error Values for Speed Zero, Halt and Door Durations vs Video

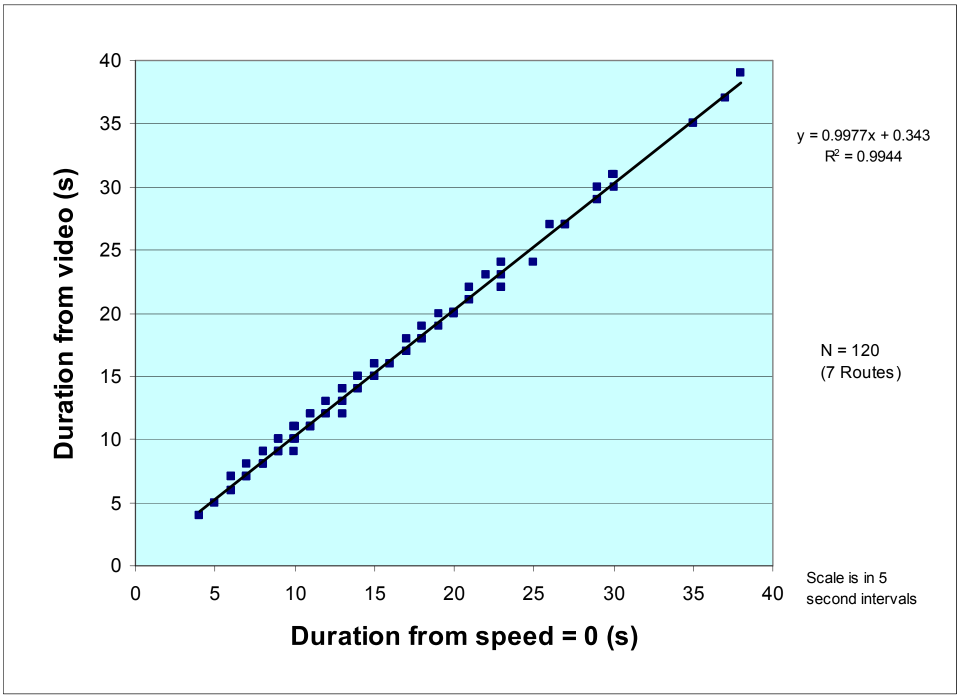
	Video - Sp Zero	Video - Halt	Video - Doors
Mean Squared Error (MSE) (N=120)	0.44	1.91	3.54

It can be seen from Table 5.6 and Figure 5.3 further above, that the Speed Zero durations provide the closest estimators of dwell times as derived from video (MSE = $0.44s^2$), and the analysis therefore focused on the consistency between the durations obtained from video and those measured from Speed Zero events.

5.1.4.2 Correlation

Figure 5.4 shows the plot of dwell time durations as measured by the Speed Zero records against those captured by video recordings, in seconds (N = 120).

Figure 5.4 Correlation of Durations between Video and Speed = 0 (Clean Stops Only)



It can be seen from Figure 5.4 that there is a strong correlation between the values of dwell duration as measured from video and the Speed Zero events, with r = 0.994 ($p<0.01$). A paired T-Test was conducted to compare the distribution and means between the video durations and those obtained from the Speed Zero measurements. Although the result showed there exists a difference between the two measured times, $t(119) = 6.01$, $p < 0.05$, the paired T-Test is known to be very sensitive, and it was suggested by Bland and Altman (1986) that when comparing the agreement of observations from different equipments, the graphic method, e.g. as use in Figure 5.4, may provide a more direct and meaningful judgment when comparing the agreement of two different measurements. The small difference between the two measurement methods could be due to an element of human error in transcribing the vehicle start and stop times from video, as such errors are known to contribute for example a variation of 0.3s in starting and/or stopping a stopwatch (Gust et al., 2009). Also, the difference between the two methods is close to the level of accuracy for the equipment used in both the iBus and video measurements, which are recorded to the nearest second, i.e. the accuracy of the measurements is within ± 0.5s. Therefore the difference may be significant, but hardly important (or meaningful), given the small MSE. It was therefore concluded that the iBus Speed Zero durations provided a close measurement for the dwell times as observed on-street through video.

5.1.5 Preliminary Analysis and Validation Conclusion

The preliminary analysis of the video-related data from the on-street trial (see Section 5.1.3) suggests that bus stopping times varies according to many factors. In addition to passenger numbers, the time-of-day and vehicle type (which have been suggested by the Literature), the observed stopping times during the trial also varied according to the bus route, and the location and region of the bus stop, which may in turn reflect the changes in passenger demand, a factor which is not measurable through iBus. A comparison of the durations derived from the four possible iBus measurement methods, i.e. from Stop Zone Entry/Exit events, Halt events, Doors events, and where the vehicle speed = 0 shows that the Speed Zero method provides the most accurate measure of observed on-street dwell times (see Section 5.1.4). The durations based on the Halt Begin/End events also provide a close approximation to observed dwell times, but these are not being considered by TfL for reporting at present. The durations based on Stop Zone Entry/Exit are significantly longer than those observed, while those from Doors Opened/Closed events are a few seconds less than observed. Given TfL are also developing reports that make use of these Doors events (Robinson, 2009), they are likely to provide lower dwell times than those actually observed - but see Section 5.3 for a comparison between the Doors event times and those derived from Speed Zero durations. The Speed Zero durations, as derived from the bus log files, provide the most accurate measurement of dwell time as defined by TfL, which are comparable to those observed on-street. However, these durations need a confirmation that the bus is in the Stop Zone, and that they are associate with passenger boarding-related events and not, e.g. with the queuing from traffic signals.

5.2 Analysis of Dwell Time from iBus Speed Zero Measurements

Having established the accuracy of using Speed Zero durations as a measure for dwell times, the next stage of the study focussed on the analysis of these measurements across a range of different factors, as suggested by the preliminary analysis of video-related data from the on-street trial, and as described previously in Chapter 4, i.e. dwell times by route, bus stop, time-of-day, location/region and vehicle type. This would enable like-for-like comparisons to be made between dwell times derived through this method and those obtained previously through manual surveys, and demonstrate the potential of applying this method to measure bus stop dwell times, which could then be used for a wide variety of purposes by TfL, as discussed in Section 2.4. The analysis also allows some *indicative* values to be provided, although (as highlighted previously in Sections 2.2.5 and 2.2.6) some caution should be taken in using these values, given the range of factors that could influence dwell across different stops, and generalised value should only be used where it is impossible to obtained them by any other means (including the ones recommended here). As part of the analysis, a review of the extreme values and outliers was conducted, which helped to inform and refine the process by which dwell time measurements could be obtained. This overall data extraction, consolidation and refinement process is described in Section 5.2.1. This is followed by an analysis of dwell times by route in Section 5.2.2; by time-of-day in 5.2.3, location/region in 5.2.4, and vehicle type in 5.2.5. The resultant indicative Speed Zero dwell times, which take into account some of these parameters, are then summarised in Section 5.2.6.

5.2.1 Data Extraction, Consolidation and Refinement

5.2.1.1 Automatic Data Extraction

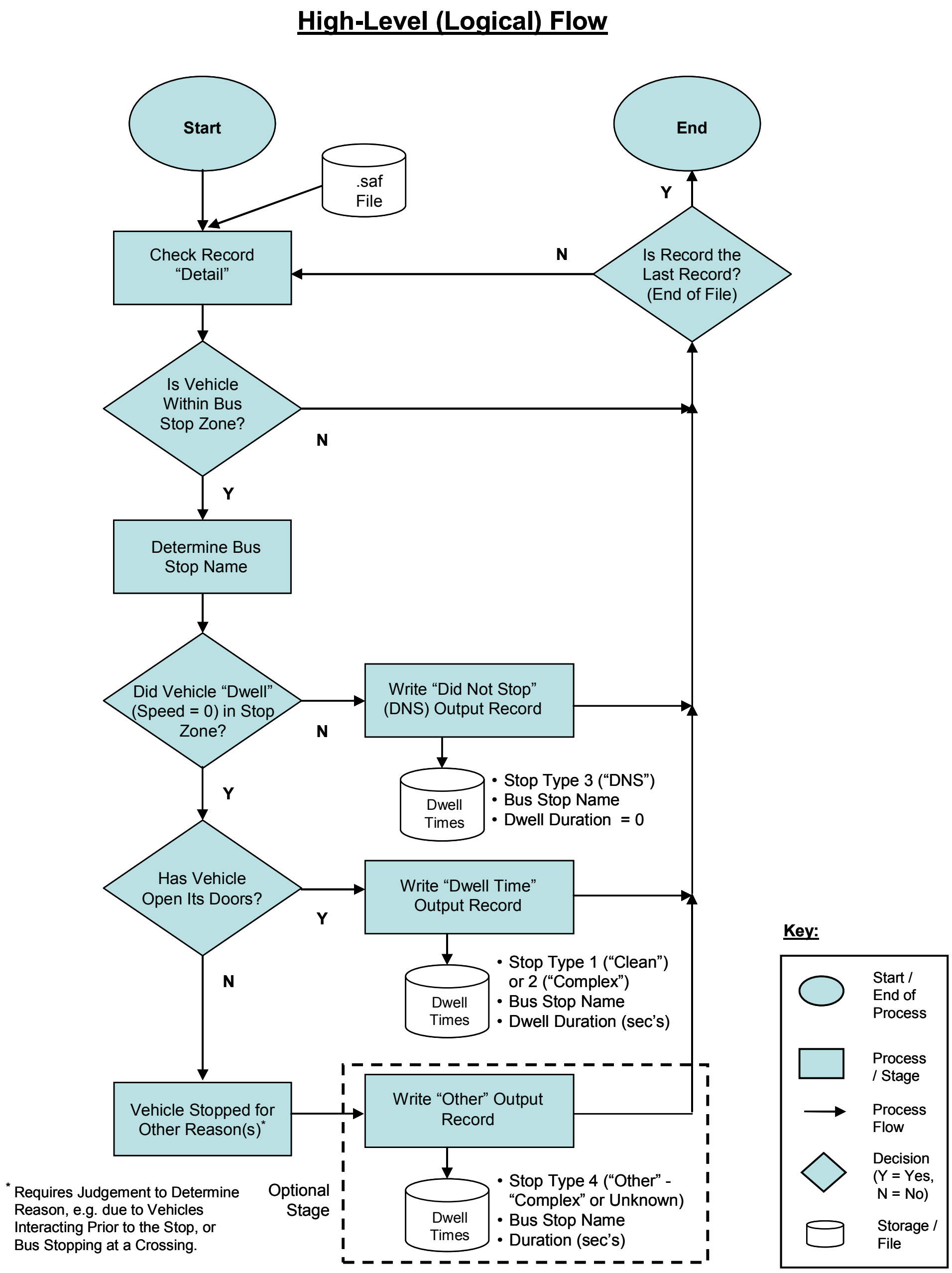
From the experience gained in the on-street trial, and a review of the different types of clean and complex stops that was performed at the same time (see Section 5.4 further below for details), a "truth table" was constructed to determine the logic for distinguishing between the different types of stopping events to be found in the bus log files, e.g. clean, complex or did not stop. A new "Speed Zero Processor" algorithm was then written to deal with the higher volumes of log files records involved, distinguish between the different types of stopping events (as per the truth table), and output the clean dwell time values for analysis. The algorithm also included logic for performing all the "log file processing" and "data pre-processing" steps described previously in Sections 5.1.1 and 5.1.2. The algorithm therefore automatically:

- identifies the route and Technical Vehicle Number;
- determines when the bus entered (and exited) each bus stop zone;
- identifies the stop name;

- reviews each Detailed GPS record to determine the Speed Zero start and end events, and calculates the intervening duration;
- determines the door opened and closed times, as applicable;
- separates/rejects records where the bus did not stop or there are multiple or complex stopping events which do not allow a clean dwell time to be calculated;
- performs time and other format conversions e.g. calculate durations in seconds; and
- "collapses" all the different associated bus stop events into a single dwell time record for each stop zone in the output.

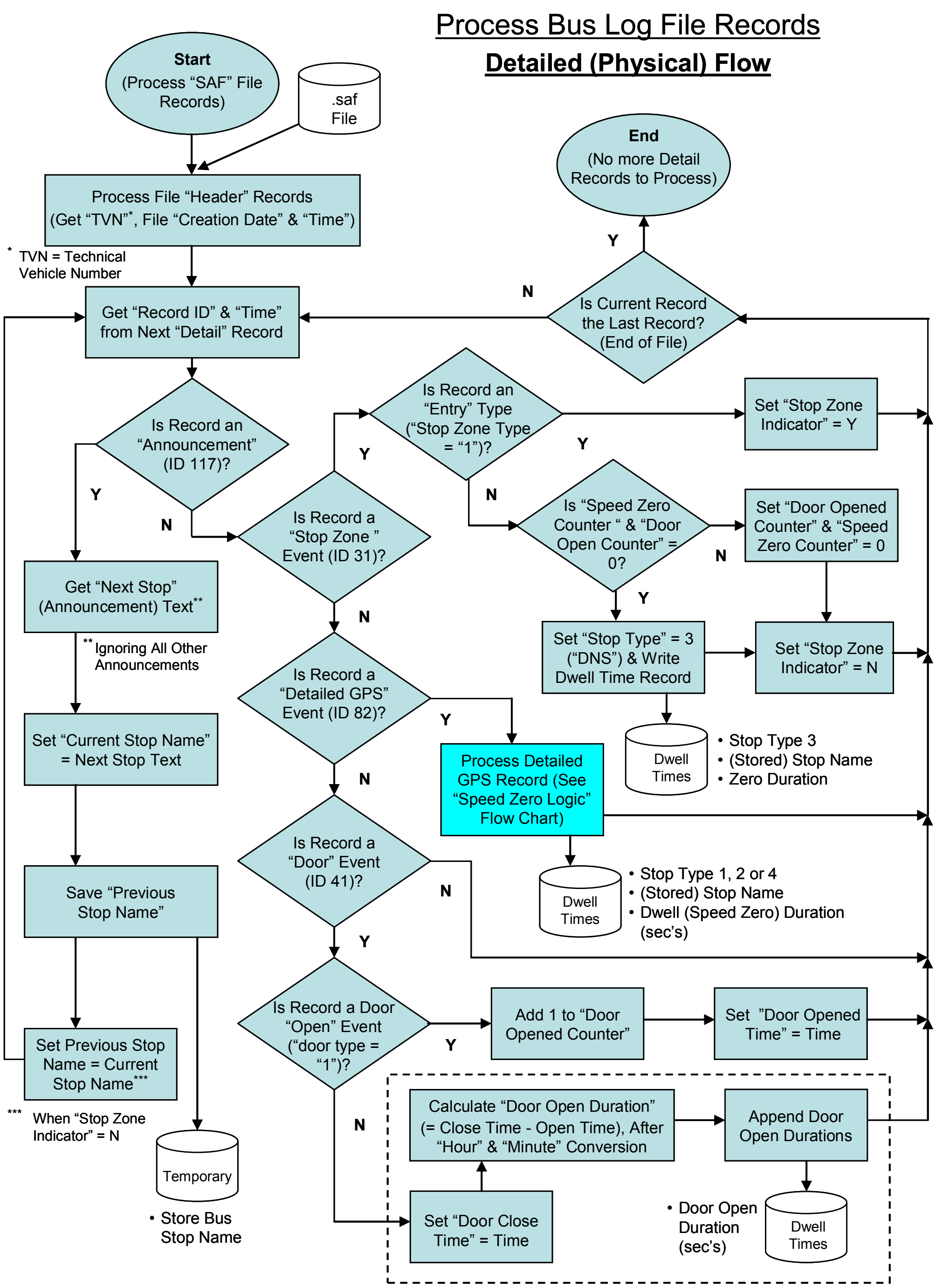
A high-level flowchart showing the key processing logic for the algorithm is given in Figure 5.5.

Figure 5.5 Flowchart for Processing "Dwell Times" from iBus Vehicle Log Files



The detailed logic involved in processing the Stop Zone, Door and Speed Zero records, including the steps to extract the bus stop name and the vehicle' technical number is shown in Figure 5.6.

Figure 5.6 Detailed Flowchart for Processing Bus Log File (.saf) Records



The design of the Processor was altered from the original extraction program so that each dwell time duration was now output as a single record, and not reported as their individual Start and End constituent (Detailed GPS) records as stored in the log files - the highlighted "process" box shown in Figure 5.6, the logic of which is expanded on in Figure 5.7 below.

