Using GIS to Assess the Potential for Centralised Planning of Bus Networks

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(Received 7 March 2016; accepted 29 July 2016)

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The current regulatory and planning environment means that road-based public transport in UK urban areas (with the exception of London) tends to be planned on a piecemeal basis, and there are often conflicts between the needs and priorities of operators, passengers and planners. In consequence, several local authorities are considering adopting an alternative regulatory environment using quality contracts, with a consequent shift towards centralised service planning. There are though no tools readily available to ensure this centralised service planning will lead to a situation which provides a better balance between the interests of the different stakeholders. This paper describes the development of a methodology to fill this gap, using Southampton as a case study to explore the corresponding improvement methods which could be applied based on the alternative regulatory environment. The improvement methods, including both bus route design and frequency setting, are considered in this paper, which demonstrates how this service improvement problem can be solved by making use of an optimisation technique, the tabu search algorithm, developed under the environment of ArcObjects for Java. While the methodology is developed in the UK context, the general principles used could be applied more widely to improve transit network planning.

**Keywords**: transit network design problem; network planning; tabu search algorithm; geographical information systems

Words: 7597/8000

# 1. Introduction and Background

## 1.1 Introduction

Urban growth is driving continued demand for transport within many cities, and the consequent growth in congestion together with environmental and fiscal pressures means that the provision of effective and efficient public transport services is of crucial importance in supporting urban economies and societies. While rail-based metro systems are often seen as being a first choice option to enable such provision, the high cost of constructing and operating such systems mean that in the majority of cities there will be a continued role for extensive bus networks. Such networks can, in the right circumstances, be extremely effective in moving large numbers of people efficiently from one place to another. However, public perception of bus travel tends to be rather mixed, with buses perceived as being an ‘inferior’ mode of transport in some areas and amongst certain social groups. This problem is exacerbated in some contexts by a lack of regulation or coordinated planning, with bus routes planned and timetabled on a piecemeal basis with little consultation between different service providers. This can be compounded by the conflicting motivations for operating bus services which exist in unregulated environments, with profit-making not always well-aligned with optimal service provision. Recognition of these issues has led to a renewed interest in integrated planning for public transport services in a number of areas around the world. However, methodologies to determine what a well-integrated customer-focused public transport network in a given area would look like are in short supply. This paper describes the development of a methodology to help fill this gap by optimising bus network structure to provide maximum accessibility to key services. While the application described here focuses on the British context, the general principles could be applied equally well in other contexts around the world.

## 1.2 Structure of British Bus Operations

Bus services in Great Britain outside Greater London were deregulated in October 1986, with the previous system of road service licensing (which imposed quantity control on bus service supply) replaced with a system where operators merely had to register their plans to operate a route 42 days (subsequently increased to 56 days) before operations commenced. This permitted full inter-operator ‘on the road’ competition for passengers, which led to major changes in service patterns and frequencies in many areas. While deregulation drove some reductions in average costs, it also tended to lead to increased fares, and inadequate regulation for quality allowed poor quality operators to become established in some areas of the country (Hibbs and Higginson 2013). Deregulation also made it very difficult for transport planners to maintain coherent and integrated public transport systems within particular areas, with for example competition legislation limiting the potential for network-wide ticketing structures. In contrast with the regulated and integrated system in London, where bus patronage has grown strongly in recent years, levels of bus usage in most other areas of Great Britain declined steadily in the years after deregulation. In order to try to arrest this decline, and the conflicts between the needs and priorities of bus operators, passengers and planners caused by deregulation, local authorities in many areas have introduced voluntary Quality Bus Partnerships (QBPs) on particular corridors (Nelson 2013). These involve operators and local government working together to improve the standard of bus services and facilities on these corridors, but while they were successful in some areas, there was always a risk that lower quality (and cost) operators would introduce competing services which took advantage of the improved fixed infrastructure but did not make corresponding improvements to the quality of their vehicles, undermining the principles of the partnership. The limited success of QBPs together with a desire to increase bus usage levels as a means of dealing with congestion and pollution has in recent years led several British local authorities to consider a system of Quality Contracts for bus services (as permitted by the Transport Act 2000 and Local Transport Act 2008). This would involve the introduction of centralised planning for bus services, effectively reproducing the structure that exists in London across the rest of the country. With this system the local authority would specify the services to be provided with the private bus companies then competing for the contracts to provide them. Such Quality Contracts could attract positive bids which would permit the local authority to be recompensed for its quality investments, and would also allow for simple integrated ticketing across the bus network, fares capping and enforceable standards for performance and quality (pteg 2014). So far only one authority, the North East Combined Authority, has submitted their proposal for a Quality Contract Scheme (QCS) for Tyne and Wear on October 21st 2014 (Nexus 2014), which was subsequently rejected on 3rd November 2015. However, on 3rd November 2014, the Greater Manchester Combined Authority signed a deal with the government which stated that Transport for Greater Manchester (TfGM) would be able to bring forward a Quality Contract scheme following a consultation. Other UK Local Transport Authorities which are currently actively pursuing the Quality Contract option (but have not triggered the formal legislative process) include West Yorkshire and Merseyside (pteg 2014).