Figure 5.7 Flowchart for Processing Detailed GPS Records ("Speed Zero Logic")

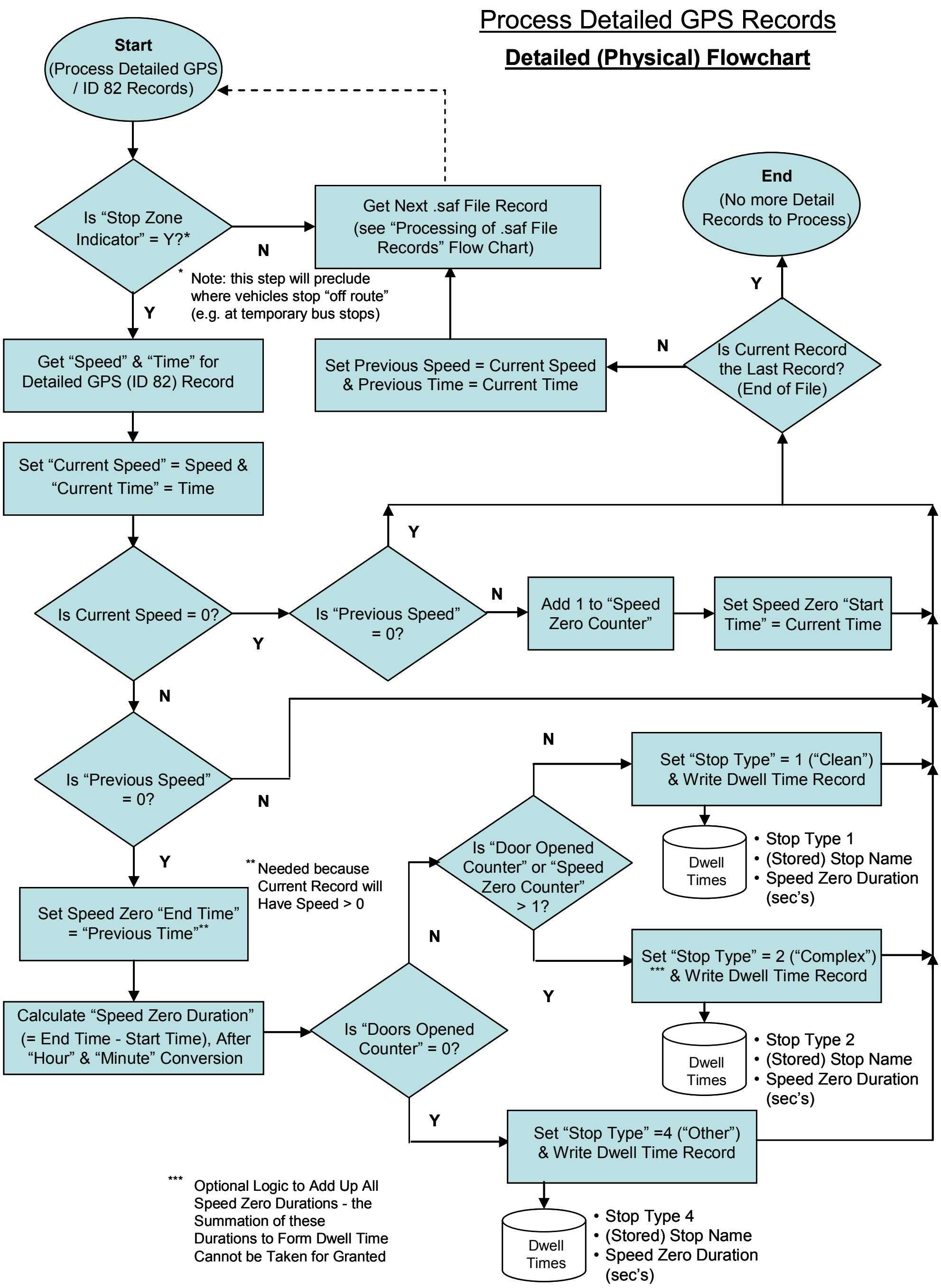


Figure 5.7 shows the detailed logic in the algorithm for processing the Detailed GPS (or ID 82) records for deriving the required clean Speed Zero durations. Doors Opened/Closed and Stop Zone Entry/Exit times associated with these durations were also included in the same output dwell time record (as opposed to separately for the extraction program originally) - see Appendix V for the full Speed Zero Processor algorithm listing.

5.2.1.2 Data Consolidation and Refinement

The Speed Zero Processor algorithm was used to output pre-processed dwell times from the bus log files of 16 vehicles and 10 different routes - see Section 4.2.1 for details of the routes/vehicles. The log files cover the full period for which the buses were in service, i.e. out of the depot, during the two days selected for the Validation/on-street trial comparisons, which included nearly 2,100 clean bus stop dwell time records that covered the main "daytime" period as defined by TfL, i.e. from 07:00 to19:00.

The dwell time records for all routes and bus stops were consolidated, and extreme values and/or outliers analysed. From the experience of the on-street trial, and the associated analysis of clean (and complex) stops, it was noted that the dwell times derived from the Speed Zero durations could contain anomalies or non-typical events that resulted in extreme values. For example, a dwell time of over two and a half minutes (153s) experienced at Pemberton Gardens, the bus stop nearest to Holloway Garage, was caused by delays due to a change of driver, and not associated with TfL's definition of a productive stop, as discussed in Chapter 2. Without supporting on-street data however, it was impossible to predict and/or remove these non-typical events. For practical reasons, based on the evidence observed during the trial (see Section 5.4), it was decided these anomalies or extreme values could be removed by statistical means. According to Moore (2010), as a "simple rule of thumb", any data point falling more than 1.5 time the Inter-Quartile Range (IQR) below the first quartile or above the third quartile values are considered to be outliers. Therefore, dwell time durations which are outside 1.5 * the IQR above and below (respectively) the Upper and Lower Quartile values for each route were excluded from further analysis. This criteria is consistent with the techniques employed by TfL (e.g. Robinson, 2009) to define journey time reports for iBus, as used in Reports 240 and 300, and the method deployed previously in manual surveys (London Buses, 2003). These excluded extreme stopping values or events account for less than 7% of the total dwell time records in the consolidated dataset, and further examples of such events may be found in Section 5.4 further below. The remaining 1,950 Speed Zero dwell time records were then analysed by route, different Time-of-Day periods, location/region, and vehicle type using SPSS version 17.0, and the findings for these discussed in Sections 5.2.2 to 5.2.5 respectively below. The number of derived dwell time data points used is in keeping with those provided to the International Bus Benchmarking Group (Trompet et al, 2011) for performance and regularity measurements in 2009 and 2010. However, the largely automated method developed in this study for deriving bus stop dwell times has the potential to provide much larger dataset sizes in future, provided access to the iBus vehicle log files is available.

5.2.2 Dwell Times by Route and Bus Stop

The main dwell time analysis was conducted using the consolidated iBus dataset of 10 Routes, with the extreme values removed and complex stops excluded, i.e. N=1,950 - see Table 5.6.

Table 5.7 Dataset Used in Main iBus Dwell Time Analysis (10 Routes)

Proportion of iBus-derived Speed Zero duration records (07:00-19:00 Period):

	N	% of Total	Average (s)	s.d. (s)
Clean Stops (Processed)	1,950	77%	13.84	6.04
Complex stops* (Excluded)	442	17%		
Extreme values** (Removed)	145	6%		
Total Stops***	2,537	100%		

* where a single stopping duration cannot be determined from iBus
** duration falling outside 1.5 x the Inter-quartile range of all values
*** Includes complex stops and extreme values, i.e. Unprocessed.

From the experience of the on-street trial (see Section 5.1.3 above), the main dwell time analysis was conducted initially by route and bus stop, because apart from passengers numbers (which cannot be obtained from iBus), scheduling and service headway (which are route specific) are considered to be the main factor that affects dwell durations (Shalaby and Farhan, 2004). This approach is also consistent with previous research (London Buses, 2003; York, 1993), and enables detailed comparisons to be made with the previous results for London buses over the years. The data from each route were explored first for outliers, and then visual inspection of the underlying distributions. They were then further tested for randomness and distribution; and after a specific distribution was recognised, the average values and deviations for each bus route calculated. Despite the wide variation in dwell times across individual stops (as discussed in Chapter 2.2), the iBus data collected was also analysed across a representative sample of stops, from which typical values were calculated, to help improve the understanding of dwell times for specific stops. The findings are discussed in Sections 5.2.2.1 to 5.2.2.6 below.

5.2.2.1 Exploratory Data Analysis

Figure 5.8 below shows the box-plots of the consolidated dwell times across all bus stops for the 10 routes in the main iBus dataset, i.e. for Routes 14, 31, 65, 74, 85, 134, 168, K3, 507 and 521. (Note this dataset excludes complex stops and extreme values, i.e. N=1,950.)

It can be seen from these box-plots that the dwell time distributions for all the routes are positively skewed, with long tails. There is a wide spread of dwell times across the different routes, which do not appear to follow a Normal distribution, as is commonly assumed in many predictive models (as discussed previously in Section 2).

Figure 5.8 Box Plots of Dwell Times for Ten Routes in London (N=1,950)

(excludes extreme values and complex stops)

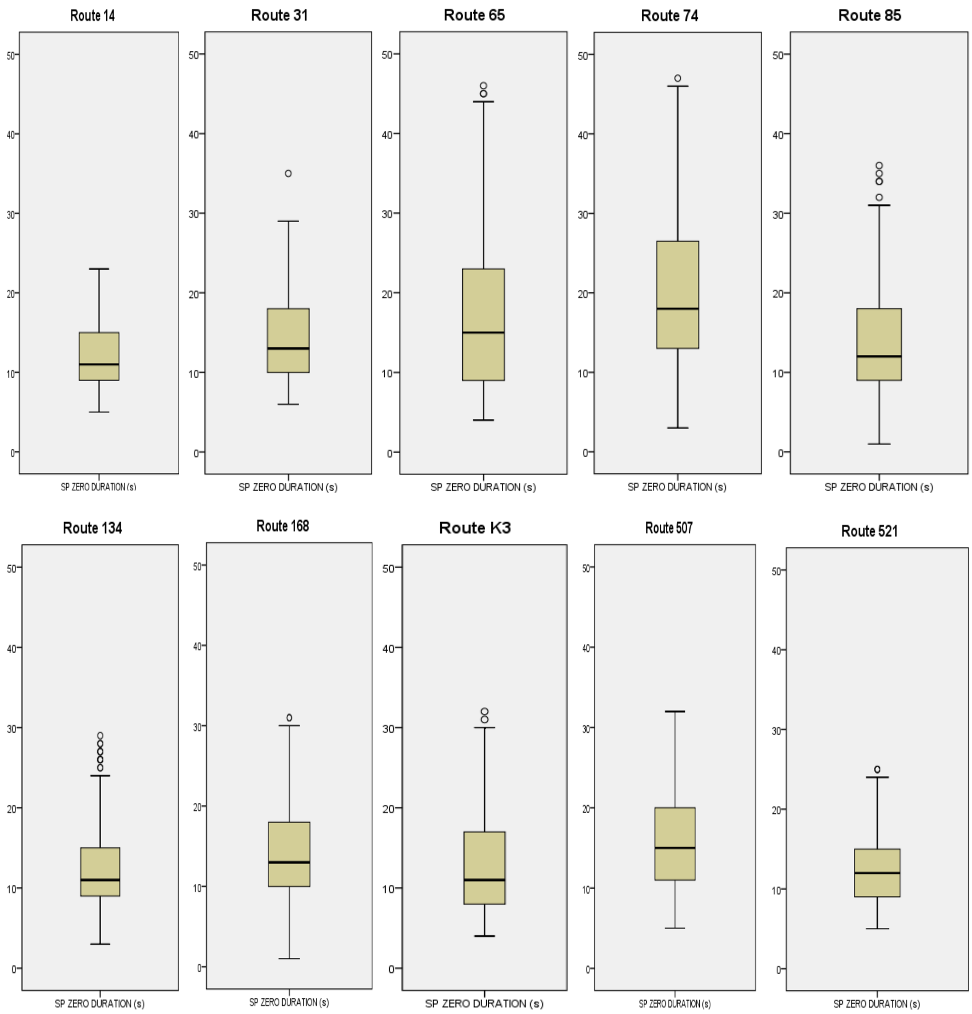


Table 5.8 below shows the average, median, lower and upper quartile dwell time values in seconds and the Inter-quartile range for the ten routes (N=1,950), as calculated by SPSS. Table 5.8 shows that the average values are higher than the median ones, and there is wide variation in the median and inter-quartile range of dwell times across the different routes, e.g. from 11 and 6 seconds (s) respectively for Route 14, to 15 and 14s for Route 65, and 18 and 13.5s for Route 74.

Table 5.8 and the box plots from Figure 5.8 therefore show there is a wide variation in bus stop dwell time between routes, as has been suggested by the literature, and previously in the on-street trial (see Section 5.1.3). However, the *Cv* (coefficient of variation) values are comparable to those in the literature, which suggests a range between 0.4s and 0.8s.

Table 5.8 Dwell Times Descriptive Statistics and Coefficient of Variation in Seconds

(excludes extreme values and complex stops)

Route	Descriptive Statistics Average	s.d.	Median	Lower Quartile	Upper Quartile	Inter-quartile Range	Cv*
14	12.02	4.38	11	9	15	6	0.37
31	15.24	7.15	13	10	18	8	0.46
74	20.56	10.14	18	13	26.5	13.5	0.56
168	14.47	5.65	13	10	18	8	0.43
65	17.07	10.28	15	9	23	14	0.63
85	13.89	6.83	12	9	18	9	0.57
134	12.59	5.31	11	9	15	6	0.43
K3	14.5	7.71	12	9	18	9	0.52
507	15.96	5.88	15	11	20	9	0.39
521	12.5	4.41	12	9	15	6	0.36
Across all routes	13.84	6.04	12	9	17	8	0.47

* Coefficient of Variation (see Section 2.2.5)

These variations are reflected in the values/statistics for individual bus stops - see Table 5.9.

Table 5.9 Descriptive Statistics and Coefficient of Variation for Individual Stops in Seconds

(excludes extreme values and complex stops)

Bus Stop	Average	s.d.	Median	Low. Quart.	Upp. Quart.	IQR	Cv
WESTMINSTER CITY HALL	15.67	4.89	15	12	19	7	0.31
PRATT STREET	13.36	5.24	12	9.75	14.75	5	0.39
ALDWYCH / ROYAL COURTS	12.29	5.20	11	8.5	14.25	5.75	0.42
LAMBETH PALACE	16.54	5.80	15	12	22.5	10.5	0.35
MARSHAM STREET	17.33	4.84	18	15	20	5	0.28
CHANCERY LANE STATION	16.31	4.77	18	11.5	20.5	9	0.29
HOLBORN CIRCUS / FETTER LANE	14.08	4.61	13	11	16	5	0.33
NEW CHANGE / CANNON STREET	13.64	4.06	15	10	16	6	0.30
PUTNEY / ST MARY'S CHURCH	17.73	10.21	16	12	18	6	0.58
ROBIN HOOD LANE	13.45	5.77	12	9	16	7	0.43
RAVENSWOOD COURT	11.46	4.20	11	8.5	13	4.5	0.37
KINGSTON HOSPITAL	16.00	8.82	13.5	8.25	24	15.75	0.55
Across all stops	13.84	6.04	12	9	17	8	0.47

Table 5.9 shows the descriptive statistics and *Cv* for a representative sample of different buses stops in London, including those in the West End (e.g. Westminster City Hall), City of London (e.g. New Change / Cannon Street), and Suburban London (e.g. Putney). It can be seen from this table that there are wide variations in dwell times between individual bus stops, with:

- their median values ranging from 11 to 18s, and average ranging from 11.5s to 17.7s;
- inter-quartile ranges (IQR) between 4.5 to 15.75, and standard deviation values from 4.2 to 10.21s; and
- the Cv's varying from 0.28 to 0.58.

Although the *Cv*'s are generally lower than those recommended by the TCQSM (Ryus, 2003), i.e. less than 0.6, the *range* of *Cv*'s is still high (0.3) and these wide variations suggest it is impractical to provide one default bus stop dwell time for London, as has been suggested by the literature, and for use e.g. in simulation modelling. The variations, and therefore some of the factors that influence dwell time, for example likely passenger demand and service frequency or route, need to be further explored before general indicative dwell times can be given.

5.2.2.2 Tests for Randomness of Sample Dwell Time Values

A Runs Test was performed to determine whether the Speed Zero durations at bus stops were random along each route, and therefore whether the dwell time values on the routes could be treated as independent. Table 5.10 shows an example of the output on the Runs Test performed on the 107 bus stop dwell times on one route, which has a median value of 11s.

Table 5.10 Runs Test for Randomness on Route 14

Runs Test

	SP ZERO DURATION (s)
Test Value[a]	11
Cases < Test Value	48
Cases >= Test Value	59
Total Cases	107
Number of Runs	58
Z	.798
Asymp. Sig. (2-tailed)	.425

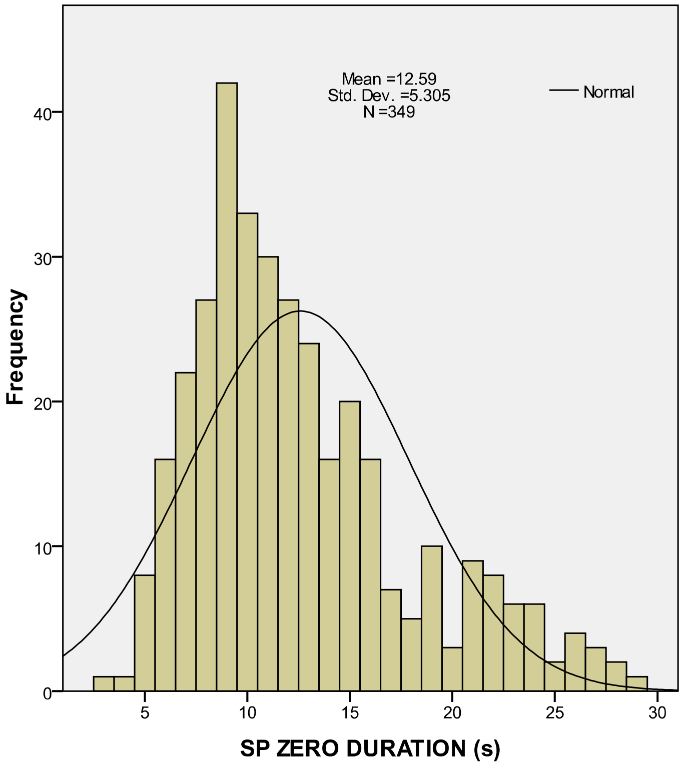
a. Median

In this, and the case for all the other routes analysed, the Test did not reject the assumption that the dwell time values on each route were random ($p > 0.05$). Therefore, dwell times collected from each test route were considered as independent for the purpose of further analysis.

5.2.2.3 Test for Normality

Figure 5.9 shows the cumulative frequency distribution for one route (Route 134), which is representative of all the routes. From Figure 5.9, it can be seen that the derived dwell time values do not appear to follow a Normal distribution, and therefore a test for Normality was performed on each of the ten routes. While the derived values are discrete, the underlying distribution of dwell times is continuous, and hence (Chakravati et al., 1967) a one-sample Kolmogorov-Smirnov (K-S) “Goodness-of-fit” Test was performed for each route.