While Quality Contracts are often portrayed as a solution to the disadvantages of deregulation, there are though no tools readily available to ensure that they will lead to a situation which provides a better balance between the interests of the different stakeholders. This paper describes the development of a methodology to fill this gap, using Southampton as a case study to explore what improvements in bus services could be obtained under the alternative regulatory environment, and to compare the performance of bus networks under both regulatory scenarios in order to evaluate the potential of centralised service planning to improve public transport in UK urban areas outside London.

## 1.3 Transit Network Planning

According to Ceder (2007), the process of public transport network planning, known as the Transit Network Planning (TNP) problem, can be decomposed into four stages: network route design, network scheduling (includes frequency setting and timetable development), vehicle scheduling and crew scheduling, which are sometimes alternatively termed strategic (step 1), tactical (step 2) and operational (step 3 and 4) planning, respectively (Desaulniers and Hickman 2007). Network route design (or strategic planning) is the single most important planning step among this four-step network planning process, because it will invariably affect frequency setting and bus and crew scheduling (Ceder and Wilson 1986, Pattnaik et al. 1998). This paper therefore focuses on the problem of designing a system of bus routes and their corresponding frequencies, which is also known as the Transit Network Design Problem (TNDP).

The TNDP is usually formulated as a non-linear optimisation problem by minimising (or maximising) intended objectives subject to a variety of constraints which reflect system performance and/or resource limitations. The TNDP is also known to be NP-hard, which means that it is impossible to find a definitive optimal solution. Instead, some reasonably ‘good’ solutions can be obtained by algorithms in a reasonable length of calculation time, which should provide a significant improvement on an initial or random solution. The NP-hard intractability is due to the need to search for optimal solutions from a large search space made up by all possible solutions (i.e. the set of theoretically possible transit routes), and it causes difficulties in developing efficient optimisation methods with traditional mathematical programming techniques (Zhao 2006, Desaulniers and Hickman 2007, Guihaire and Hao, 2008, Ibrra-Rojas et al. 2015). As a result, TNDP heavily relies on heuristic and meta-heuristic techniques, with the most widely used example being the genetic algorithm (Pattnaik et al. 1998; Fan and Machemehl 2004, 2006a, 2011; Huang et al. 2010; Cipriani et al. 2012; Camporeale et al. 2016). The simplicity of the calculations and the ability to find good solutions within a reasonable period of time are two characteristics that make the genetic algorithm approach very attractive. However, a key limitation of this approach is that it only outputs locally optimal solutions that may be far from the theoretical global optimum. In order to overcome the limitations of the genetic algorithm approach, the tabu search algorithm was designed by Glover (1977), and it is now one of the most successful meta-heuristic algorithms used for solving optimisation problems. Although the tabu search algorithm has a number of relative theoretical advantages compared to genetic algorithms, it has seldom been used in published studies on the TNDP, with the papers by Fan and Machemehl (2004, 2008a, 2008b) the only ones which are known to the authors. The numerical results from the research of Fan and Machemehl clearly indicate that the tabu search algorithm outperforms the genetic algorithm in solving the TNDP.

Potential approaches to solve the TNDP are proposed by literature reviews, such as Desaulniers and Hickman (2007), Guihaire and Hao (2008), and Ibrra-Rojas et al. (2015), but these approaches have the following shortcomings:

* Complicated but impractical methodologies: Many studies focus on using complicated methodologies to improve small-scale networks. For example, Pattnaik et al. (1998) apply their methodology to a case study network, made up of 25 road nodes and 39 links. Similarly, the network used in the studies of Fan and Machemehl (2004, 2006a, 2006b, 2008a, 2008b, 2011) included 28 travel demand zones and 65 road nodes, while Camporeale et al. (2016) implemented their methodology in a test network with 5 demand zones, 10 nodes and 19 links. These networks are an order of magnitude smaller than a real life bus network in anything other than the smallest of urban areas, and therefore the approaches described in these papers could not be directly applied to the city-scale bus network being considered in this paper.
* Data demanding: An OD matrix is used to provide the input demand data for most studies, and is essential for the route planning and frequency setting associated with the assignment sub-model of studies which take a four-stage modelling approach. However, comprehensive OD matrices are unavailable for British bus networks outside London due to commercial confidentiality under the current deregulated environment where multiple operators run (or could in theory run) services in a particular urban area. While mode-specific OD data is available from the 2011 Census for commuting trips, there is no corresponding demand data for other travel purposes making it impossible to construct a comprehensive OD matrix without carrying out extensive survey work.
* Limited range of methodologies: Previous studies mainly focus on Genetic Algorithms, despite their known shortcomings, whereas other potential meta-heuristic algorithms, such as Tabu Search, are seldom used to solve the TNDP.
* Lack of intermodal integration: The published studies only focus on the improvements of single mode transit networks, and there is less consideration of integrated improvements of multi-modal public transport networks, which might in practice be expected to form the basis of a regulated transit system.