Figure 5.9 Frequency Distribution of Dwell Times (Route 134)



Traditionally (as discussed in Chapter 2), the public transport modelling tools used in the U.K. tend to assume bus stop dwell times follow a Normal distribution, e.g. as shown by the examples for South West London (Arup, 2010) and Liverpool (e.g. Thorrignac, 2008). However, Table 5.11 below illustrates the output for a K-S Test on one Route (65) previously analysed by York (1993), and the assumption of dwell times following a Normal distribution was violated ($p < 0.05$) on this, as well as the other routes.

Table 5.11 Kolmogorov-Smirnov Test for Normality on Route 65

		SP ZERO DURATION (s)
N		121
Normal Parameters[a,,b]	Mean	17.07
	Std. Deviation	10.280
Most Extreme Differences	Absolute	.161
	Positive	.161
	Negative	-.104
Kolmogorov-Smirnov Z		1.772
Asymp. Sig. (2-tailed)		.004

a. Test distribution is Normal.

b. Calculated from data.

This is not surprising, given dwell times cannot be negative, which provides a lower limit on the dataset, and this is a typical reason (Buthmann, 2010) why such datasets do not follow a Normal distribution. In the vast majority of cases, dwell times involve two or three passengers boarding and/or alighting (as was witnessed from the video in the on-street trial), so the majority of values are near the limit, yet it could involved many more passngers, particularly in urban areas, and at peak hours, and this increases the spread of dwell times along the tail.

5.2.2.4 Testing for Other Distributions

The literature (see Chapter 2) indicates that one of the biggest factors affecting dwell times is the number of passengers boarding and alighting, which has been suggested to follow either a Poisson (Guenthner and Sinha, 1983) or Exponential distribution (Rajbhandari, Chien and Daniel, 2003). Li et al (2006) has shown that the K-S Goodness-of-fit method can also be used to test whether the sample dwell time values were taken from these two common distributions. Table 5.12 shows the output for the K-S Test for a Poisson distribution on the dwell times for one route. From this, and similar Tests for the other routes, showed that the sample dwell times do not follow either a Poisson or Exponential distribution ($p < 0.05$).

Table 5.12 Kolmogorov-Smirnov Test for Poisson Distribution on Route 65

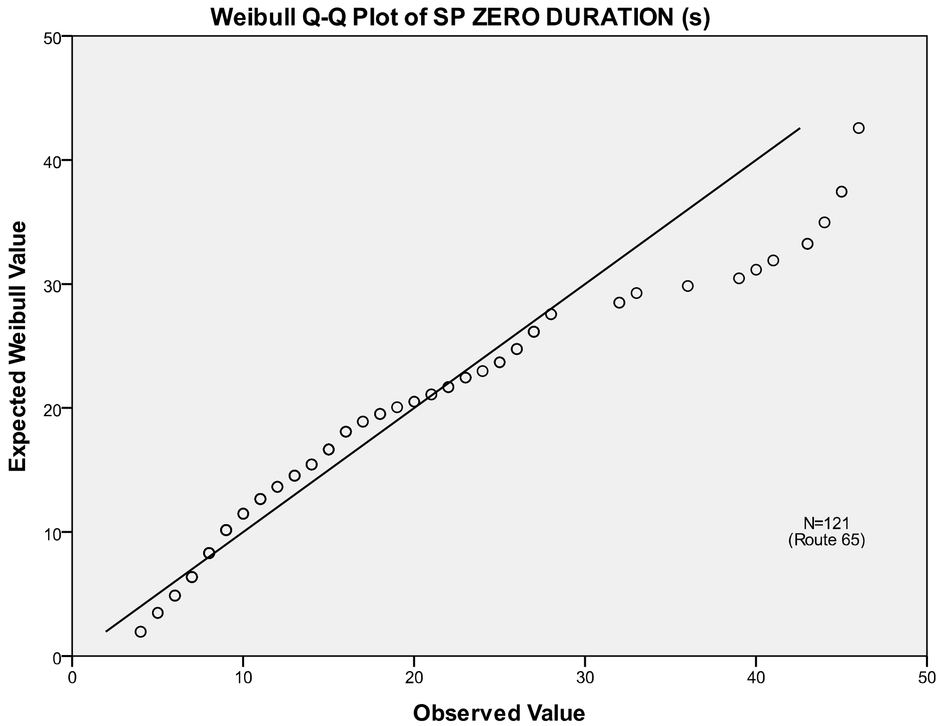
		SP ZERO DURATION (s)
N		121
Poisson Parameter[a,,b]	Mean	17.07
Most Extreme Differences	Absolute	.298
	Positive	.298
	Negative	-.181
Kolmogorov-Smirnov Z		3.276
Asymp. Sig. (2-tailed)		.000

a. Test distribution is Poisson.

b. Calculated from data.

Fries et al. (2009) suggest that the rate of passenger arrivals at a bus stop could also follow a Weibull distribution or a more generalized form of the Exponential distribution, while Adamski (1992) suggests passenger service times at bus stops follow a Gamma distribution. The sample dwell times for each route were therefore also compared against these two distributions using graphical Quantile-Quantile (or “Q-Q”) Plots, which are particularly effective (Wilk and Gnanadesikan, 1968) when the distributions have long tails. Figure 5.10 shows the Q-Q Plots from SPSS comparing the observed dwell time quantile values on Route 65 with the expected values at the equivalent quantiles from a test Weibull distribution derived from the same sample data.

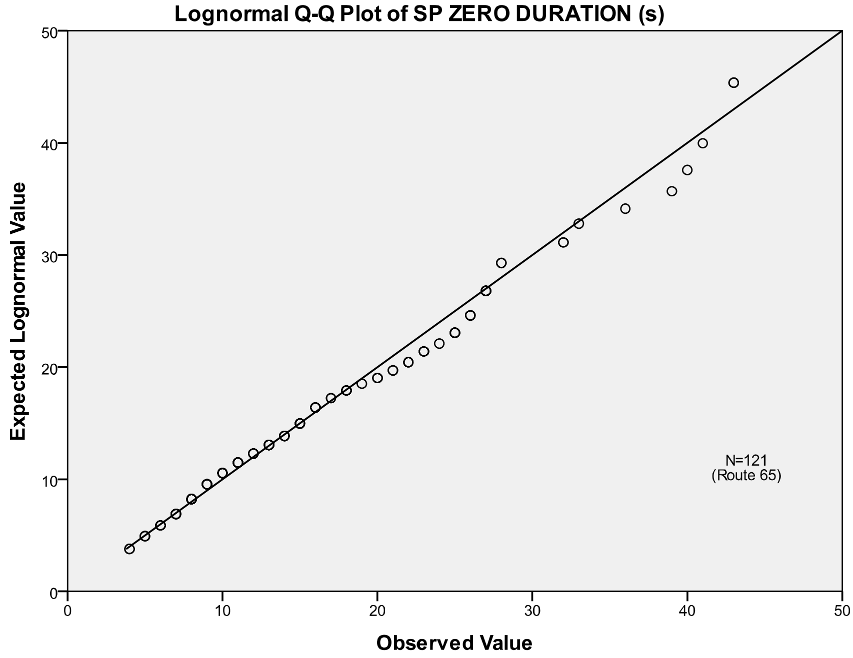
Figure 5.10 Q-Q Plot of Dwell Times on Route 65 against a Weibell Distribution



The Q-Q plot is used to check whether the sample data follows a theoretical distribution (Weibull or Gamma Distribution in this case). In SPSS, the expected values of quantiles for the target population were plotted (on the *y* axis) against the quantiles for the sample (on the *x* axis), and a 45 degree reference line drawn on the plot to represent a "perfect fit". The closer each point on the plot is to this line, the more likely that the sample follows this theoretical or test distribution. While Figure 5.10 shows the Q-Q plot for the sample from one route against the Weibull distribution, similar Q-Q plots were conducted for all the other routes against both the Weibull and Gamma distributions. From these figures, it was concluded that the sample dwell times do not follow either a Weibell or Gamma distribution, as it can be seen from the figures that some data points are far away from the reference line.

The Q-Q plots in SPSS also allow comparison of the sample dwell times with a test Lognormal distribution - see Figure 5.11 for an example from the same route. These show a strong correlation to the 45 degree line, and a similar match was found for all the other routes. Dwell times have been shown to follow Lognormal distributions in other cities, e.g. Barcelona (Estrada et al, 2011), although this assumption has never been made for London buses (2003) previously.

Figure 5.11 Q-Q Plot of Dwell Times on Route 65 against Lognormal Distribution



If the derived dwell times do follow a Lognormal distribution, then their transformed log values should follow a Normal distribution (Laurent, 1963). A one-sample K-S Test for Normality (see Section 5.2.2.3 above) was therefore performed on the transformed dwell values for each of the routes, using natural logs in this case. Table 5.13 illustrates the SPSS output for the K-S Normality Test for the transformed dwell time values for Route 65.

Table 5.13 Kolmogorov-Smirnov Test for Normality on Transformed Dwell Times (Route 65)

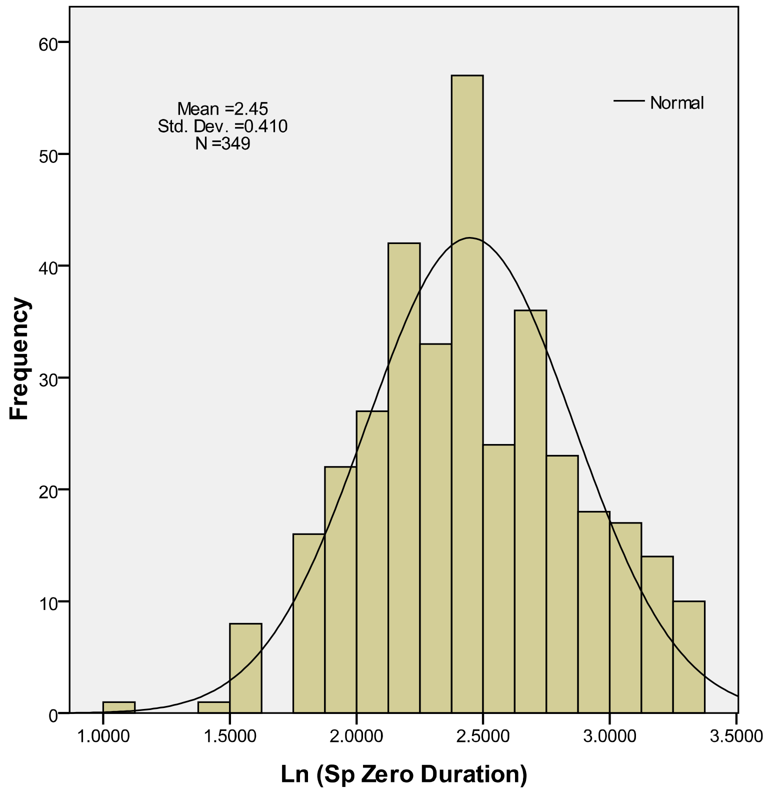
		Ln (Speed Zero)
N		121
Normal Parameters[a,,b]	Mean	2.669716
	Std. Deviation	.5822072
Most Extreme Differences	Absolute	.064
	Positive	.064
	Negative	-.050
Kolmogorov-Smirnov Z		.706
Asymp. Sig. (2-tailed)		.701

a. Test distribution is Normal.

b. Calculated from data.

As can be seen from Table 5.13, the transformed values follow a Normal distribution ($p > 0.05$), which was also true for all the other routes. As further illustration of this, Figure 5.12 shows the frequency distribution of the transformed dwell times for Route 134 (as used previously), which appears Normal compared to the un-transformed original values (cf. Figure 5.9).

Figure 5.12 Frequency Distribution of Transformed Dwell Times (Route 134)



5.2.2.5 Deriving Expected Values of Dwell Time for London Buses

Assuming x represents the sample dwell time values which follow a Lognormal distribution, then (Laurent, 1963):

$\ln(x) \sim N(\mu, \sigma)$, where:

μ is the *location* parameter, and

σ is the *scale* parameter of the transformed distribution,

and the *expected value* of x, $E[x]$ and *variance*, $D[x]$ are calculated by:

$$E[x] = \exp(\mu + \sigma^2/2) \quad \text{...(5.3)}$$

$$\text{and} \quad D[x] = \exp(2\mu + \sigma^2) * (\exp(\sigma^2) - 1) \quad \text{.....................(5.4)}$$

$$\text{or} \quad D[x] = \exp(E[x]^2) * (\exp(\sigma^2) - 1) \quad \text{..........................(5.5)}$$

The values of μ and σ for the transformed distribution were calculated using SPSS, being the *mean* and *standard deviation* of the Normal distribution of the *transformed* log values of the sample dwell times, i.e. given y are the transformed dwell time values, or $y = \ln(x)$, then $\mu = E[y]$ and $\sigma = \sqrt{E[y-\mu]^2}$. Therefore, once μ and σ are known, the expected value $E[x]$ and standard deviation ($= \sqrt{D[x]}$) of the dwell times for each route can be calculated using Equations (5.3) and (5.5) above.

The coefficient of variation *Cv* for lognormal distributions (Baek et al., 2006) is again calculated by dividing the standard deviation ($\sqrt{D[x]}$) by the expected value ($E[x]$) of the distribution (from Section 2.2.5). However, by substituting terms, its calculation can be simplified to (Baek et al., 2006):

$$Cv = \sqrt{(\exp(\sigma^2) - 1} \qquad (5.6)$$

5.2.2.6 Summary of Dwell Times by Route

Table 5.14 shows the calculated expected value, standard deviation and coefficient of variation of dwell times across the ten different routes, along with the average and median values calculated previously, and the associated lognormal location (μ) and scale (σ) parameters, as calculated by SPSS.

Table 5.14 Dwell Time Statistics for 10 Routes across London (N= 1,950) in Seconds

(excludes extreme values and complex stops)

Route	Nature	Descriptive Statistics					Lognormal parameters		
		pected Valu	s.d.**	Average	s.d.***	Median	μ	σ	Cv****
14	Urban (E-W)	11.98	4.389	12.02	4.380	11.0	2.42	0.355	0.37
31	Jrban (Orbita	15.29	7.085	15.24	7.150	13.0	2.63	0.441	0.46
74	Urban (E-W)	20.83	11.656	20.56	10.141	18.0	2.90	0.522	0.56
168	Urban (N-S)	14.51	6.241	14.47	5.650	13.0	2.59	0.412	0.43
65	uburban (N-S	17.10	10.861	17.07	10.280	15.0	2.67	0.582	0.63
85	Juburban (E-W	14.02	7.984	13.89	6.829	12.0	2.50	0.530	0.57
134	uburban (N-S	12.60	5.393	12.59	5.305	11.0	2.45	0.410	0.43
K3	Juburban (E-W	14.44	7.523	14.5	7.706	12.0	2.55	0.490	0.52
507	ty - CBD (E-W	15.98	6.243	15.96	5.881	15.0	2.70	0.377	0.39
521	Urban (E-W)	12.55	4.476	12.5	4.405	12.0	2.47	0.346	0.36
Across all routes		13.85	6.448	13.84	6.041	12.0	2.53	0.443	0.47

* Expected value = E [x], as calculated using Equation 5.3 above, where μ and σ are the mean and standard deviation for the transformed distribution of log values of dwell times.
** s.d. = $\sqrt{D[x]}$, where $D[x]$ is calculated using Equation 5.4 above, where μ and σ are the lognormal parameters as for E [x].
*** Standard deviation, assuming a Normal distribution.
**** Coefficient of Variation, calculated from E [x] and $\sqrt{D[x]}$ (see Section 2.2.5)

From Table 5.14, it can be seen that the expected values for all the routes are a second or two higher than the median ones, as dwell times follow a Lognormal distribution and the spread of values is skewed to the right. However, the expected values are nearly the same as the average ones and the standard deviation (s.d.) values in the majority of cases are similar to those as calculated for a Normal distribution, which suggests the normality assumption provides a close approximation. For bus priority and modelling purposes though, this study shows the underlying distributions for the absolute mean and s.d. values are Lognormal, and therefore sampling values from a Normal distribution will generate less accurate dwell times, the error of which depends on the route. In some cases, for example on routes 74 and 85, the s.d. values can differ by more than a second to the equivalent Normal values, suggesting normality estimates of dwell times will be distorted, and higher errors will occur. This degree of error may be important for accurate microscopic modelling and bus priority purposes, where a few seconds could affect for example, the accuracy of the "bus vary" (or journey time variability) value given to SCOOT, which reduces its effectiveness to provide priority extensions, and therefore the delay savings given to vehicles (Hounsell et al., 2008b), which are typically 3-6 seconds per bus per junction. For other applications though, while the difference is significant, an error of one or two seconds may not be important.

From Table 5.14 above, the range of expected values and spread of dwell times across different services also suggest that the routes vary in nature, e.g. that they serve different locations and regions, and these factors should be accounted for before any indicative dwell time values are provided - see Section 5.2.4. Nevertheless the expected values as derived through Speed Zero durations are broadly consistent with earlier research, i.e. York (1993) and London Buses (2003), and a detailed comparison of dwell times with previous published studies follows.

5.2.3 Dwell Times by Time-of-Day

While average daytime values are useful, the literature suggests (see Chapter 2) that dwell times can also vary by Time-of-day, and an analysis of Speed Zero durations was therefore performed across the three main daytime periods as defined by TfL, i.e. the AM Peak, PM Peak and the Inter-Peak, or 07:00 to 10:00, 16:00 to 19:00 and 10:00 to 16:00 respectively. These current TfL time periods are similarly to those used previously for research on London buses, although York (1993) amalgamates the two Peak periods and prefers the term "Off Peak" to describe the duration in-between, which can be misleading as the daytime usage of buses outside peaks hours is typically a factor of 2 to 3 times higher than those for the evenings and early mornings (TfL, 2007), and can be even higher then the peak periods on occasion. A more recent manual survey (London Buses, 2003) used the same Time-of-day periods as suggested here, except the AM Peak period ended (and started) half an hour earlier, in line with the usage of Travelcards. However, London traffic (TfL, 2003) and transport (TfL, 2010d) reports suggest the morning peak period endures longer, and therefore the later definition to 10am was used.

An analysis of dwell times across the three time periods was conducted for all the routes used in this study. Where possible, a comparison of sample dwell times against those derived from previous surveys was also conducted, i.e. against 1993 and 2002, and these are described separately in Sections 5.2.3.1 and 5.2.3.2 below. The dwell times by Time-of-day across the other, non-compared routes are then summarised in Section 5.2.3.3.

5.2.3.1 Comparison with Manual Survey in 1993 (York)

The last major review found of bus stop dwell times across London was conducted by York (1993), which covered a similarly wide variety of routes, locations/regions and vehicles. With the move to one-person operated (OPO) two-door vehicles throughout London, and the introduction of low-floored double-decked buses as standard (TfL, 2006b), the diversity of York's research is no longer as relevant. In addition, the trend by TfL to reduce the operating distance on many long routes over the past decade (e.g. for Route 11 and 25) [ref], makes a like-for-like comparison with York's manual surveys difficult. However, it is still possible to compare York's results against those derive from iBus on at least one route, which has remained unchanged during the intervening period (Harris, 1995), i.e. Route 65, a double-decked, one-person operated suburban service, which covers the same route at similar frequencies between Ealing Broadway and Kingston today. A comparison of the dwell times for this route is shown in Table 5.15.

Table 5.15 Dwell Time Comparisons for Route 65 in Seconds

			iBus (2010)		**York** (1993)	
Time-of-day Period	Between	And	Expected Value	s.d.	Mean	s.d.
"All Times" / "All Day"	07:00	19:00	17.10	10.86	20.74	Not stated
Both (AM and PM) Peaks:	07:00-10:00	16:00-19:00	14.94	8.97	19.48	Not stated
Inter-/Off-Peak:	10:00	16:00	19.19	12.41	21.59	Not stated

From Table 5.15, it can be seen that on this particular route, the Inter-Peak dwell time is higher than the Peaks, which is reflected in both the values derived from iBus, and those from York. From the literature review, this suggests either the number of passengers and/or the average boarding/alighting time per passenger could be higher during the Inter-Peak than the Peaks, which is not surprising given the service links three major suburban shopping centres, at Ealing Broadway, and Richmond and Kingston Town Centres. The impact of location and region on dwell times is discussed in more detail in Section 5.2.4 further below.

From Table 5.15, the expected dwell times from iBus have also reduced since York's day by between 2.4 to 4.5 seconds, depending on the time period. This reduction does not appear to be due to a lowering of passenger demand as, from the video data captured during the on-street trial, the average number of passengers boarding was observed to be 2.82, which is only just higher than the 2.78 value quoted by York (1993). Assuming traffic conditions and the number of bus stops on the route remained unchanged, these improvements in dwell times are more likely due to a significant reduction in the number of passengers paying cash and/or receiving change when boarding. According to the Mayor of London (Johnson, 2008), the number of such passengers have dropped dramatically since the introduction of the Oyster card, from an average for buses of 18% in 2003/4 to 1.6% in 2008, i.e. the number paying by cash is now minimal. This suggests the expected values derived from the Speed Zero durations are broadly similar to those from York, if the latter's mean survey dwell times were adjusted to account for this, although the distribution of dwell times for individual routes is not stated explicitly in his surveys. As illustration, York (1993) suggested that the boarding time to pay increases by an average of 3.4s per passenger over those who used a pass, i.e. from 2.4s to 5.8s, and by a further 2.3s for those who required change. The reduction in dwell time is less pronounced during the Inter-Peak period, suggesting (TfL, 2009) a higher proportion of shopping and leisure trips during this period, where cash payment by passengers could still occasionally apply.

5.2.3.2 Comparison with Manual Survey in 2002 (TfL)

A study in 2002 (London Buses, 2003) was conducted by an external transport consultancy on behalf of TfL. This focussed on the before-and-after performance of Red Arrow express services due to the introduction of new vehicles to the London fleet, and covered three separate routes. One of these (Route 501) no longer operates, but the two remaining services, the 507 and the 521, have stayed unchanged, i.e. they operate between the same destinations at approximately the same frequencies as previously, and follow the same routing (Harris, 2002). A comparison of the dwell times with the survey in 2002 is shown in Table 5.16.

Table 5.16 Dwell Time Comparisons for Red Arrow Routes 507 and 521 in Seconds

Routes 507

			iBus (2010)		**TfL** (2002)	
Time-of-day Period	Between	And	Expected Value	s.d.	Mean	s.d.
"All Times" / "All Day"	07:00	19:00	15.98	6.24	15.5	8.9
Am Peak:	07:00	10:00	12.78	4.87	14.3	9.4
PM Peak:	16:00	19:00	17.10	5.49	18.2	11.9
Inter-/Off-Peak:	10:00	16:00	16.65	6.58	14.9	7.1

Routes 521

			iBus (2010)		**TfL** (2002)	
Time-of-day Period	Between	And	Expected Value	s.d.	Mean	s.d.
"All Times" / "All Day"	07:00	19:00	12.55	4.48	15.7	8.60
Am Peak:	07:00	10:00	13.34	3.90	14.4	6.30
PM Peak:	16:00	19:00	14.44	7.16	17.3	10.60
Inter-/Off-Peak:	10:00	16:00	11.47	4.09	Not surveyed	-

Table 5.16 again shows that the iBus-derived expected dwell times follow a similar trend to those compiled through the manual survey in 2002. On Route 521 (R521) for example, the afternoon PM Peak value continues to be higher than the morning AM Peak in 2010 as for

2002. Similarly for Route 507 (R507), the PM Peak value is also higher than the AM Peak in 2010, but the Inter-Peak dwell time is higher than the AM Peak, as in 2002.

The general trend suggested by London Buses (TfL, 2007), as can be seen in the iBus-derived values for R521, is that dwell times tend to fall slightly during the Inter-Peak compared to the two Peaks, although these are still much higher than those in the evenings and at night time. This variation by time-of-day is more complex than at first sight, and is discussed in more detail in Sections 5.2.3.3 below. In the case of R521, the higher "All Day" mean of 15.7s shown for 2002 is only due to the Inter-Peak period not being sampled. The equivalent value calculated from iBus for 2010 is 13.9s, but an expected value of 12.6s is given in Table 5.16 to reflect the lower expected Inter-Peak dwell time on this Route. The ability to sample and report on different/longer time periods (Robinson, 2009) illustrates another benefit of using the bus log files over manual surveys to derive dwell times. As with the comparison against York, the iBus-derived dwell times for the Red Arrow Routes in 2010 are lower than those for 2002, suggesting again an impact of increased Oyster card usage, which is also reflected in reduced spreads of values in 2010 - as shown by Table 5.16 above. Given a pass or Oyster card is a much faster payment method than cash (York, 1993), the elimination of cash payments on these Routes since 2003 (White, 2008) is likely to lead to lower and more consistent boarding times, particularly as the other impact factors have largely remained the same. For example, similar vehicles were observed during the on-street-trial in 2010 to those employed in the earlier survey, i.e. single decked, rigid-bodied buses with two sets of doors (London Buses, 2003). The number of passengers boarding for R521 is also similar, with an average of 2.0 counted during the trial compared to 1.9 quoted by TfL for 2002 (London Buses, 2003). However, the number of passengers boarding for R507 has increased during the Inter-Peak period, from an average of 2.1 in 2002 to 2.5 observed during the trial in 2010, which may explain why the expected dwell time for this period is higher than the 2002 value, at 16.7s versus 14.9s - York (1993) quotes an average boarding time of 2.2 to 2.4s per passenger for those using a pass, for example.

To summarise, the dwell time comparisons with previous research in 1993 and 2002 show the value and accuracy of deriving dwell times using the bus log files Speed Zero durations. If such comparisons are representative, then the iBus-derived values are similar to those obtained through manual surveys, provided other factors such as the difference in payment methods and passenger numbers are account for. iBus therefore provides an effective alternative measurement method to time-consuming and relatively expensive on-street surveys.

5.2.3.3 Variations in Dwell Times by Time-of-day

Table 5.16 above highlighted the difference in expected dwell times and their spread between the two Red Arrow Routes in 2010. R521 for example, has a daytime expected value of 12.6s and standard deviation of 4.5s, whereas for R507 these are 16.0s and 6.2s respectively. Although the two expected AM Peak values are similar, at 13.3s and 12.8s respectively, they are very different outside this period. The expected value for R521 drops to 11.5s during the Inter-Peak, before rising to the highest value of 14.4s for the PM Peak. In contrast, the expected dwell times for R507 *increases* to 16.7s during the Inter-Peak, before reaching a high of 17.1s for the PM Peak. Similarly, while the greatest spread of dwell times for R521 occurs during the PM Peak (s.d. = 7.2s), it is highest during the Inter-Peak for R507 (s.d. = 6.6s). The dwell times for the two Routes were therefore compared using a two-sample Kolmogorov-Smirnov (K-S) test for the different time-of-day periods. The test result for the AM Peak suggests dwell times across the two routes share similar means or are from the same distribution during this period ($p>0.05$), which reflects the similar historical nature of all Red Arrow services, i.e. they were originally designed (Haines, 1969) as express routes that used faster payment methods to serve commuters from Central London mainline rail stations. Nowadays, both Routes employ the same operator (Munster, 2010), i.e. Go-Ahead, and deploy the same rigid, single-deck Mercedes Citaro vehicles, which operate with similar Daytime frequencies, e.g. 2 to 4 minutes during the Peak periods. The similar dwell times during the AM Peak therefore suggests the two Routes experience similar levels of passenger demand during this period - this being the other major factor governing dwell times suggested by the literature (see Section 2). However, Table 5.17 below shows the result of the two-sample K-S test conducted for the *whole* daytime period (7am to 7pm) for the two Routes.

Table 5.17 Kolmogorov-Smirnov Test of All Daytime Dwell Times for Routes 507 and 521

Two-Sample Kolmogorov-Smirnov Test

Test Statistics[a]

		SP ZERO DURATION (s)
Most Extreme Differences	Absolute	.245
	Positive	.245
	Negative	-.002
Kolmogorov-Smirnov Z		2.443
Asymp. Sig. (2-tailed)		.000

a. Grouping Variable: ROUTE_NO_Converted

Table 5.17 shows that, although the two Red Arrow Routes are similar operationally, their dwell times are significantly different across *all* time periods ($p<0.05$). This is also true for the Inter-Peak and the PM Peak time periods ($p<0.05$ in both cases), which shows it is impractical to combine dwell times across all time-of-day periods, without accounting for the variations in passenger demand due to the routing or different types of bus stops served by each service.

As suggested by the preliminary analysis of the on-street trial (see Section 5.1.3), the difference in dwell times may be due to the two Routes possessing different *stop location* characteristics, which give rise to different levels of passenger demand during the Inter- and PM Peaks. A detailed map of the route and bus stop locations for R521 is shown in Figure 5.13.

Figure 5.13 Stop locations for Route 521
(from TfL, 2010e)

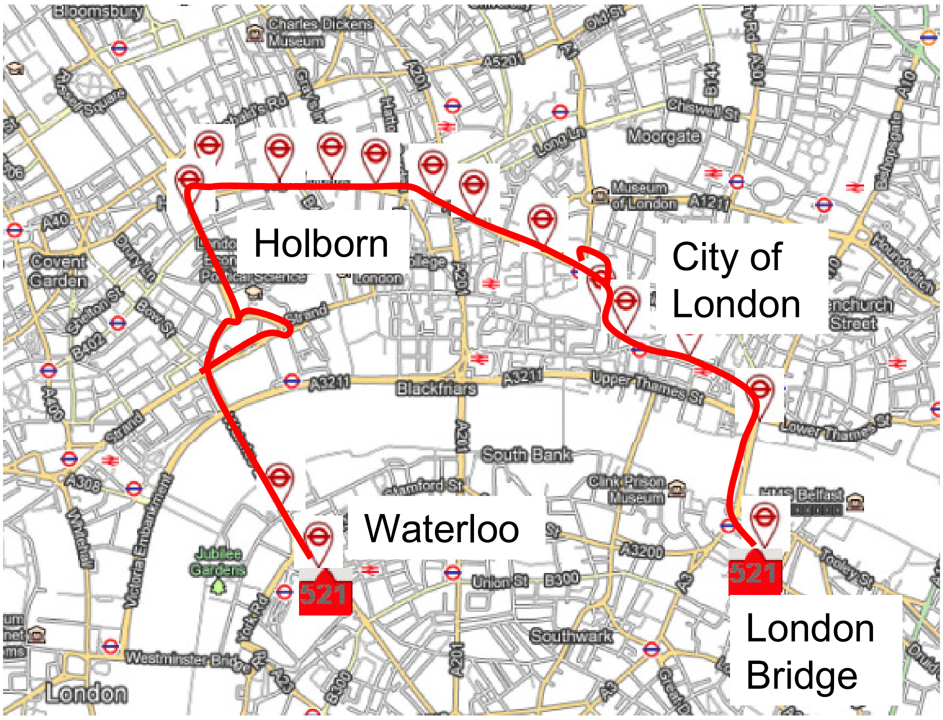
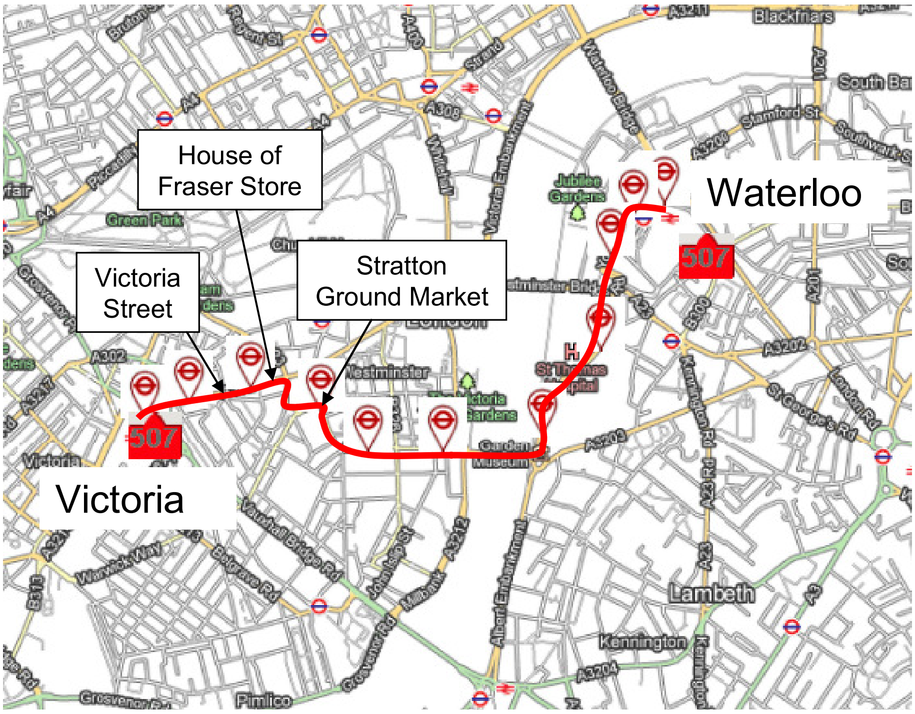


Figure 5.13 shows R521 remains principally a commuter service linking passengers from Waterloo and London Bridge Stations to the offices in Holborn and the City of London business districts, where a drop-off in expected dwell times for the Inter-peak period is expected.

In contrast, although R507 also connects two Rail Stations (Waterloo and Victoria) with office commuters in the Millbank and Westminster areas, the western end of this Route also acts as a shopping service running through Victoria Street, encompasses e.g. a major House of Fraser Department Store and nearby Strutton Ground Market - see Figure 5.14 below. These extra shopping area attractions are likely to cause additional demand for R507 during the Inter-Peak, which is carried over into the PM Peak period while the shops remained open, and this may explain the different expected dwell time patterns observed for this Route compared to R521 during these Daytime periods.

Figure 5.14 Stop locations for Route 507
(from TfL, 2010e)



These AM Peak, PM Peak, and Inter-Peak dwell time variations were also observed for other routes sampled in this study, as shown by the contrasts between for example Route 85 (R85) and 134 (R134) in Table 5.18.

Table 5.18 Dwell Times for Three Daytime Periods for Routes 85 and 134 in Seconds

Route 85

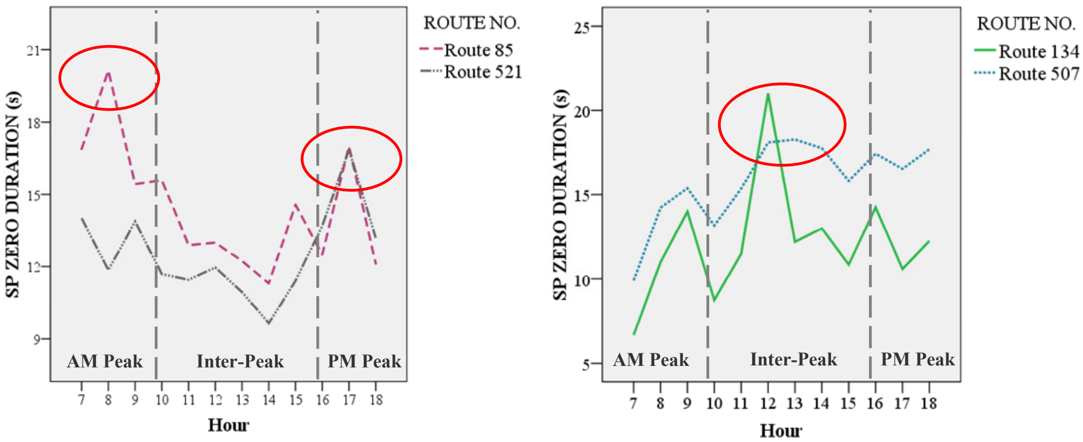
Time-of-day Period	Between	And	Expected Value	s.d.
All Daytime:	07:00	19:00	14.02	7.984
AM Peak:	07:00	10:00	16.35	8.672
PM Peak:	16:00	19:00	14.19	12.071
Inter-Peak:	10:00	16:00	13.43	6.898

Route 134

Time-of-day Period	Between	And	Expected Value	s.d.
All Daytime:	07:00	19:00	12.60	5.393
AM Peak:	07:00	10:00	10.57	4.357
PM Peak:	16:00	19:00	12.48	5.339
Inter-Peak:	10:00	16:00	13.34	5.570

Table 5.18 shows R85 follows a similar trend to R521 in having a lower expected dwell time during the Inter-peak than for the Peak periods, while R134 shows a similar trend to R507 (and the reverse of R85) in having a higher expected dwell time during the Inter-Peak than the Peaks. These dwell time variations between the AM Peak, Inter-Peak and PM Peak, and by hour-of-day are illustrated in Figure 5.15 for the four routes.