In order to overcome these shortcomings, this paper therefore describes the development of a practical optimisation model with the following characteristics:

* Using possible OD pairs instead of an OD matrix to calculate user cost: Because of the difficulties in obtaining OD matrices for British urban areas, alternative ways of estimating user cost across a network were considered.
* Real-world size network: The methodology was designed for us with city scale bus networks, with the case study for implementation being the current Southampton bus network, which includes 686 bus stops, 3143 links and 72 routes in the base case.
* Complex road network topology: the model was built using GIS and based on the real world network topology, not the straight lines modelled in most studies.
* Multimodal public transport system: rail services were considered in the model alongside bus and walk options in order to develop an integrated improvement of the public transport network.
* Tabu Search-based methodology: an adapted tabu search algorithm was applied to solve the optimisation model.

The remainder of the paper is divided into four sections. Section 2 lists the mathematical formulation of the research problem. A detailed methodology follows in section 3, consisting of three main components: the candidate route set generation procedure, the solution evaluation procedure and the optimal solution search procedure. Section 4 focuses on the process of implementing process of the methodology, including both the sensitivity tests and output results from the Southampton case study. The final section summarises and discusses the results obtained so far, and highlights some priorities for further research.

# 2. Mathematical formulation

## 2.1 Basic concepts, assumptions and notation

Before describing the composition of the methodology, it is necessary to set out the basic concepts and assumptions which underpin the research. The road network is represented as a directed graph G = {N, A}, where N is the set of nodes and A is the set of links representing connections between nodes. A bus route is a sequence of adjacent links in G. A solution S for the TNDP is a pair (R, F) where R = {r1, r2, …, rn} is the set of routes and F = {f1, f2, …, fn} is the set of frequencies. The set of origin-destination (OD) pairs is defined as OD = {odij} where i and j are the origin and destination point respectively. For simplicity, the following assumptions were made in this study:

* The bus network improvement methods only include route planning and frequency setting, while the fare system and quality of services and facilities remain at current levels.
* Bus speed is constant on all routes, and is not subject to congestion effects. Based on the current bus timetable data from the National Public Transport Data Repository, the average bus speed is 18 km/h within the Southampton boundary.
* There is no consideration of vehicle overcrowding and capacity constraints, so it is assumed that all passengers can and will board the first bus to arrive.
* The assignment sub-model assumes that all passengers share a perfect and equal perception of the travel cost to their destinations and that all choose the cheapest option in terms of total travel cost (all-or-nothing assignment model).

The notation used in the mathematical formulation is as follows:

|  |  |
| --- | --- |
|  | Weights of operator cost, user cost and external cost, which must sum to equal 1 |
|  | Unit operation cost, distance related (£ per vehicle-kilometre) |
|  | Unit operation cost, time related (£ per vehicle-hour) |
|  | Length of route k (km) |
|  | Frequency of route k |
|  | Headway of route k |
|  | Round trip time of route k (minutes) |
|  | Minimum frequency permitted for any route |
|  | Maximum frequency permitted for any route |
|  | Number of buses required to operate route k |
|  | Total bus frequencies linking Southampton with nearby towns and cities based on the current bus network, including: |
|  | Average bus speed (km/h) |
|  | Perception of a given unit of walking time compared to the same unit of in vehicle time (e.g. if *Wwkt* = 2 then walking time is given double the weight of in vehicle time when calculating travel cost) |
|  | Perception of a given unit waiting time compared to the same unit of in vehicle time |
|  | Transfer penalty (in minutes) |
|  | Weight of destination type, where the sum of weights across all destination types must equal 1 |
|  | Number of transfers within OD journey *n* |
|  | Value of passenger time (£ per in-vehicle hour) |
|  | Unit air pollution cost (£ per vehicle-kilometre) |
|  | Unit noise pollution cost (£ per vehicle- kilometre) |
|  | Unit climate change cost (£ per vehicle-kilometre) |
|  | Unit external accident cost (£ per vehicle-kilometre) |
|  | Maximum bus fleet size available for operations across the network |

## 2.2 Objective function and constraints

The main objective of bus service planning is to find an equilibrium between the sometimes conflicting interests of passengers and operators. Passengers expect the bus network to be fully compatible with their demand, with features such as highly accessible stops, short travel times, and cheap and direct services. However, from the operators’ perspective, the number of routes and the level of services should be kept under a certain bound in order to minimise operator costs per passenger and therefore maximise profits. The bus service planning problem can therefore become a complex multi-objective problem (Desaulniers and Hickman 2007, Guihaire and Hao 2008, Ibrra-Rojas et al. 2015).