Figure 5.15 Variation of Dwell Times Across Daytime Periods



Similar to the difference between R507 and R521, the time-of-day variations between R85 and R134 cannot be explained by operational reasons: in this case, both services were observed to employ low floored, double decked vehicles with two sets of doors, and operated to similar daytime frequencies (Munster, 2010). An analysis of the routing used by each service again suggests that the dwell time variations are caused by differences in the bus stop locations served, with R134 serving a much higher proportion of stops in shopping areas compared to R85, which gives rise to different passenger demand patterns during the day.

Table 5.19 shows the average expected dwell times across all bus stops and their standard deviations by the three time-of-day periods. This shows dwell times tend to rise overall from the AM Peak to the Inter-Peak, before falling slightly for the PM Peak, although there is a wide variation between different routes and stops, as shown previously by comparing R85 and 134, and 507 and 521, which are similar services (see Tables 5.16 and 5.18, and Figure 5.15).

Table 5.19 Expected Dwell Times for All Routes Across Three Daytime Periods in Seconds

Time-of-day period	Expected Value	Std. Deviation	Coeff. of Variation
1 (AM Peak)	12.70	5.347	0.42
2 (Inter-Peak)	14.75	7.349	0.50
3 (PM Peak)	14.45	7.203	0.50
Total (All Daytime)	14.24	6.911	0.49

A non-parametric Kruskal-Wallis (K-W) test for *k*-independent samples was performed for the three different time-of-day groups, and the result suggests there exist a significant difference in dwell times between the three periods ($p<0.05$). (The K-W test is an alternative non-parametric test for ANOVA, which compares the means and variances between different groups in normal distributions.) As there is no "Post Hoc" for this test, the test between two independent variables (i.e. two-sample K-S test), was repeated between the different time-of-day periods to establish where differences exist. The Bonferroni Correction Method (Abdi, 2007) was used to avoid the increase of Type I Error caused by the repetition of statistics tests. This involved using a smaller level of the significance level as the cut-off point, or (p=0.05/the number of tests to be conducted), in this case =0.05/2, or =0.025, as it can be seen from Table 5.19 above that the expected values for the Inter-Peak and the PM-Peak are broadly similar, with the PM Peak having only a slightly smaller value, while the AM peak is much lower, so comparisons between the AM Peak and PM Peak, and between the Inter-Peak and PM Peak were made. Table 5.20 shows the result of the two-sample K-S test conducted between the AM Peak and the Inter-Peak bus stop dwell times.

Table 5.20 Kolmogorov-Smirnov Test of AM Peak and Inter-Peak Bus Stop Dwell Times

Test Statistics[a]

		SP ZERO DURATION (s)
Most Extreme Differences	Absolute	.118
	Positive	.002
	Negative	-.118
Kolmogorov-Smirnov Z		2.022
Asymp. Sig. (2-tailed)		.001

a. Grouping Variable: ToD

The result shows there is significant evidence ($p<0.025$) that the dwell times during the AM Peak are shorter than those during the Inter-Peak, while those from the Inter-Peak and PM Peak are comparable - see Table 5.21 below.

Table 5.21 Kolmogorov-Smirnov Test of Inter-Peak and PM Peak Bus Stop Dwell Times

		SP ZERO DURATION (s)
Most Extreme Differences	Absolute	.035
	Positive	.034
	Negative	-.035
Kolmogorov-Smirnov Z		.606
Asymp. Sig. (2-tailed)		.856

These results suggest, when providing guidance values on dwell times, it may be possible to use a single value outside the AM Peak period, but that a separate value needs to be provided for the AM Peak for general estimating purposes.

From Table 5.19 further above, the overall trend of dwell times across the AM, Inter- and PM Peak periods found in this study is perhaps surprising, given the literature (see Section 2) had suggested that passenger demand, and therefore dwell times, should generally be at their highest during the morning and evening rush hours. In fact, bus services in London have historically attracted a higher proportion of shoppers, schoolchildren and leisure travellers, as opposed to business users, than rail (Competition Commission, 1997). Nevertheless, given the results suggest that the Inter-Peak and PM Peak dwell times share similar characteristic, a detailed breakdown of the average dwell times on an hour-by-hour basis on the clean stops dataset (N=1,950) was performed - see Figure 5.16.

Figure 5.16 Dwell Time Variation by Hour in a Day (Clean Stops)

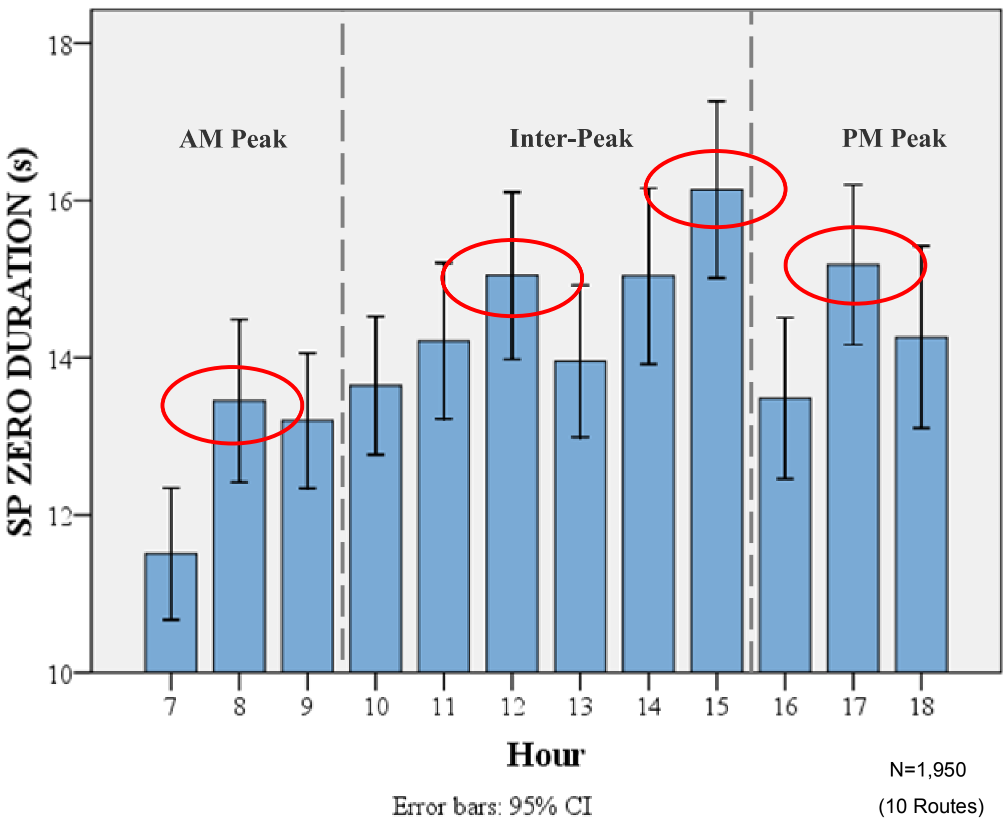


Figure 5.16 shows the variation of expected dwell times across all bus stops and routes by hour-of-day, which suggests that dwell remains high *throughout* the main Daytime period. In addition to the two peaks occurring around 8am and 5pm, which can be associated with traditional AM and PM rush hours, there are two extra peaks, with:

- one occurring around midday or 12 noon; and
- another occurring in the early afternoon, around 3pm.

Figure 5.16 appears to follow a similar trend to the Trips Profile made by London residents as part of the last major London Travel Demand Survey (TfL, 2009), as referred to in Section 2.2.6. While the two rush hour-related AM and PM peaks are to be expected, i.e. they are likely to reflect the higher demand due to commuting and other work-related trips that occur traditionally around these periods, the midday peak is surprising, although this could perhaps reflect the higher demand from shopping and leisure trips that are said (TfL, 2009) to dominate this middle part of the day. Similarly, the second extra peak occurring around 3pm could be reflecting an increase in education-related and other trips, as well as the ongoing demand from shopping and leisure trips, that occur in this period. These findings suggest that the demand *variations* as highlighted in the previous Travel Demand Survey are reflected in the overall dwell times that are derived through this study. However, the *scale* of the different dwell time peaks do not appear to reflect the relative increases in passenger demand as highlighted by the Survey, but this could be due to several reasons, for example:

- buses typically run at higher frequencies during the Peaks than the Inter-Peak, to cope with the increase in passenger demand due to work trips, and this could have a compensatory or lowering effect on the average dwell times per vehicle; and
- as discussed previously, and similar to previous findings by York (1993), the boarding and alighting times due to shopping and leisure passengers are higher on average than those for commuters, e.g. due to payment of cash fares, and delays associated with e.g. shoppers carrying heavy bags, and this could account for the higher expected dwell time peaks during the middle/afternoon part of the day.

The trend for the midday, afternoon and evening peak dwell times to be higher than the morning peak is reflected in a previous study by Dueker et al. (2004), which was conducted across four similar time bands, although the start and end times of these periods were slightly different to the period groupings shown here. Nevertheless, the lower AM peak times compared to the three other peaks is attributed to regular passengers who used bus passes and asked fewer questions, and to more directional traffic which reduced the mix of people boarding and lighting at the same stop. The overall dwell time profile shown in Figure 5.16 also reflects the time-of-day passenger demand profile for the bus stop in Brixton Town Centre given in the literature (Hall et al, 2006), which is not served by any of the routes sampled in this study. However, it should be noted that these overall dwell times belie the wide variations between different routes, as shown previously in Table 5.14 and Figure 5.15, which reflect changes in demand due to the varying stop locations served. An attempt to generalise this passenger demand by route, i.e. the bus stop locations served, was therefore carried out, and their impact on dwell times discussed in the next section.

5.2.4 Dwell Times by Location / Region

iBus does not currently provide any information on bus passenger numbers. However, the on-street trial (see Section 5.1.3) and the previous Section (5.2.3) have shown the value of reviewing different bus stop locations, e.g. for the Red Arrow Routes, because the location provides an indicator of likely passenger demand patterns generated throughout the day, and can therefore help to explain the differences in expected dwell times across different time periods. For example, increased demand, and therefore dwell times, could be expected at rail interchange stops during the peak hours, while higher boarding and alighting numbers is expected at bus stops in shopping areas throughout the main part of the day.

5.2.4.1 Dwell Time by Stop Location Types

Four different bus stop location "types" were defined, and each stop in the dataset allocated to one of these categories, based on practical experience and the evidence from the on-street trial:

- Type 1 - ***Interchange*** stops, i.e. those within two minutes' normal walking distance of a London Rail and/or Underground station;
- Type 2 - ***Shopping Area*** (Ibrāhīm and McGoldrick, 2003) stops, i.e. those within two minutes' walking distance of a concentration of retail outlets, such as a shopping centre or district, or an area known for the clustering of shops, or a parade or megastore;
- Type 3 - ***Hospital*** stops, or those within two minutes' walking distance of a Hospital; and
- Type 4 - "***Regular***" stops, i.e. those with no specific distinguishing features, apart from the Region (Urban, City, Suburban or Rural) in which the stop is located.

Table 5.22 shows the expected dwell times between the four different bus stop location types.

Table 5.22 Expected Dwell Times for Different Stop Location Types in Seconds

Stop Location Type	Expected Value	Std. Deviation	Coeff. of Variation
1 (Interchange)	15.49	7.283	0.47
2 (Shopping Area)	16.51	7.518	0.46
3 (Hospital)	14.11	6.150	0.44
4 (Regular)	13.41	6.508	0.49

A Kruskal-Wallis test was again performed to establish whether any difference exists between the dwell time distributions of the four different location types. The result suggests there exists a significant difference ($p<0.05$) in dwell times between the four types, and therefore the Bonferroni Correction Method was again applied to a series of two-sample K-S tests to establish where the difference(s) exist. In this case, the smaller significance level taken as the cut-off point was p=0.05/(four tests) or 0.0125.

Table 5.23 shows the results of the four two-sample K-S tests conducted between Location Type 1 (Interchange) and Type 4 (Regular) stops, between Types 2 (Shopping Area) and 4, Types 3 (Hospital) and 4, and Types 1 and 2 stops.

Table 5.23 Kolmogorov-Smirnov Tests Between the Four Stop Location Types

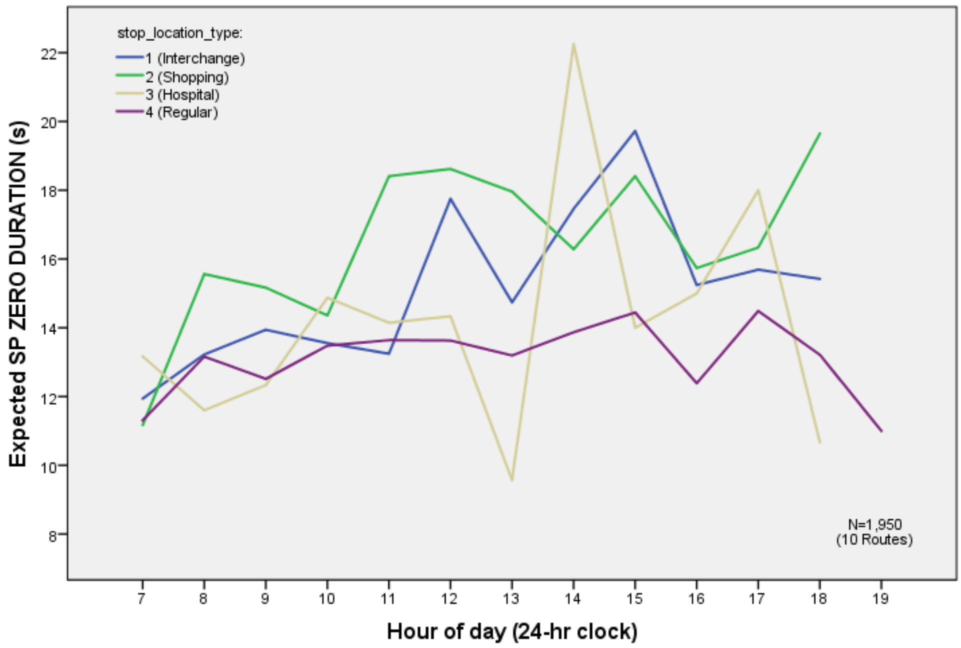
Test Statistics[a]

		SP ZERO DURATION (s)	SP ZERO DURATION (s)	SP ZERO DURATION (s)	SP ZERO DURATION (s)
Between Stop Location Types:		1 & 4	2 & 4	3 & 4	1 & 2
Most Extreme Differences	Absolute	.144	.198	.129	.081
	Positive	.144	.198	.129	.081
	Negative	-.002	.000	-.027	-.003
Kolmogorov-Smirnov Z		2.482	2.858	1.028	1.002
Asymp. Sig. (2-tailed)		.000	.000	.241	.268

a. Grouping Variable: stop_location_type

It can be seen from Table 5.23 that the dwell times at Interchange and Shopping Area stops are significantly higher than those at Regular stops ($p<0.0125$), but no significant difference was found between Interchange and Shopping Area stops. This was not surprising, given on further analysis many Interchange stops were also found to be close to shopping areas, e.g. as at Knightsbridge, Tottenham Court Road and Putney. There was also no evidence to suggest that bus stops located near hospitals tend to incur higher dwell times, although the number of hospital stopping points in the dataset was relatively small (N=67), accounting for less than 3.5% of the total, and it is possible these stops gave rise to a high proportion of abnormal or extreme events, which were excluded due to data consolidation and refinement. This is further illustrated in Figure 5.17, which shows the variation of expected dwell times by bus stop Location Type for each hour of the main day.

Figure 5.17 Expected Dwell Times by Bus Stop Location Type and Hour-of-Day (Clean Stops)



The expected dwell times for hospital stops do not appear to follow the same trend as other stops, and they consists of more extreme values, which suggest that passengers using these stops consist of a higher proportion of hospital patients who have ailments that require unusual or extended boarding/alighting times. It can also be seen from Figure 5.17 above that the expected dwell time values are a function of the stop location, as well as the time of day. For Regular stops, dwell times follow a similar pattern to the profile for all stops shown previously in Figure 5.16, although the variation between high and low expected values are within ± 2.5 seconds through the day. The expected dwell times for Interchange and Shopping Area stops, on the other hand, are generally higher throughout the day than those for Regular stops, and are marked by distinct peaks and troughs, as discussed previously in Section 5.2.3.3. These findings therefore suggest that, while it is possible to provide one general daytime guidance value for Regular stops, more specific values need to be given for Interchange and Shopping Areas stops, where dwell times are generally higher, and that take into account their different demand patterns during the day, i.e. to include an additional *Afternoon Peak* period between 2 and 4pm, or to distinguish between the following four Daytime periods:

- the AM Peak (07:00-10:00);
- the Inter-Peak (10:00-14:00);
- an Afternoon Peak (14:00-16:00); and
- an Evening Peak (16:00-19:00).

A Kruskal-Wallis test was performed, which showed that a significant difference in dwell times existed between these four time-of-day periods ($p<0.05$) for both Interchange and Shopping Area stops. Following this, two-sample K-S tests were again performed, which showed that the Afternoon Peak dwell times were significantly higher than the AM Peak in both cases ($p=0.000$ and $p=0.004$ respectively). While a distinction between these four periods is less important for Regular stops, the results from Section 5.2.3.3 suggest a higher level of accuracy is obtained by adopting a separate value for the AM Peak period, compared to the rest of the Daytime period.

5.2.4.2 Region

A similar analysis for bus stop Region was performed as for Stop Location Type. Table 5.24 shows the expected dwell times between the four Regions: 1 - Central London, 2 - City of London (Central Business District), 3 - Inner and Outer Suburban London, and 4 - Rural (outside Greater London boundary).

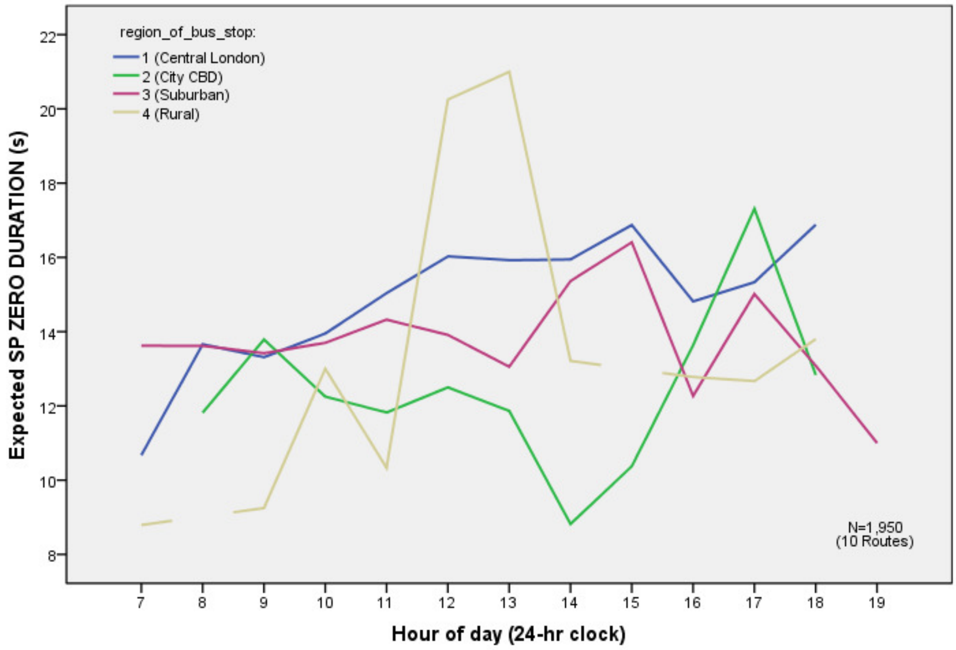
Table 5.24 Expected Dwell Times for Bus Stops in Different Regions in Seconds

Region	Expected Value	Std. Deviation	Coeff. Of Variation
1 (Central London)	14.93	6.762	0.45
2 (City CBD)	12.58	4.584	0.36
3 (Suburban)	14.01	7.280	0.52
4 (Rural)	12.19	6.077	0.50

Similar to Interchange and Shopping Area stops, bus stops in Region 1 (Central London) were expected to give rise to longer dwell times than those in other regions, e.g. due to a higher population density (TfL, 2010c) and increased passenger demand. The result from a Kruskal-Wallis test showed that a significant difference ($p<0.05$) did exist in the expected dwell times between the four Regions. A series of two-sample K-S tests was then performed, which showed the significant difference existed between Region 1 (Central London), and Regions 2 (City), 3 (Suburban) and 4 (Rural). (Bonferroni Correction was again applied to theses tests, with the cut-off point taken as $p=0.05/4$ or $=0.0125$.) Although these differences may be significant statistically, it should be noted that the distinction between regions may not be meaningful or important for e.g. bus operators, who tend to provide the TfL-franchised bus services on a route and stop basis.

Figure 5.18 shows the plot of expected dwell times by region across different hourly periods.

Figure 5.18 Expected Dwell Times by Region by Hour-of-Day (Clean Stops)



As can be seen from Figure 5.18, expected dwell times were generally higher for Region 1 (Central London, shown in blue) compared to e.g. Regions 2 (City, shown in green) and 3 (Suburban, shown in purple) for all time periods during the day. Indeed, the dwell times of bus stops in Region 1 did not drop off after 6pm compare to those in the City and suburbs, reflecting the continued shopping demand in Central London (given shops remain open until 8pm or later) and the increase in leisure demand for e.g. bars and restaurants which occurs in the evenings (TfL, 2009). In contrast, the expected dwell times for Region 2 or the City Central Business District, follows a more traditional passenger demand profile, with distinct AM and PM Peaks and a sharp drop during early afternoon, reflecting the higher density of offices and a lower residential population in this region compared to other areas (Johnson, 2009), i.e. the demand for buses in this Region is principally due to commuters. The expected dwell time profile for Region 3 (shown in purple) reflects that of Regular stops (see Figure 5.17 further above), apart from a wider spread in values that is reflected in a higher standard deviation (7.3s, cf. 6.2s for Regular stops, and an overall expected value of 14.0s compared to 14.1s respectively), which suggests the Suburban Region has a lower proportional of Interchange and Shopping Area stops than Central London. The pattern of expected dwell times for Region 4 (Rural, shown in grey) suggests a peak in passenger demand and/or longer boarding times between late morning and early afternoon (compared to other periods), which is in sharp contrast to the other Regions. This trend may reflect similar bus demand patterns in other Rural areas, where there is an increase in patronage outside the peaks due to for example (Baker and White, 2010), the use of free/concessionary fares by pensioners. However, these dwell times were sampled using only one route, and therefore the trend may reflect merely the route characteristics rather than the Region as a whole. It should also be noted that the topological demographics across the London region are very complex (Johnson, 2009), and any grouping by region represents merely a "rough guide", and should only be used where more precise information, e.g. on bus stop location, is not available. For example, the Isle of Dogs area in East London, which includes Canary Wharf and Heron Quays, has been identified (ibid) as generating similar office and business services demand to the City of London. Therefore, the dwell times of bus stops in this area are more likely to follow time-of-day profiles provided by a commuter route (e.g. R521) than that for the Suburban Region in which it falls, i.e. Inter-Peak values are lower than the AM/PM Peaks.

5.2.5 Dwell Times by Vehicle Type

The type of vehicle (whether single or double decked) could also affect bus dwell time, because bus operators tend to deploy double-deckers on busier routes, where passenger demands are relatively high, and therefore a longer dwell time is expected. Table 5.25 shows the expected dwell times and standard deviations between Type 0 (single decked) and Type 1 (double decked) vehicles.

Table 5.25 Expected Dwell Times for All Routes by Vehicle Type in Seconds

Vehicle Type	Sample %	Expected Value	Std. Deviation	Coeff. Of Variation
0 (Single Decked)	51.4%	13.67	5.896	0.43
1 (Double Decked)	48.6%	14.52	7.409	0.51
Total (All Vehicles)		14.24	6.911	0.49

From Table 5.25, double decked buses have a slightly higher expected dwell time than single decked vehicles (at 14.5 seconds compared to 13.7), and a higher standard deviation (of over 1.5 seconds) and coefficent of variation. However, these higher dwell times could merely be due to doubled decked vehicles serving the more popular routes. A two-sample Kolmogorov-Smirnov test for the two vehicle types was therefore performed and the result suggests there is no significant difference between their expected dwell times ($p>0.05$). This is not surprising when compared to previous studies, as all buses in London are now relatively modern (TfL, 2010c) and fully accessible. For example, the majority of vehicles are less than 10 years' old, and operate with two sets of doors, which has eliminated the contention time between boarding and alighting passengers found in previous studies, e.g. York (1993). They also have low-platform floors (TfL, 2010d), and therefore do not require passengers to negotiate extra steps in boarding or alighting, which is cited as another factor causing variations in dwell times between vehicle types. This compares with for example, Arriva's fleet over 10 years' ago, when fewer than 40% of their vehicles were less than 10 years' old (Competition Commission, 1997). (Arriva, formerly known as T. Cowie, is one of the major companies that operate buses in London on behalf of TfL.) The modernising of London's vehicle fleets over the past decade is also likely to have reduced the time taken for doors to open and close (when compared to older vehicles), as more recent/developed door mechanisms are employed, and improved the deceleration/accelerating performance of buses, which were both said to contribute to vehicles' dead time at bus stops (see Section 2).

5.2.6 Summary of Dwell Times and Conclusion to Main Analysis

The analysis in this Chapter shows that the vehicle log files from iBus can be used to provide an accurate method for deriving bus stop dwell times (see Section 5.1), and an automation algorithm has been developed to assist TfL with the process of extracting and processing the requisite records from these files to enable specific values to be obtained (see Section 5.2.1). Of the four potential iBus methods, Speed Zero duration provides the *most accurate* measurement of dwell time, which should benefit the operation of bus priority in SCOOT, by providing precise values of the delay of vehicles at bus stops, and without the need for expensive and time consuming on-street surveys. This method is also beneficial to some microscopic modelling applications, where for example precise dwell times are required to determine the journey time or delay of vehicles along a given link. For these purposes, *actual* values derived from the Speed Zero durations for *each* stop should be used where possible, as the literature and the results here suggest there are wide variations in dwell times from individual bus stop to bus stop, which can depend on many factors.

However, it is recognised that deriving these times through the Speed Zero method may not be possible in every case (e.g. because the relevant bus log files are not obtainable), and therefore some indicative or guidance values for different categories of bus stops should be provided through this study. Research has shown that the *expected* dwell times derived through this study are comparable with those obtained previously using on-street surveys (see Sections 5.2.3.1 and 5.2.3.2), e.g. they are similar or within the range of values quoted by York (1993) and London Buses (2003). However, the derived expected values show wide variations between different bus stops and services (see Section 5.2.2), time-of-day periods (see Section 5.2.3.3), bus stop locations and regions (see Section 5.2.4), and therefore some judgment *must* be applied to determine which indicative values should be used in what circumstances - and some examples of these are shown in Table 5.26 below.

Table 5.26 **Indicative** Dwell Times by Category in Seconds

Specific Stop Location Types	Between	And	Expected Value	s.d.	Coeff. Of Var.	Location (μ)	Scale (σ)
Interchange Stops - Overall:	07:00	19:00	15.5	7.28	0.47	2.64	0.447
Interchange Stops - **AM Peak**:	07:00	10:00	13.1	4.63	0.35	2.51	0.344
Interchange Stops - **Inter-Peak**:	10:00	14:00	14.9	6.56	0.44	2.61	0.422
Interchange Stops - **Afternoon Peak**:	14:00	16:00	19.2	11.96	0.62	2.79	0.573
Interchange Stops - **Evening Peak**:	16:00	19:00	15.6	6.26	0.40	2.67	0.387
Shopping Area Stops - Overall:	07:00	19:00	16.5	7.52	0.46	2.71	0.434
Shopping Area Stops - **AM Peak**:	07:00	10:00	13.7	5.99	0.44	2.53	0.418
Shopping Area Stops - **Inter-Peak**:	10:00	14:00	17.7	8.80	0.50	2.76	0.471
Shopping Area Stops - **Afternoon Peak**:	14:00	16:00	17.2	6.85	0.40	2.77	0.384
Shopping Area Stops - **Evening Peak**:	16:00	19:00	17.0	6.87	0.40	2.76	0.388

Specific Regions	Between	And	Expected Value	s.d.	Coeff. Of Var.	Location (μ)	Scale (σ)
Central London (West End) - Overall:	07:00	19:00	14.9	6.76	0.45	2.61	0.432
Central London - **AM Peak**:	07:00	10:00	12.4	4.31	0.35	2.46	0.338
Central London - **Inter-Peak**:	10:00	14:00	15.3	7.23	0.47	2.63	0.448
Central London - **Afternoon Peak**:	14:00	16:00	16.6	8.95	0.54	2.68	0.506
Central London - **Evening Peak**:	16:00	19:00	15.5	5.62	0.36	2.68	0.351
City of London - Overall:	07:00	19:00	12.6	4.58	0.36	2.47	0.353
City - **AM Peak**:	07:00	10:00	13.4	4.24	0.32	2.55	0.308
City - **Inter-Peak**:	10:00	14:00	12.1	4.40	0.36	2.43	0.353
City - **Afternoon Peak**:	14:00	16:00	9.8	2.79	0.29	2.24	0.280
City - **Evening Peak**:	16:00	19:00	15.2	5.45	0.36	2.66	0.348
Suburban - Overall:	07:00	19:00	14.0	7.28	0.52	2.52	0.489
Suburban - **AM Peak**:	07:00	10:00	13.5	6.54	0.48	2.50	0.458
Suburban - **Inter-Peak**:	10:00	14:00	13.6	6.86	0.50	2.50	0.475
Suburban - **Afternoon Peak**:	14:00	16:00	16.0	8.07	0.50	2.66	0.476
Suburban - **Evening Peak**:	16:00	19:00	13.6	7.77	0.57	2.47	0.531

General Stops	Between	And	Expected Value	s.d.	Coeff. Of Var.	Location (μ)	Scale (σ)
Regular Stops - Overall:	07:00	19:00	13.4	6.51	0.49	2.49	0.460
Regular Stops - **AM Peak**:	07:00	10:00	12.3	5.46	0.44	2.42	0.424
Regular Stops - **Inter-Peak:**	10:00	14:00	13.4	6.49	0.48	2.49	0.459
Regular Stops - **Afternoon Peak:**	14:00	16:00	14.1	6.78	0.48	2.54	0.457
Regular Stops - **Evening Peak:**	16:00	19:00	13.4	6.96	0.52	2.48	0.487
All Stops - Overall:	07:00	19:00	14.2	6.91	0.49	2.55	0.460

In general, this study shows that "average" or expected dwell times depend significantly on the bus stop location or region, as well as the time-of-day period (see Sections 5.2.2 to 5.2.4), and from Table 5.26, expected dwell times are higher in Shopping Areas and at Interchanges, compared to other i.e. Regular stops. Similarly, expected values for Central London are higher than those from Suburban (Inner/Outer) London, while dwell times for the City of London tend to tail off outside the AM/PM Peaks, reflecting the high proportion of office/commuting demand in this region. Expected values for the other regions also increase during the traditional AM/PM Peaks, although there are significant variations between routes, particularly those which serve Shopping Area stops, where Inter- and Afternoon Peak dwell times can be higher than the traditional peaks (see Section 5.2.3). The expected values for Interchange stops also seem to be at their highest during the Afternoon Peak, but the variability of dwell times during this period is also much higher. In comparison to stop location, region and the time-of-day, the variation of dwell times between single and double decked vehicle types is *not* significant (see Section 5.2.5).

Given the values from Table 5.26 are comparable to those found in previous surveys for London (see Sections 5.2.3.1 and 5.2.3.2), it is assumed that these values provide *general indicators* of dwell times, unless there are major shifts in passenger demand or the operational frequencies and the size or distribution of the London fleet changes substantially. However, for bus priority purposes, individual bus stop dwell times should always be derived using the Speed Zero method where possible, and failing that, estimated through the Door Opened and Closed durations, e.g. via the TfL Running Time reports. The values given in Table 5.26 are therefore representative only, and should be applied as follows:

- where actual dwell time values are not derivable, an estimator from Table 5.26 based on where the bus stop is located may be used, i.e. whether by an Interchange or Shopping Area, depending on the time-of-day or for an overall daytime period;
- if a specific stop location is not known, a general value by region may be used, where this is discernible, i.e. Central London, the City of London, or for Suburban London; and
- in the absence of both bus stop location and region information, a more general value may be applied for Regular stops, assuming these are not located near Interchanges or Shopping Areas.

In using Table 5.26, it should be noted that:

- although the *AM Peak* period was defined as 7am to 10am to coincide with existing TfL definitions, dwell times *prior* to 08:00 were observed to be significantly lower. Applications which do *not* require use of this 7-8am period should therefore consider using higher expected values for the AM Peak period compared to those indicated in Table 5.26. In these cases, the expected AM Peak values are generally half a second higher than those indicated, apart from in Central London, where the dwell times are over a second higher (expected value = 13.5s, s.d. = 3.95s);
- a separate *Afternoon Peak* value has been given in all cases, assuming that passenger demand profiles at bus stops mirror those from the London Travel Demand Survey (as discussed in Sections 5.2.3.3 and 5.2.4). However, the demand due to education and other trips may be subject to seasonal variations, for example during the school holidays, and this will have a corresponding effect on the indicative dwell times shown, particularly during the Afternoon Peak period, and lower values should be used where such seasonal variations are important; and
- for *Regular* stops overall, the difference between the expected Inter-, Afternoon and Evening Peak values was not found to be significant. Therefore, if required, a single expected dwell time may be used for *outside* the AM peak period (expected value = 13.6s, s.d. = 6.71s).

In addition to the guidelines given above, further care should be taken when considering the *indicative* dwell times from Table 5.26 in the following circumstances:

- no specific guidance values have been provided for Hospital stops, given these are subject to high fluctuations/extremes in values, and it is prudent to derive actual values for these stops, or to deploy alternative methods, e.g. by using additional detectors downstream of the bus stop to “correct” any bus priority which has been given;
- the dwell times of bus stops near major mainline Rail Stations, such as Euston, King’s Cross, Liverpool Street, London Bridge, Paddington, Victoria and Waterloo are likely to be significantly higher than those indicated here, particular for the AM and PM Peak periods. However, these locations tend to act as “Head Stops” for many bus services, e.g. as at Waterloo, and given such end stops were excluded from the analysis in this study, no indicative dwell times for these locations have been provided; and
- while indicative values have been provided for other Interchange stops (as shown in Table 5.26), it is recognized that these may also lie in (and often serves) Shopping Areas, and may therefore display some time-of-day characteristics similar to those stops. However, these separate aspects could not be discerned from the information supplied by iBus (or that available in the public domain), so they are provided as a rough guide only. In some cases, such as at Richmond and Camden Town stations, the dwell times were observed to be consistently 2-3 times higher than the values given here, and extra care should therefore be taken in applying such values to the Interchange stops located at major urban or suburban centres, where passenger demand is expected to be very high.

In addition to providing indicative values, an understanding of the underlying distributions or general variation of dwell times is also useful for calibration and sampling purposes in modelling and for transport planning purposes. The experience from this study suggests that bus stop dwell times in London generally follow Lognormal distributions for all routes (see Section 5.2.2). However, in some cases, i.e. depending on the route or bus stop, a Normal approximation *may* be adequate (see Section 5.2.2.6), provided average errors of a few seconds per bus per stop are acceptable to the user.