The objective function for the methodology described in this paper is to minimise total social cost (TSC), which is defined as the weighted sum of total operator cost (TOC), total user cost (TUC) and total external cost (TEC). The three weights are introduced to reflect the trade-offs between the relative importance attached to TOC, TUC and TEC. The values to attach to these weights are dependent on the planner’s experience and expert judgement. Clearly, different values of these weights may result in different optimal designs of the transit network. The total operator cost is calculated as a combination of total operated bus distance and total bus running time. The total user costs are a weighted sum of in-vehicle travel time (IVT), walk time (WKT), waiting time (WTT) and transfer penalties. Total external costs involve all costs related to air pollution, noise pollution, climate change and accident costs across the network. Accordingly, the mathematical formulation of the model can be expressed as follows:

Equation (1)

Where

Equation (2)

Equation (3)

Equation (4)

Subject to

Equation (5)

Equation (6)

Equation (7)

There are three main constraints involved in this model. The first constraint concerns frequency feasibility, setting the minimum and maximum frequencies permitted for each candidate bus route. The second is the fleet size constraint, which guarantees that the optimal network never uses more vehicles than are available to operate the base network. Obviously, this could be adjusted to allow a larger (or smaller) fleet size than the base case depending on particular local circumstances and funding considerations. The last constraint is to retain the service levels to nearby towns and cities at current levels, thus avoiding the cross-boundary problem where optimising a network in one area might have a detrimental impact on the network provided in an adjacent area.

# 3. Methodology

The methodology of bus network improvement, including both route design and frequency setting, consists of three main components: the candidate route set generation procedure, the solution evaluation procedure and the optimal solution search procedure (see Figure 1). In the candidate route set generation procedure, all candidate routes are created with a set of possible frequencies associated with each one. Next, then optimal solution search procedure selects a possible optimum set of routes (potential solution) from the candidate route set. Each potential solution is then evaluated by the objective function (TSC) in the solution evaluation procedure, with iteration then occurring between this and the solution search procedure until a pre-specified time period or number of solutions has elapsed. The final output of this optimisation model is then an optimal bus network as measured by TSC, consisting of a set of bus routes with associated frequencies. The stages of the methodology are described in more detail in the following sections.

## 3.1 Candidate route set generation procedure

In the candidate route set generation procedure, candidate routes are generated by the k-shortest path algorithm for each terminal pair in the possible terminal set. The candidate terminal set includes the terminals of the current bus network, as well as all other possible terminals, which are defined as bus stops located within the maximum walking distance (based on WebTAG (Department for Transport 2014a) advice, a value of 1,200 metres was used in this model) of the main service centres within the city boundary. Eight categories of main service centres are selected; they are railway stations, ferry stations, airport, hospitals, universities and colleges, employment centres, city/town/district centres, and main open spaces. In total, there are 293 stops selected as the candidate terminals in the Southampton implementation of the model, and any two of them can be grouped as a candidate terminal pair, resulting in 41,243 terminal pairs (routes) in the possible terminal set. When the candidate route set is created, frequencies are set for each candidate route in the set, where the possible frequency set expressed as number of buses per hour in each direction is f = {0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12}.

## 3.2 Solution evaluation procedure

In this procedure each proposed solution network is evaluated by the objective function (TSC). As set out above, TSC consists of three components: TOC, TEC and TUC. Once the proposed solution network is generated, the associated candidate bus routes and related frequencies are determined, allowing the TOC and TEC to be calculated based on vehicle mileage. The TUC for the solution network are calculated by summing the travel cost of each OD pair, weighted based on the destination types served by each route. The set of possible OD pairs is generated by matching each possible origin point with each possible destination point. The population centroids of six/seven digit postcode units (which typically contain 10 households) are defined as the set of possible origin points. Key services, including educational establishments, health services (GPs), employment centres, city/town/district centres and open spaces, are defined as possible destination points, with each type of service given a weight based on data on the frequency of different trip purposes from *Transport Statistics Great Britain 2014* (Department for Transport 2014b). The weights used are as follows:

* Educational establishments - 0.21
* Health services – 0.10
* Open spaces - 0.10
* Employment centres - 0.19
* City/town/district centres - 0.40.

For the Southampton area, these definitions generated a total of 5,075 origins and 150 destinations, resulting in 761,250 possible OD pairs which have to be evaluated for each potential solution.

Although some commercial software packages, such as Visography TRACC, are available for calculating travel costs across multimodal networks, they are lack flexibility in their custom settings and could not be easily adapted to fit the objectives of this research. An integrated ArcGIS model was therefore developed using ArcObjects for Java, which provides the flexibility to generate customised models of the kind required here. Travel costs were calculated based on the UK Department for Transport’s Transport Analysis Guidance (WebTAG) (2014a), which states that the travel cost (Cij) from origin point i to destination point j comprises a weighted sum of the walking time (WKT), waiting time (WTT), in-vehicle time (IVT), and transfer penalty, which were defined in the model as follows:

* Walking time (WKT): Walking is considered to be the only available access and egress mode for bus services. The maximum permitted walking time is 15 minutes and the average walk speed is 4.8 kilometres per hour.
* Waiting time (WTT): For the first bus service used in a trip, the origin waiting time is defined as a function of the headway, being set as half the headway for headways up to 15 minutes, after which the waiting time is capped at 7.5 minutes. For subsequent services, passengers arrive at transfer bus stops randomly (due to the constraints of the timetable), and for simplicity the value of the transfer waiting time is therefore set to be equal to half the headway of the service boarded at the transfer stop.
* In-vehicle time (IVT): This is calculated by dividing the bus route length by the average bus speed.
* Transfer penalty: based on WebTAG (Department for Transport 2014a) advice a transfer penalty of 7.5 minutes of IVT per interchange was applied.

## 3.3 Optimal solution search procedure

This methodology makes use of a modified tabu search algorithm, with such algorithms having first been designed by Glover (1977); both basic and advanced versions of the algorithm can be found in Glover and Laguna (1997). The tabu search algorithm begin the search procedure with one single initial solution, then explores the solution space by moving from this input initial solution to the solution with the best objective function value in its neighbourhood at each iteration. Moves are defined as the sequences that lead from the initial solution to another solution. For example, the standard swap (or add/drop) move transforms the current solution into a new one by replacing one variable in the current solution by another one randomly selected from the search space. The tabu search algorithm permits moves that temporarily lead to a deterioration in the current objective function value in order to escape from local optima. In order to avoid cycling between the same subset of solutions, solutions that were recently examined are declared forbidden or ‘tabu’ for a certain number of iterations (tabu tenures) and associated attributes with the tabu solutions are also stored in tabu lists. The tabu status of a solution might be overridden if it is better than the current best solution in the neighbourhood, which is called ‘aspiration’.

The efficiency of tabu search can be improved by adding intensification and diversification strategies. Intensification strategies focus on examining neighbours of the good solutions, which may initiate a return to attractive regions to search them more thoroughly. Diversification encourages the search process to examine unvisited regions and to generate solutions that differ in various significant ways from those seen before. However, the performance of the tabu search algorithm is heavily dependent on the initial solution: a good initial solution is likely to output satisfactory results, while a poor one would reduce the speed of convergence and might lead to a failure to find an improved solution.

In order to further improve the performance of the search procedure, an adapted tabu search algorithm was applied in the methodology developed here. Firstly, the current bus network was selected as the initial solution, instead of a randomly selected initial solution, as it was assumed that the current network was more likely to be a moderately ‘good’ initial solution in terms of accessibility. Secondly, rather than using small standard moves (the swap moves), large moves, where half of the bus routes in the solution are replaced by new routes in each iteration, were used in this tabu search methodology (adding a key feature of the very large-scale neighbourhood search algorithm (Ahuja et al. 2002) into the tabu search algorithm). Hence, a larger neighbourhood space will be searched within a given time period, and more global optima should be output.

Figure 2 presents the flowchart of the adaptive tabu search methodology used in the optimal solution search procedure. The steps in the process can be described as follows:

* Step 1: input the current bus network as the initial solution.
* Step 2: initial solution evaluation procedure: evaluate the initial solution using the objective function.
* Step 3: tabu search neighbour search process for the initial solution
* Step 3.0: preparation process:
  + Set the set of tabu neighbours to be empty.
  + Save the initial solution as the current best solution.
* Step 3.1: generate the set of feasible neighbours using the neighbourhood function and evaluate each solution in the set.
* Each neighbourhood solution should meet cross-boundary and fleet size constraints
* Evaluate each neighbourhood solution using the objective function
* Step 3.2: define the set of non-tabu neighbours as the difference between the set of feasible neighbours and the set of tabu neighbours.
* Step 3.3: find the best neighbour (evaluated by objective function) from the set of feasible neighbours and set of non-tabu neighbours (they may coincide).
* Step 3.4: If the best neighbour from the set of non-tabu neighbours is better than the current best solution, update it as the current best solution and add it to the set of tabu neighbours.
* Step 3.5: If the best neighbour from the set of non-tabu neighbours is worse than the current best solution, compare the best neighbour from the set of feasible neighbours and the current best solution.
  + If the best neighbour from the set of feasible neighbours is better than the current best solution, update it as the current best solution and add it to the set of tabu neighbours (tabu search aspiration process).
  + If the best neighbour in the set of feasible neighbours is worse than the current best solution, update it as the current best solution and add all neighbours in the set of feasible neighbours to the set of tabu neighbours.
* Step 3.6: apply the diversification and intensification procedure to the current best solution.
* Step 4: update the initial solution as the current best solution, and repeat step 3 until the maximum number of generations allowed in the study has been reached.

# 4. Case study application of methodology

The methodology described above was built under the environment of ArcObjects for Java, and been implemented based on the current Southampton bus network on several desktop computers with similar characteristics.

Detailed information on the current bus network (the initial solution), including bus stops, bus routes, and timetable, was extracted from the National Public Transport Data Repository (NPTDR). This showed that there were 7 operators providing a total of 38 services in the current (2015) bus network in Southampton during the Monday morning peak hour (0800-0900). In addition to services entirely within the city boundaries, Southampton City Centre is linked with nearby towns and districts along six corridors, known as the Western approach, Shirley, Avenue, Bevois Valley, Northam, and Itchen Bridge (see Figure 3).

Over recent years, there have been a number of local government initiatives to improve local bus services and increase bus patronage in Southampton, including the Local Sustainable Travel Fund (LSTF) and the Better Bus Area Fund (BBAF) (Southampton City Council 2012, Song et al. 2014, Newcombe 2014). The majority of the measures which were implemented as part of the CBTF and BBAF focused on providing improvements to service quality to give a more positive travel experience, including improvements to existing bus and rail interchanges, refurbishment of buses, real time passenger information, the introduction of a smart card ticketing system and improved bus priority (particularly at junctions) on some corridors.