In all cases therefore, the indicated values from Table 5.26 should be used with care, taking into account the circumstances required, and the level of error which can be tolerated.
While some differences in the results have been found to be statistically significant, for example dwell times across different locations, regions or time-of-day, care will need to be taken to ensure that these differences are meaningful and robust for practical application.

The coefficients of variation of dwell times found in this study are comparable to those described in the literature, but they are generally smaller, i.e. less than 0.5 overall, and can be less than 0.4, the minimum indicated by the TCQSM (Ryus, 2003). This is possibly due to the effect of more regular services and faster payments (and therefore boarding) in London, which in turn may reflect the benefits of TfL's initiatives to encourage Oyster card usage and cashless payments, and other improvements made to bus services e.g. through bus priority, the implementation of iBus, and fleet modernisation. These results also demonstrate the benefit of using *Cv* as a supplementary measure for dwell time variations, and potentially for evaluating the regularity of bus operations.

While the results and indicative dwell times given in this section are derived from the specific stops and bus routes used in this study, they could have equal application to other bus stops in London, and indeed to those in other major cities around the world which operate under similar conditions, e.g. with comparable levels of passenger demand and service frequencies. The indicative values could also apply to other cities in Great Britain, although the wider share of cash fares outside London (White, 2008) is likely to lead to longer dwell times than those suggested here, even where passenger demand and service frequencies are the same. Indeed, while these two factors have been increasing generally in London, the different regulatory regime that operates in other metropolitan areas (i.e. with deregulated buses) have typically resulted in fewer bus-kilometres operated or less regular services, which would further increase their dwell times compared to those given here, although this could in turn be offset by a corresponding decrease in ridership that has also occurred as a consequence. On the other hand, where demand and operating conditions in other European cities are similar to those in London, then it is possible that their bus dwell times will follow similar trends to those indicated here. For example, the dwell for two different stops in Barcelona (Estrada et al, 2011) have also been shown to follow Lognormal distributions, and their mean and s.d. values (at 14-19.5s and 5.3-8.6s respectively) are comparable to those shown in Table 5.26. Similarly, results have been found in other conurbations in the U.S., e.g. in Newark (Rajbhandari et al., 2003) and the Fort Lauderdale areas (Li et al., 2006), which show similar distributions in passenger service times, and have comparable mean dwell times to those given here (assuming the same passenger numbers as those for the on-street trial in London). Earlier findings from Portland, Oregon (Dueker et al, 2004) also suggested the existence of a midday, as well as mid-afternoon peak period, which are in addition to the traditionally-observed AM and PM Peaks.
This suggests such intra-day variations in dwell times are not unique to London, but may be found in other cities.

The Portland research also showed that boarding times during the AM peak can be lower on average than those for other periods, which was attributed to a higher proportion of regular commuters who used passes and were less likely to ask questions, and to bus trips that were more directional during this period. This trend was also observed for the results in London, but it could equally apply to any bus stop in other cities that incur a high proportion of regular commuting passengers.

In addition to the dwell time findings, the Speed Zero derivation method used in this study could also have application in other cities where similar AVL systems operate, i.e. where the system is capable of recording vehicle speeds at bus stops to the same fine degree of time intervals as London (e.g. second-by-second or better). As shown by, for example Milkovits (2008), Feng and Figliozzi (2011) and El-Geneidy and Vijayakumar (2011), the examples where AVL systems have been used to derive bus stop dwell times in major cities is increasing. The implementation of AVL systems where vehicle speeds and bus stop location data are collected in real-time therefore provides an opportunity for other cities to develop alternative dwell time measurement methods to on-street surveys. However, from the experience in London, such a process needs to be automated, if it is to prove cost-effective against manual surveys, as the information needed is not directly calculated (or readily captured) by these systems, and the data required from the on-road vehicles for their derivation is typically archived. Indeed, the large quantities of data available from AVL systems can be problematic, and retaining or locating the necessary input data may not be straightforward, although this issue could become less important as the incremental cost of storage and archiving decreases. More importantly though, the requisite location and speed data may be onerous to store and accumulate in the first instance, if the AVL System does not allow for the wireless and automatic transfer of information from individual vehicles to their associated bus depots and central databases; and while AVL-derived measurements could potentially replace more expensive and time-constrained manual surveys, the collection of further information, e.g. through passenger counts or CCTV/video data, may also be required if a more detailed understanding of the passenger and stopping activities that occur at the bus stops is to be obtained. Nevertheless, despite some drawbacks, the experience from London shows the potential of this method, and the benefits that could be obtained for other major cities.

5.3 Analysis of Door Duration Measurements

Subsequent to the start of this study, TfL have been provided with management reports of Journey Time and bus operations from the iBus System (Robinson, 2009). This includes part reporting of bus stop dwell times, which are defined as the difference between the "Arrival" and "Departure" times of vehicles at bus stops. Given what was possible at the time, these Arrival and Departure times (and therefore the calculation of dwell) were taken from the sequence and timings of vehicles' Doors Opened and Closed events that occur at bus stops (as described previously in Section 5.1), and in the very rare cases where these are absent, from the vehicles' Stop Zone Entry and/or Exit events. As these Doors Opened/Closed events are also captured through the iBus vehicle log files, a comparison of the dwell times as derived through these events and the Speed Zero method was therefore performed using the all clean stops data from the 10 Routes collected as part of this study (N=1,950).

5.3.1 Correlation between Door and Speed Zero Durations

Figure 5.19 shows the correlation between the dwell times as derived from Speed Zero durations (on the y-axis) against those from Doors Opened/Closed (on the x-axis).

Figure 5.19 Correlation of Speed Zero and Doors Opened/Closed Durations (Clean Stops)

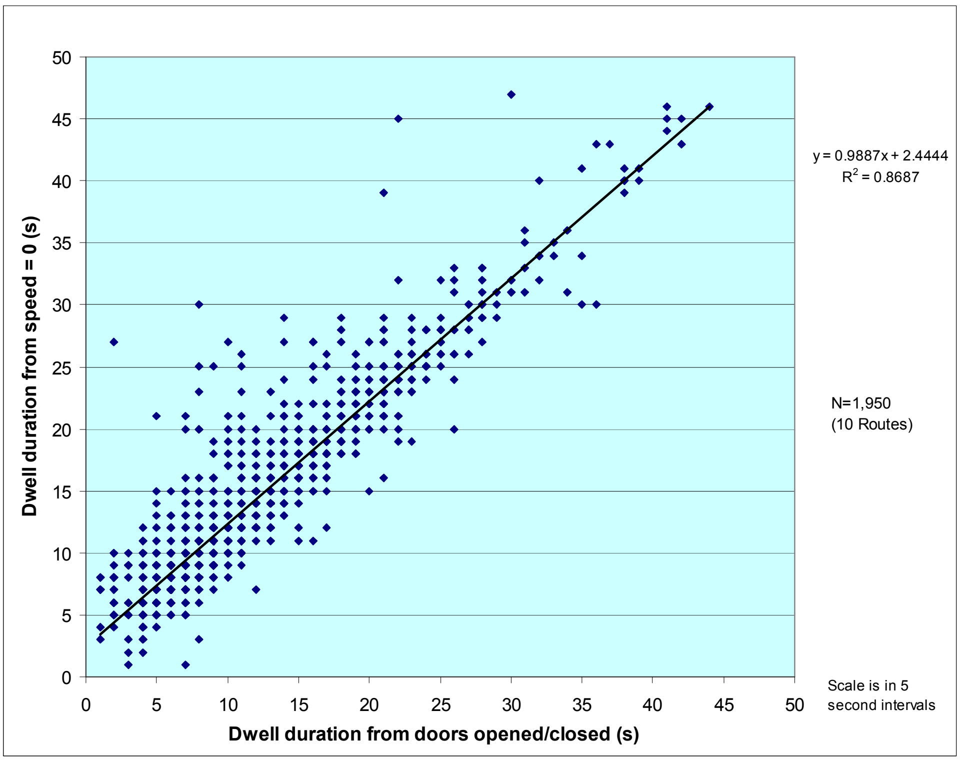


Figure 5.19 shows there is a strong correlation between the Door Opened/Closed durations and dwell times as derived from Speed Zero. The regression from Doors duration to Speed Zero is:

$y = 0.9887 * x + 2.444$ ($R^2 = 0.869$), where y is the Speed Zero dwell time and x is Doors duration. Table 5.27 shows the mean differences across the four main Daytime periods between Doors durations and the Speed Zero dwell times, as well as their associated expected values and standard variations.

Table 5.27 Dwell Time Comparisons between Speed Zero and Door Opened/Closed Durations

			Speed Zero Duration (s)		Doors Opened/Closed Dur. (s)		
	Between	And	Expected Value	s.d.	Mean	s.d.	Difference in Mean
AM Peak:	07:00	10:00	12.70	5.347	10.22	5.111	2.48
Inter-Peak:	10:00	14:00	14.24	6.911	11.85	6.367	2.39
Afternoon Peak:	14:00	16:00	15.62	8.081	13.28	7.426	2.34
Evening Peak:	16:00	19:00	14.45	7.203	12.17	6.155	2.28
All Daytime:	07:00	19:00	14.24	6.911	11.88	6.395	2.36

It can be seen from Table 5.27 that the Door Opened/ Closed durations generally underestimate Speed Zero dwell times by an average of 2.4 seconds. This result is not surprising, given the Door durations do not include other components of vehicle dead time, such as that due to drivers checking and waiting for the traffic to be free before pulling out (York, 1993), or the delays due to the interaction of vehicles at bus stops (Fernandez and Tyler, 2005). A T-Test was then conducted to compare the distribution and means between the Speed Zero dwell times and those estimated from the Doors durations (i.e. estimated dwell time = 0.9887 * Doors Duration + 2.444) - see Table 5.28.

Table 5.28 Paired Samples t-test between Speed Zero Dwell and Door Duration Estimates

T-Test

Paired Samples Test

	Paired Differences					t	df	Sig. (2-tailed)
	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference: Lower	Upper			
Pair 1 SP ZERO DURATION (s) - y1[a]	.00059	2.45823	.05567	-.10858	.10976	.011	1949	.992

a. Calculated from fitted regression line (dwell time = 0.9887 * DR DURATION (s) + 2.444)

From Table 5.28, it can be seen that the values estimated from the Doors durations have no significant difference with the Speed Zero-derived dwell times, t (1949) = 0.011, p = 0.992. The Doors durations therefore provide a good approximation to actual dwell times, provided a constant or offset of approximately 2.4 seconds is accounted for. It can also be seen from Table 5.27 further above that the Doors durations generally have lower standard deviations than the Speed Zero dwell times, i.e. their values are more consistent by comparison. As discussed further above, this additional variation could be due to the other dead time components that constitute the total stationary dwell time of vehicles at bus stops. For example, having closed the doors, the time delay before drivers can pull out from a stop can vary depending on the traffic flow from behind, as well as any parked cars or other obstacles, including buses in front or oncoming vehicles, which may get in the way. The use of Door durations may therefore provide a more consistent estimator of dwell time compared to Speed Zero measurements.

5.3.2 Effectiveness of Existing TfL Reports

In conclusion, assuming "dwell time" is defined as the period when a bus remains stationary at a bus stop, i.e. both the TfL and DfT's definition, then the use of Speed Zero durations provides a better measurement to what is observed on-street than Doors Opened and Closed events, as specified in the recent TfL Journey Time reports. Speed Zero measurements may therefore be necessary to provide accurate dwell time values for improving the operation of bus priority at signals, i.e. to provide improved estimators of bus vary for SCOOT, which account for the signal/bus stop location and different times of day. Dwell as derived from Doors Opened/Closed durations are generally be less than the observed times, so existing reports are likely to under-estimate the stationary times of vehicles by over 2 seconds on average. The existing reports could therefore be improved by using the Speed Zero start and end timing points to define the Arrival and Departure of vehicles at bus stops. However, this may involve wide changes to the processing logic and reporting databases within iBus, and TfL management should determine whether this additional level of accuracy is worthwhile. The existing reports provide an alternative method for deriving dwell time, and the values may be sufficient for most modelling purposes, particularly when adjusted for an offset of 2-3 seconds on average. The Speed Zero measurements should again be used where more precise values are required, as there can be wide variations depending on location/route/time-of-day. This is also true where a significant number of Doors events may be absent from the bus log files, as existing reports revert to the use of Stop Zone events, which have been shown to result in significantly different/higher durations, as was observed in the on-street trial, although such occurrence are suggested as rare.

5.4 Stopping Activities at Bus Stops

This Section provides further discussion on the different types of vehicle-related stopping activities that could occur at a bus stop, based on the experience from the on-street trial, and how these activities have been recorded in the bus log files. The purpose is to provide further guidance on the logic used to develop the Speed Zero Processor algorithm, and to summarise other findings uncovered as part of this study, which helps to inform future research and other work being conducted by TfL.

5.4.1 Clean and Complex Stops

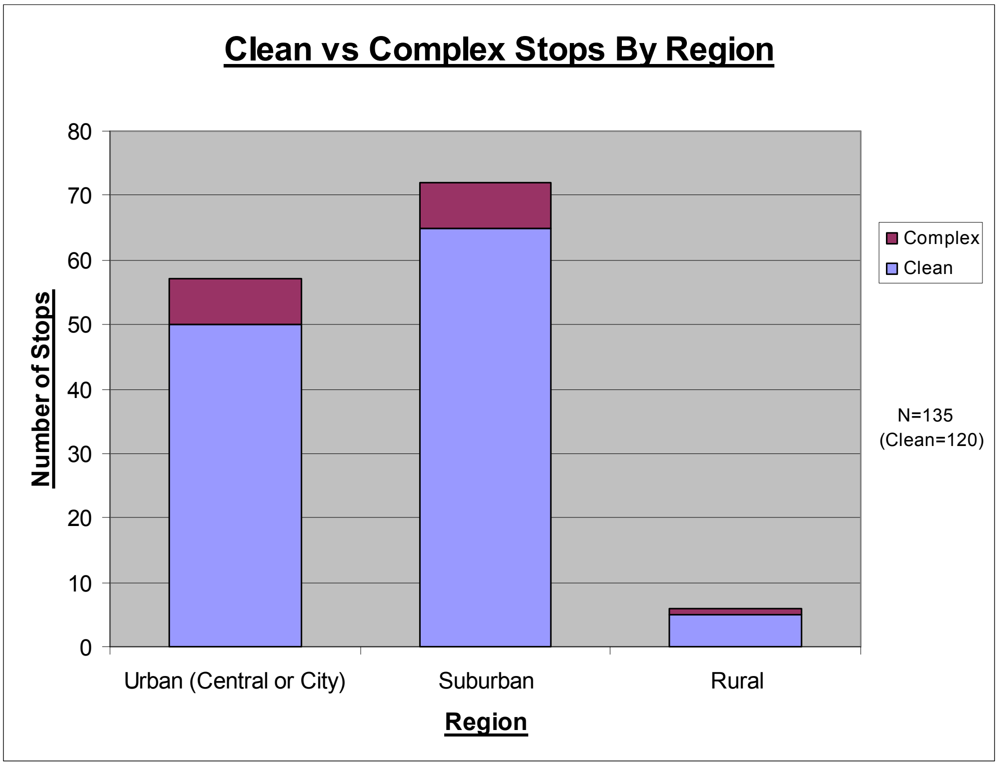
From the experience of the trial, the vehicle-related *stopping* activities at bus stops may be divided into two types:

- "clean" or normal stops, that form the vast majority of cases, where the bus was observed to stop once within the Stop Zone, and opened and closed its doors once for passengers; and
- "complex" stops, where the bus was observed to either halt more than once, or opened and closed its doors multiple times.

In bus log file terms, the clean stops mirror TfL's existing definition for a productive stop, i.e. where a bus becomes stationary at a bus stop for the purpose of picking up and/or dropping off passengers. Deriving dwell times from clean stops is therefore relatively straightforward, and involves extracting and calculating Speed Zero durations through their associated Stop Zone Entry/Exit and Doors Opened/Closed events, as described previously in Section 5.2.1. Complex stops, on the other hand, involve multiple records where the causes of the bus stopping is hard to determine based on the iBus data alone, i.e. without supporting on-street information. Some of these multiple halts within the Stop Zone are arguably valid (Fernandez and Tyler, 2005), for example where the bus is blocked (and halted at least once) from arriving at the bus stop flag due to another vehicle in front, i.e. these extra Speed Zero events are associated with the process of the bus stopping to pick up/drop off passengers, and could therefore be counted as part of an overall dwell time duration. Other complex Speed Zero events however, are not related to passenger boarding and alighting, for example where the bus is halted due to congestion within the Stop Zone or a pedestrian crossing downstream from the bus stop. These halts are more typically associated with other journey time delays along a link (DfT, 2009), and therefore should not be a constituent of dwell time. However, these different types of halts or Speed Zero events are difficult to discern without either manual intervention or further on-street sampling to develop automatic filtering logic.

More importantly, these non-passenger related delays due to e.g. congestion, signals and crossings are already accounted for by SCOOT in the link journey time, and therefore such complex events should *not* be included in the dwell time calculation for bus priority purposes. However, where more general values of bus stop dwell times are required, it may be necessary to include some of these events in measurement. In any case, while the exclusion of some complex stops could be a potential drawback for the Speed Zero method, the experience from the on-street trial suggests that the occurrence of multiple stopping activities is random, and they comprise a relatively small proportion of the total possible stopping cases - see Figure 5.20 for a breakdown by region between the clean and complex stop events discovered during the trial.

Figure 5.20 Clean vs Complex Stops By Region (Video/Trial Data)



From Figure 5.20, it can be seen that the complex stops account for a small percentage of the total stopping cases, i.e. 12%, 10% and 17% for the Urban (Central and City), Suburban and Rural regions respectively, and less than 12% overall.

Further examples of the different clean and complex stopping activities observed during the on-street trial are shown in Table 5.29.