## 4.1 Sensitivity analysis

The results produced by the optimisation model depend to some extent on the values assigned to the user-defined parameters, such as the maximum number of solutions generated by the tabu search algorithm, the weights given to the three components of the objective function, the weights given to the walking time (WKT) and waiting time (WTT) in TUC, and the value set for the transfer penalty. Different values of these parameters will result in different output results. Each parameter is continuous and has many possible values, as for example the number of generations can vary from 1 to infinity. It is therefore impossible to compare the performance of each possible value of each parameter in order to determine the range of associated ‘optimal’ network solutions which might result. However, it was possible to carry out a sensitivity analysis of these parameters based on the current Southampton bus network, to assess how the performance of the model is affected by varying the generation number, the weights associated with different elements of the TSC, the weights given to WKT and WTT, and the value of the transfer penalty.

### 4.1.1 Effects of varying the generation number

Generation is a user-defined parameter, deciding the number of iterations the tabu search algorithm will run before outputting the final optimal solutions. The larger the chosen number of generations, the larger the neighbourhood space which will be searched and therefore the more global optima which will be output. However, a larger number of generations will also require more calculation time, and therefore an appropriate generation number needs to be chosen to output a reasonable number of potential optimal solutions within a reasonable calculation time. For simplicity, this section examines the effect of increasing the generation number from 10 to 100, with the corresponding calculation times ranging from six hours to three days on a standard desktop PC. Only the generation number was varied, with the other settings for the tabu search algorithm held constant, as follows: 0.4, 0.4, and 0.2 as the weights of TOC, TUC and TEC, respectively, 1.75 and 2.0 as the weights of WKT and WTT, and 7.5 minutes of IVT per interchange as the transfer penalty. Figure 4 displays the results, showing that the value of the objective function (TSC) tends to decrease as the number of generations increases. When the number of generations reaches 80, TSC achieves the minimum value.

### 4.1.2 Effect of weight set of the multi-objective function

The objective function of the optimisation model is to minimise total social cost (TSC), which is a composite multi-objective function defined as the weighted sum of three components: total operator cost (TOC), total external cost (TEC), and total user cost (TUC). The three weights are introduced to reflect the relative importance of TOC, TEC and TUC in determining TSC. As noted above, different values of these weights may result in different optimal designs of the transit network. In this section, the sensitivity of the model is checked by assigning different weight sets to the objective function, giving the results shown in Figure 5. In order to control for the effects of other parameters, the results were calculated by holding the other optimisation settings constant, as follows: 80 as the maximum generation number, 1.75 and 2.0 as the weights of WKT and WTT, and 7.5 minutes of IVT per interchange as the transfer penalty.

For each graph in Figure 5, the weight of TEC () is fixed at a value between 0.1 and 0.4. The horizontal axis indicates the weight of TUC (), and the vertical axis shows the value of TSC. Therefore, a total of 26 weight sets were tested in this section. For each possible weight set, the TSC of both the current bus network (red bar) and the optimal solution output from the model (blue bar) are displayed and compared. The results show that the TSC of both initial and optimal solutions tend to increase as the weight of TUC increases. This is expected because the value of TUC is much greater than the TOC, and the increase in TSC resulting from a 0.1 unit increase in the weight of TUC outweighs the decrease in TSC resulting from a 0.1 unit decrease in the weight of TOC. Figure 5 also shows that the difference between the initial and optimal solutions increases when TUC is given a greater weight. This is because the fluctuations of the objective function mainly result from changes in TUC due to the maximum fleet size constraint which limits variations in TOC and TEC.

Figure 5 indicates a strong positive correlation between the weight of TUC and the value of TSC, but does not determine whether the fluctuations in the TSC are determined only by differences in the weight of TUC or are also linked to the value of TUC. The relationship between the weight set of the objective function and the TUC of the optimal solution was therefore also checked (see Figure 6). For each line in Figure 6, the weight of TEC () is fixed at a value between 0.1 and 0.4. The horizontal axis indicates the weight of TUC (), and the vertical axis shows the value of TUC for the corresponding optimal solution. The results show that the model outputs better solutions when TUC is given a greater weight. When the weights of TOC, TEC, and TUC are 0.4, 0.2, and 0.4 respectively, the model outputs the optimal solution with minimum TUC.

### 4.1.3 Effect of weight set of WKT and WTT

Under the fixed fleet size constraint, the major improvements to the optimal solutions come from a reduction in TUC compared with the current bus network. The parameters used for calculating TUC should therefore be tested in a sensitivity analysis before implementing the model. Two categories of parameters, the weight set of WKT and WTT and the value of the transfer penalty, are essential in the process of calculating TUC, and sensitivity analyses of them are displayed in this and next section.

According to WebTAG (Department for Transport 2014a), the value of WKT is equivalent to 1.5-2.0 times the value of the same amount of IVT, while WTT is equivalent to 1.5-2.5 times IVT. Thus, the Wwkt set is {1.5, 2.0}, the Wwtt set is {1.5, 2.0, 2.5}, and weight set of (Wwkt, Wwtt) = {(1.5, 1.5), (1.5, 2.0), (1.5, 2.5), (2.0, 1.5), (2.0, 2.0), (2.0, 2.5)}. In this section, the sensitivity of the model was tested by assigning each value in the weight set of (Wwkt, Wwtt) to TUC, and the results are shown in Figure 7 and 8. Figure 7 shows that the TSC of both the initial (red bar) and the optimal solution (blue bar) increase when Wwkt and Wwttare given a greater value. This is because the value of TUC will increase if WKT and WTT are assumed to have a greater cost for users. With the same weight set, the difference between the red and blue bars shows the improvement of the optimal solution compared with the initial solution, and Figure 8 shows this in more detail. The magnitude of the improvement in the optimal solution shows no strong relationship with the weight set of WKT and WTT, ranging between 4.62% and 6.85%. The optimal solution with maximum improvement is output by the model when 1.5 and 2.5 are weights of WKT and WTT, respectively.

### 4.1.4 Effect of varying the transfer penalty

According to WebTAG (Department for Transport 2014a), the value of the transfer penalty is equivalent to 5-10 minutes of IVT per interchange, so the possible transfer penalty set is {5, 6, 7, 8, 9, 10}. The results from varying the value of the transfer penalty are shown in Figures 9 and 10. Figure 9 shows that the TSC of both the initial and optimal solutions increases when higher values are used for the transfer penalty. This would be expected because the value of TUC will increase if a larger transfer penalty is used. The relationship between transfer penalty and the level of improvement in TSC is displayed in Figure 10. This shows that there is no consistent relationship between the level of transfer penalty and the corresponding improvement in TSC, which fluctuates between 5.46% and 7.61%. The model outputs an optimal solution which gives the biggest improvement over the current network when the transfer penalty is set to 8 minutes of IVT.

## 4.2 Best solution

Based on the sensitivity analysis, the optimal networks were generated by using the following optimisation settings: 80 as the maximum generation number, 0.4, 0.4, and 0.2 as the weights of TOC, TUC and TEC, respectively, 1.75 and 2.0 as the weights of WKT and WTT, and 7.5 minutes of IVT per interchange as the transfer penalty.

Without adding additional vehicles to the network, optimal solutions were output from the optimisation model, and the best three of them were chosen as the final results. Table 1 lists and compares the characteristics of these output optimal solutions, as well as the current bus network. The difference in TSC between the optimal solutions and the initial solution is around 6%, which mainly comes from the improvements in TUC (approximately 9% improvement on average) because of the maximum fleet size constraint. Compared with the current bus network, the optimal solutions have a higher number of routes, shorter lengths of individual routes on average, and a slightly lower mean frequency across the network. This is expected because the candidate routes were generated by the k-shortest path algorithm for each terminal pair in the possible terminal set. In reality, bus operators are concerned about the economic benefits as well as service convenience. Hence, despite the existence of terminals (the starting and ending bus stops of the route), bus routes tend to be designed to link more key trip attractors and residential locations between these terminals rather than necessarily following the shortest path. For example, the terminals of the U1 service provided by Unilink are Southampton Airport and National Oceanography Centre (NOC), but the service also links University of Southampton (Highfield Campus), Portswood, and City Centre on the route between these locations. The optimal solutions therefore have shorter lengths for individual routes on average compared with the current bus network. In order to meet the maximum fleet size constraint, the optimal solutions make a trade-off between the shorter lengths of individual routes and a larger number of routes across the network.

Figure 11 displays the network layouts of these optimal solutions, as well as the current network. Although the routes chosen by the best solutions are 99% different in terms of routes, as a whole they represent similar network layouts. According to Table 2, any two of the best three solutions share approximately 70% of their total road coverage, while this figure is around 60% when compared with the current network. This is partly because of the cross-boundary constraint applied in the process of selecting potential solutions from the candidate route set. In order to avoid the cross-boundary problem, the constraint retains the service levels to nearby towns and cities at current levels. Hence, six groups of cross-boundary terminals were chosen based on the six corridors linking the Southampton City Centre to nearby towns and districts (see Figure 3). In the process of selecting potential solutions, the candidate routes linking these cross-boundary terminals and the possible terminals within the city boundary are selected and set corresponding frequencies. As a result, all potential solutions (along with the current network) share the same cross-boundary terminals and have the same cross-boundary service levels along the six corridors, leading to inevitable similarities in their network layouts. Furthermore, the six key corridors which link the city to nearby districts as well as key locations within the city boundary are based on major roads across the city and are relatively straight. When the candidate routes are generated based on the k-shortest algorithm, the routes along these corridors are therefore highly likely to be chosen by the model. This also helps to explain the high percentage of sharing roads available in the networks of optimal solutions, and makes a contribution to the slightly higher route overlapping factors of optimal solutions compared with the current bus network.