Table 5.29 Stopping Activities / Events at Bus Stops (Observed during the on-street trial)

Bus Stopping Type		Attributes		Examples
1. ***"Clean" Stop***	====>	Bus stops once (doors opened/closed once)	------->	***Typical activities*** : • able-bodied passengers boarding and/or alighting in the "normal" course of a journey • passengers show pass / Oyster card to driver or buy a ticket • driver closes doors, and checks mirrors/traffic, before pulling out • other cases where doors are opened and closed, but no one got on/off (due to driver's anticipation, particularly in urban areas)
			------->	***Passenger delays*** or where driver allows extra time for certain passengers to board/alight: • elderly or physically challenged passengers (e.g. using crutches or wheelchair) • those carrying heavy luggage and/or shopping bags • those with young children and/or buggies/pushchairs
			------->	***Other boarding/alighting delays*** : • crowding at the bus stop, causing delays in boarding and/or alighting • passenger querying journey or ticket / talking to driver • bus full - delays due to on-board passengers blocking gangway, making it difficult for others to board or alight • (for double decked vehicles) delay in passengers getting off the upper deck
			------->	***Non-typical activities*** : • extended delay in pulling out to traffic, e.g. due to congestion • drivers hold up the bus to maintain regularity, on which service performance is based • delay due to a change of driver mid-route
2. ***"Complex" Stop*** (excluded from dwell time processing)	====>	Bus stops more than once and/or opens/closes doors more than once	------->	• Multiple door open/close for passengers (e.g. at bus stations and other major interchanges, where there may be exceptionally long bays, or where the bus stops separately to alight and pick up passengers) • Vehicle interactions at the bus stop (e.g. access to bus stop flag blocked by vehicles in front), as well as stopping to pick up/drop off passsngers • Other vehicle halts within the same Stop Zone, e.g. due to congestion or queuing from signal or pedestrian crossing

Table 5.29 shows that the clean stopping activities can be further divided into those that are "typical", e.g. where able-bodied passengers board and alight from the bus stop in a normal way, and those where additional delays are incurred due to, for example:

- passengers with young children and/or pushchairs, or those who are elderly or physically challenged (which may require wheelchair boarding, or the driver to ensure the bus remained stationary until the person is seated);
- crowding on board the bus or at the bus stop, which leads to delays in passenger boarding and alighting, or where passengers talked to the driver or queried the validity of their pass/ticket (whilst holding up the bus); and
- other anomalous or non-typical dwell time events, such as a change of driver at a bus stop en route, or an extended delay before the bus can pull out from the stop due to congestion.

While the majority of these clean stopping activities were included in the calculation of dwell time as discussed in Section 5.2, certain events, such as the usually long dwell time of over two minutes due to a change of driver, is considered an extreme value, which distorts the validity of any indicative dwell times derived. These extreme values were therefore excluded statistically from further analysis. (The change of driver events only occurred at a few stops, like Pemberton Gardens. However, these stops can't be excluded completely from the dwell time analysis, because these change of driver events arose rarely at these stops, while the other values captured remain valid.)

The evidence from the on-street trial also suggests that the passenger boarding and alighting factors which govern dwell times in London are more complex now than was originally suggested by, e.g. York (1993). In addition to passenger numbers and payment methods (which is arguably a minor factor now), dwell times were observed to depend on the *type* of passenger boarding, which varied according to the time of day, and the origin/destination of the trips being made. For example, while more (typically able-bodied) commuting passengers were counted during the traditional Peak hours, the pattern observed in this study suggest they tend to *board* a bus at major stations and other interchanges, while *alighting* at intermediate stops en route during the AM Peak; and vice-versa during the PM Peak. Previous research (White, 1997) has shown that the use of passes/travel cards in London has removed the financial penalty for passengers in making bus/rail interchanges for longer journeys to improve time-efficiency, and the tendency of TfL to shorten the length of bus routes over the years to improve their service reliability will also have encouraged commuters to use buses as feeder/distributor services. It is therefore not surprising that the average dwell time at intermediate bus stops during the AM Peak is not as high as for other Peak periods, because despite the higher numbers, the alighting time per commuting passenger was observed to be less than a second on average. Subsequent to the AM Peak however, the profile of bus passengers was observed to switch generally from commuters to pensioners or older passengers, as well as shopping and leisure travellers, who took longer to board and alight on average, e.g. because they are less mobile or are carrying shopping bags. This change in demand, and increase in average boarding time per passenger, may also help to explain the higher-than-expected dwell times observed during the Inter-and Afternoon Peak periods (as discussed in Section 5.2.3 further above).

5.4.2 Other Vehicle Stop-related Activities

As well as clean and complex stops, two other cases of vehicle-related activities were observed to occur within bus Stop Zones. These involve cases where:

- the bus either did not stop ("DNS" records); or
- the bus halted for reasons *other* than to pick up and/or drop off passengers.

In the first case, buses were observed to not stop for two reasons - either because the driver could see that no passengers were waiting to board at the stop (or wanted to alight from the bus), or the vehicle was full beyond capacity and the driver decided not to stop for more passengers. While Stop Zone Entry and Exit events are recorded in the bus log files for these activities, there are no associated Speed Zero (or Door Opened/Closed) duration records. Given the bus was not stationary at the bus stop in these cases (using TfL's definition of dwell time), these DNS events were excluded automatically from further processing in the Speed Zero Processor algorithm. However, such records could be extracted/retained for future use, e.g. to assess bus stop usage, and eliminate those that are no longer heavily used.

As with complex stops, buses were also observed to stop within Stop Zones for reasons other than to pick up and drop off passengers, and there could be multiple occurrences of these events for a given bus stop. Examples include where the bus is halted due a pedestrian or zebra crossing close to the bus stop, or it is queued due to congestion or other traffic from a downstream signal. However, without supporting on-street data, the exact cause of these delays is hard to determine based on the log file records alone, although the Speed Zero records generated (within the Stop Zone) by these delays are not be associated with any Doors Opened/Closed events, i.e. they are not related to passengers boarding and alighting (or else they would form part of a complex stopping event). These records are therefore also excluded automatically from further processing in the developed Speed Zero Processor algorithm.

Chapter 6 Conclusion

6.1 Key Research Products for TfL

The following products were provided to TfL as part of this research:

1. A knowledge framework of the iBus System, particularly as they relate to the workings of the .saf files, and the data required to derive bus stop dwell times. This includes testing what is stored in the file structures, including field formats and data items contained in the record headers and the detailed fields for different types of events and records.

2. In addition to the general research findings (see Section 6.2 below for a summary), TfL have been provided with two different options for measuring / estimating dwell times from iBus, i.e.:
   - where a high degree of precision is required, e.g. for the operation of bus priority in SCOOT, the Speed Zero records from iBus vehicle log files can be used to measure dwell times for individual bus stops or routes; and
   - where only a close approximation is necessary, dwell times may be derived using the Doors opened and closed times, e.g. as defined previously in the specification of vehicles' arrival and departure times at bus stops for Report 240; although the accuracy of these estimates is improved by the inclusion of an offset value, where total stationary times are required.

3. The Speed Zero measurement method includes dedicated algorithms and software developed for this purpose. This includes the flow chart logic and C++ programs to extract and process the data required from the .saf files to derive bus stop dwell times. Such algorithms and programs are provided "as is", and TfL have the option to "industrialise" them in future, should this measurement method become routine.

4. A table of updated indicate dwell times has also been provided, based on typical routes in Central and Suburban London, across different time-of-day periods. However, some caution should be applied in using such generalised values, as bus stop dwell times have been found to vary widely from location to location, and TfL will need to ensure that any values taken are appropriate to the route or stop, as well as the accuracy of the application.

Note: this list of products does not include other project work conducted for TfL as part of the EngD Programme, including new Bus Priority functionality testing for iBus, developing further tools for interpreting traffic signal messages, and assistance with the Benefits Realisation project, which are all documented elsewhere for TfL.

6.2 Summary of General Findings

The research in this study shows that Speed Zero durations from iBus vehicle log files provide an accurate method for deriving dwell times, and an algorithm has been developed to assist TfL with the extraction and processing of the records required to derive specific bus stop values, which has the potential to replace labour intensive road-side surveys, and benefit bus priority implementation, service operations, traffic management and transport planning for TfL.

The dwell times measured using the iBus method show an improvement to those obtained previously through manual surveys for London Buses in 1993 and 2002, with lower expected values and smaller standard deviations for bus routes where some direct comparisons could be made. This is possibly due to faster boarding, e.g. through the encouragement of Oyster card use and other cashless payment initiatives, and improvements made to bus services e.g. through bus priority and the modernisation of the vehicle fleet during the intervening period. However, the expected values generally only show a small decrease, perhaps because of an offsetting increase in passenger demand over the same period, although the variability of dwell times have reduced, and appears more consistent, as shown additionally by the coefficients of variation, which is lower than those recommended in the literature.
The measured dwell times across all routes were also found to follow a lognormal distribution, and not normal as has traditionally been thought, which was also found in recent studies e.g. in Barcelona.

In keeping with the literature, the dwell times measured through this study show considerable variation across different routes, bus stops and times of the day, even though the service frequencies remain generally the same. Bus stops on commuter routes tend to experience higher dwell times during the traditional AM and PM Peak periods, while those serving shopping areas also see an increase during traditional shopping hours, which tend to run for longer in London, i.e. through midday and into the evening on weekdays. Further analysis shows that dwell also varies according to the region or bus stop location served, which perhaps reflect the changes in passenger demand due to these different parameters, as suggested by the last London Travel Demand Survey (LTDS). Dwell times for bus stops in Central London are generally higher on average than those from Suburban (Inner/Outer) London, while those located by Underground or over-ground rail Interchanges and Shopping Areas are also higher than those from other areas. Within each stop location or region however, dwell times also show wide variation across different times of the day. While dwell times during the AM/PM Peak can be higher on average than at other times, reflecting the traditional increase in commuter demand during these periods, dwell can also remain high throughout the day time period from 7am to 7pm.

Indeed, depending on the bus stop location and region, expected dwell can be higher still at two other periods found during the day: one of these occurs around noon, which may be due to the extra demand from shopping and leisure trips, as it does not manifest until after the AM peak has ended, i.e. until shops/leisure facilities have opened; and the second peak occurs around 3pm, which reflects perhaps the increase in journeys made for educational and other purposes, as well as the ongoing demand from shopping and leisure trips, as suggested by the LTDS. In addition to passenger demand, these peaks in expected dwell times around midday and mid-afternoon could also be due to longer average boarding and/alighting times taken by different types of bus passengers, which was suggested by the literature and in the road-side experiment conducted as part of this research, although the iBus System does not record any such information to validate this.

Previous studies in London have suggested there are wide variations in dwell times across different vehicle types, the analysis from this research indicates there is no difference between the deployment of single and double decked vehicles, possibly due to the modernisation of the vehicle fleet in the intervening period, which has reduced differences due to e.g. different door opening mechanisms and vehicle acceleration, and the wholesale adoption of low-platform floor buses, which improves passenger accessibility. However, this situation could change again in the future, with the introduction of the new hybrid Routemaster bus.

Various indicative expected dwell times for different routes, time-of-day periods, and bus stop locations and regions were derived through this study, which are summarised in Table 5.26 in Section 5.2.6. However, these dwell times are *very general*, and should be taken as an indicative guide only, and users must determine which value is appropriate for application to the scenario they are considering, i.e. to take into account where the bus stop is located, what route(s) are served, and the daytime period(s) of interest. In cases where precise dwell times are required, such as bus priority, the Speed Zero method described in Chapter 5.2.1 should always be used to derive on-street based values, as this method has been automated to a large extent through the algorithm developed as part of this study, although a degree of manual intervention may be necessary in data refinement/consolidation, and some understanding of the iBus System is required. The provided indicative values should therefore *not* be taken by default, as the Speed Zero durations from iBus data provide accurate measurements, and the System also now provides Running Time reports for TfL through which dwell can be estimated reasonably, as shown by the comparison analysis between Doors and Speed Zero measurements. While the doors opened and closed durations typically underestimates the stationary time that vehicles demonstrate at bus stops, it provides an acceptable alternative for estimating dwell, particularly when an offset is taken into account.

6.3 Implications

The Speed Zero durations from the iBus vehicle log files provide an effective measure of bus stop dwell times, without the need for road-side manual surveys. An algorithm has been developed which automates the extraction and processing of information required from these files to derive dwell times, which can be used by TfL to improve the operation of bus priority, future route and network planning, day-to-day bus operations and to guide iBus development.

This study found that bus stop dwell times in London remained high generally throughout the daytime, and two further peak periods around midday and mid-afternoon were uncovered, which generate expected dwell times that are even higher than those for the morning peak. This suggests that either the demand and/or the profile of bus passengers changes throughout the day, given the service frequencies studied do not vary substantively during these periods, and these variations in dwell could affect future service planning and bus operations, for example, if the high afternoon peaks are not to deter more passengers from catching the bus.

While indicative guidance values have been provided, this study supports the literature for dwell times in London in showing there are wide variations across different routes, bus stops, regions and locations, and across times of the day. The assumption made elsewhere that dwell can be generalised or defaulted to constant values, as had been thought originally in the past, is therefore unlikely to be valid. The dwell times across all routes in this study were found to also follow a lognormal distribution, and not normal as had been typically assumed, and parameters of the indicative distributions have been given. Simulation and predictive models may therefore need to account for these changes in future transport scheme planning and modelling.

If other cities deploy similar AVL systems to London, then the bus stop location and speed data provided by these systems could be developed to provide not only journey time and fleet management information, but also individual constituent bus stop dwell times, which can in turn can be used to improve, for example, the operation of bus priority at traffic signals and in transport modelling. Even where such data are not stored centrally or retained for periods of time, the experience from London suggests that a close approximation to stationary dwell times can be obtained through offset door open and close durations, which are typically captured as distinct events through sensors linked to the AVL systems, and therefore this information could also be exploited to derive dwell times (although sampling on-street may be required to build or validate an effective door offset method). In the case of London, the indicative dwell time derived through the Speed-Zero method is 14.2 seconds on average during the day, while a linear offset or error involved door-derived measurements is 2.4 seconds.

However, while the various indicative dwell times and other findings obtained through this study may have application to other cities around the world, including those in the U.K., care should be taken to ensure such values and results are validated locally, given the potential for different trends in ridership, service frequencies and the proportion of cash payments in other cities compared to London.

6.4 Future Research

The archived vehicle log files collected through iBus can provide a wealth of information, which may be used to derive bus stop dwell times. However, there are a number of areas uncovered through this study, which could be explored as part of future research.

Integrating Dwell Times with Bus Passenger Counts

A major constraint in this research is that one of the biggest determinants of dwell time, or the number of passengers boarding and alighting, is not available through iBus. Some of this information is however becoming available, for example through data being collected by the Oyster card System, and it would be useful to combine the two data sources to develop a more comprehensive understanding of all the factors that affect dwell times at bus stops in future. However, the Oyster card system does hold not information for when bus passengers alight currently, which could be equally important to the number of boarding passengers at certain stops or during certain periods. Nevertheless, an analysis of the dwell times from Speed Zero durations against the number of passengers boarding could provide further insights into the impact of varying passenger demand on dwell times, and help improve predictive models used to estimate dwell, and in turn bus journey times. Alternatively, TfL could investigate the possibility of using Automated Passenger Counting technology, which according to the literature, has become more reliable for these purposes in recent years.

Dwell Time Variation by Passenger Type

This research suggests that the *type* of bus passenger (along with boarding and alighting numbers) could have a higher bearing on bus stop dwell times than other traditional factors, such as the payment method and vehicle type. This study suggests that the profile of the passenger, e.g. whether a commuter, shopper, pensioner or schoolchildren, could result in wide variations in dwell times, if the assumption that they tend to travel at different times of the day is correct. However, as iBus does not capture any information on bus passengers, this may require further road-side studies to investigate the impact of this factor on stop dwell times.

Real-Time Dwell Calculations for SCOOT

While the dwell time measurement method suggested in this study is based on data collected by vehicles on-street in real-time, the analysis and calculation of values have been performed retrospectively. A logical extension of this research is therefore to derive an enhanced method that would allow these Speed Zero durations of vehicles at bus stops to be calculated by iBus in real-time, and to enable them to be transmitted to SCOOT instantaneously to improve its bus priority algorithm, which could then be adjusted dynamically to suit the changing on-street conditions or bus stop dwell times.

Dwell Time Variations for Specific Periods

This study suggests there are two extra dwell time peak periods, around midday and 3pm, in addition to the traditional AM and PM rush hour peaks. Further work could therefore be carried out to determine the causes and variations of these peaks, which are also suggested by other literature (e.g. Dueker et al., 2004).

It may also be useful to perform further dwell time analysis around other seasonal periods to reflect other changes in demand, such as around Christmas, which could impact particular types of stops, e.g. those in shopping areas, and build up a more comprehensive understanding of how dwell times vary throughout the year, which was not achieveable within the scope of this study.

Detailed Analysis of Complex Stopping Events

In this study, a simple analysis of the different clean and complex stopping events was conducted, based on limited on-street information collected through the experiment. However, it may be possible to develop more sophisticated predictive models through further research, which would provide a deeper understanding of the different clean and complex activities that could occur at bus stops, e.g. to account for the different vehicle-to-vehicle interactions between buses, which could improve the operation of the Speed Zero algorithm used to measure dwell times.

Dwell Times for New Routemaster Buses

As suggested by Hounsell (2004), the use of new technology, such as smart cards for ticketing, and multiple-door buses, can help to reduce bus-stop dwell times, and research using “before and after” methods can provide evidence to support the effect of these factors, and used to improve future bus operational practice. With the introduction of the new Routemaster buses in London, this may be a timely opportunity to determine whether these vehicles have any effect in improving London bus stop dwell times, by conducting before and after measurements between existing vehicles and the new buses.

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Appendices

I – Header Fields in Bus Log Files.

II – Detailed Record Layouts for Halt events (ID 21), Stop Zone events (ID 31), Doors events (ID 41), and Detailed GPS Location events (ID 82).

III – Automated .saf File Extraction Program (“saf processor”).

IV – Extraction Program Output Report (Example Page).

V – Speed Zero Processor Algorithm Code.

Please refer to Transport for London