# 5. Conclusions and future work

This paper has shown that it is possible to develop a methodology which is capable of evaluating the potential of centralised service planning for public transport to generate a more socially-optimal network than is provided in a deregulated environment. Using Southampton as a case study, a practical optimisation model has been developed to explore the potential improvements which could be achieved with centralised planning of bus networks using an adapted tabu search algorithm. This optimisation model has been shown to work for real-world size multimodal public transport networks based on a complex road network topology. The output results show that the model delivered a better bus network based on the criteria used here, with a 6.69% improvement in TSC compared to the base network. This methodology could therefore help to deliver an integrated bus network with more equal network distribution and less unnecessary duplication in service provision. If this was combined with the introduction of a simple ticketing system, fare capping (equivalent to the price of a daily ticket) and enforceable standards for performance and quality, it would contribute to the provision of a high-quality bus network which better meets the needs of local residents and local economy. Because vehicle kilometres are capped at current levels it would also potentially increase the benefits per unit of cost involved in providing bus services. It could also help facilitate the incorporation of public transport in broader economic and land-use planning, and therefore help cities to develop in a more sustainable way in the future.

There is still scope for further development of the model, with the obvious next step being to implement the current optimisation model in other real world case studies. This might include a British city which has been relatively successful in implementing a quality partnership based approach to bus service provision (such as Brighton or Oxford) to investigate whether such bus networks are closer to the ‘optimum’ produced by the model. Other improvements to the model which should be considered in the future include more consideration of fares and quality improvements alongside the service quantity measures modelled in the current framework.

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**Tables:**

Table 1. Comparison between current and optimal networks

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | | Top 1 | Top 2 | Top 3 | Mean | Current Solution  network |
| Route NO | | 72 | 59 | 67 | 66 | 38 |
| VKM | | 1258.16 | 1242.75 | 1250.79 | 1250.57 | 1245.04 |
| TOC(£) | | 1274.66 | 1259.04 | 1267.19 | 1266.96 | 1261.36 |
| TEC(£) | | 547.30 | 540.59 | 544.10 | 544.00 | 541.59 |
| TUC(£) | | 2919.83 | 2979.75 | 2977.55 | 2959.04 | 3256.43 |
| TSC(£) | | 1787.25 | 1803.64 | 1806.71 | 1799.20 | 1915.434 |
| Improvement (%) | | 6.69% | 5.84% | 5.68% | 6.07% | 0% (baseline) |
| Route Length  (km) | Mean | 5.40 | 5.70 | 5.14 | 5.41 | 8.37 |
| Min. | 1.21 | 1.25 | 1.24 | 1.23 | 1.90 |
| Max. | 11.59 | 11.50 | 11.83 | 11.64 | 16.81 |
| Sum | 388.92 | 336.17 | 344.45 | 356.52 | 360.22 |
| Frequency | Mean | 3.58 | 4.11 | 3.80 | 3.83 | 3.96 |
| Min. | 0.5 | 0.5 | 0.5 | 0.5 | 1 |
| Max. | 12 | 12 | 12 | 12 | 9 |

Table 2: Comparison between current and optimal networks (in terms of network layout)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Top 1 | Top 2 | Top 3 | Current Solution  network |
| Total road length  available in the network (km) | 138.05 | 122.83 | 129.73 | 135.01 |
| Sharing road length with Top 1 (km, %) |  | 95.57  (77.81%) | 94.56  (72.89%) | 80.02  (59.27%) |
| Sharing road length with Top 2 (km, %) | 95.57  (69.23%) |  | 94.56  (72.90%) | 76.98  (57.02%) |
| Sharing road length with Top 3 (km, %) | 94.56  (68.50%) | 96.24  (78.35%) |  | 76.69  (56.81%) |
| Sharing road length with current solution  (km, %) | 80.02  (57.78%) | 76.98  (62.67%) | 76.69  (59.11%) |  |
| Route overlap factor\* | 2.82 | 2.74 | 2.66 | 2.67 |

**Figures:**

Figure 1. Methodology of the optimisation model

Figure 2. Workflow of the optimal solution search procedure

Figure 3. Bus operators and services in current bus network in Southampton (during morning peak hour 08:00-09:00)

Figure 4. Effect of varying the number of generations

Figure 5. Effect of weight set of the multi-objective function (in terms of TSC)

Figure 5(a). Weight of TEC = 0.1

Figure 5(b). Weight of TEC = 0.2

Figure 5(c). Weight of TEC = 0.3

Figure 5(d). Weight of TEC = 0.4

Figure 6. Effect of weight set of the multi-objective function (In terms of TUC)

Figure 7. Effect of weight set of WKT and WTT (in terms of TSC (£))

Figure 8. Effect of weight set of WKT and WTT (in terms of TSC improvement (%))

Figure 9. Effect of transfer penalty (in terms of TSC (£))

Figure 10. Effect of transfer penalty (in terms of TSC improvement (%))

Figure 11. Comparison of network layout between current and optimal network

Figure 11(a). Current network

Figure 11(b). Top 1 (6.69%)

Figure 11(c). Top 2 (5.84%)

Figure 11(d). Top 3 (5.68%)

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