
Reassessing the Financial and Social Costs of Public Transport

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Abstract

This paper uses a previously developed spreadsheet cost model which simulates public transport modes operated on a 12km route to analyse the total costs of different passenger demand levels. The previous cost model was a very powerful tool to estimate the social and operator cost for different public transport technologies. However, as the model is strategic based, some assumptions are very basic and idealized and the demand was assumed to be exogenous (externally fixed). When the level of demand is high for the lower capacity public transport technologies, passengers may find the incoming vehicle full and therefore they have to wait more than one service interval. This paper applies queueing theory to investigate the probability of having to wait longer than the expected service headways which will affect the average passenger waiting time. The extra waiting time for each passenger is calculated and applied in the spreadsheet cost model. The speed-flow equation in the original spreadsheet model assumes the speed decreases according to the ratio of the current frequency and the lane capacity which is based on the safety headway without any passenger boarding. However, this may vary in different operating environments. Therefore, the speed equation is improved by moving from a linear equation to a piecewise equation that considers the features of different operating environments. To evaluate the differences after applying these equations, endogenous demand rather than exogenous demand will be investigated by using the elasticities for passenger waiting time and journey time.

1. Introduction

Public transport is one of the most important means of daily travel such as commuting, shopping and education. Passenger demand for local bus services in the UK in 2010 has increased by approximately 13% since 2004/05 and the annual passenger revenues of light rail and tram systems have increased by 19% over the same period while the passenger kilometres travelled by national rail have doubled since privatisation (1994/1995) (Department for Transport, 2012). The benefits of developing public transport are being recognised by governments all around the world. Many new intermediate public transport modes have been developed to meet various passenger requirements. A number of examples are discussed in this section. The ULTra (Urban Light Transit) Personal Rapid Transit (PRT) system in London Heathrow Airport works as a feeder service for people between the business car park and the terminals and takes only 5 – 6 minutes to travel along approximately 1.2 miles (ULTraGlobalPRT, 2011). The 450 m outbound and 750 m inbound Guided Bus system in Leeds ensures punctuality and reliability and increases the attractiveness of bus services by providing a segregated busway, and this reduces journey time by 33% and increase patronage by 40% (Currie and Wallis, 2008). The light rail system operating in Greater Manchester (Metrolink) provides more frequent services as well as cheaper fares than British Rail, while maintaining the competitiveness of the rail system in terms of operating speed and punctuality, and because of these characteristics the Metrolink successfully achieved its ridership projections while most new urban rail systems failed to reach their initial targets (Knowles, 2007). A cost-effective technology, Bus Rapid Transit (BRT), is operated in a wide number of countries. Buses run on a segregated busway with dedicated stops which results in a maximum running speed of up to 100kph and no congestions in peak hours. Demand has reached 15,000 per hour after only 5 years operation of the BRT system in Brisbane while the long term maximum peak hour demand was forecasted to be 10,000 per hour (Currie, 2006). The Straddle Bus is a new invention launched at the 13th Beijing International High-tech Expo in 2010 and is believed to be able to solve the traffic congestion in metropolises such as Beijing and London by having fewer interactions with other forms of transport, while carrying many more people than normal buses (McDermon, 2010).

These new public transport modes would have different feasibility at distinct demand levels, and the costs would also vary. Therefore, comparing their costs in the same situation is an essential issue. The cost of public transport technologies consists of not only how much individuals pay but also how much the government and society in general pay (Jakob et al. 2006) which is the total social cost.

Previous studies have been carried out in the TEST (Tools for Evaluating Strategically Integrated Public Transport) project by Brand and Preston (2001, 2002a, 2002b, 2003a, 2003b, 2006). Based on the pioneering study of Meyer, Kain and Wohl (1965) on the operator costs for different transport modes (auto, bus and rail) in different population density areas, their work proposed a spreadsheet cost model in Microsoft Excel and an integrated simulation model by using transport analysis software VIPS (now part of the wider VISUM model) and CONTRAM. The spreadsheet cost model compared up to 15 conventional, new intermediate and innovative public transport technologies on the basis of the average and marginal social costs which include user costs and external costs rather than just the costs for the operator on a 12km single route corridor without considering full network detail. The speed-flow equation used in the spreadsheet model is a linear equation rather than a power law or piecewise linear function (Small, 1992). The waiting time for public transport passengers in the user cost section considers service frequency only. However, passengers may experience additional delay when they find the incoming vehicle is full at high levels of demand. The demand level increments in the model are all externally fixed which means the results are all based on fixed demand prediction. In reality, passenger demand levels are endogenous, not exogenous, and are affected by the performance of the public transport technologies such as the service interval and journey time. The actual average costs could be substantially different if the model only considers the fixed demand level because the actual passenger demand will vary due to the quality of service.

Therefore, the objectives of this paper are:

1. To improve the speed-flow equation of the spreadsheet cost model by using a piecewise function and adding the facility capacity factor for the advantages in different operating environments.
2. To take the probability of passengers having to wait longer than service headways into account for the average passenger waiting time calculation.
3. To evaluate the results of applying the revised speed-flow and waiting time functions by investigating the endogenous relationship between demand and supply and then comparing the average social costs of the Single-deck bus services in different operating environments.

The organisation of this paper is as follows. Section 2 demonstrates the application of the new speed-flow equation in the spreadsheet model by considering the impact of other vehicles in the traffic flow. Section 3 presents the equations for calculating the passenger waiting time with queueing theory. Section 4 gives the analysis of the endogenous demand impact and section 5 draws some conclusions and outlines the potential future work.

2. Speed-Flow Equation in the Spreadsheet Model

This spreadsheet cost model developed in the TEST project by Brand and Preston (2006) was based on the study of social costs by Jansson (1984) who developed the concept of social costs as the sum of total producer costs and total user costs and the work on operator costs by Meyer, Kain and Wohl (1965) who developed the equation for total operator and other non-structural costs of rail and bus transit.

The TEST project developed total social costs as the sum of total operator costs, total user costs and total external costs:

$$TSC = TOC + TUC + TEC \quad \text{Equation 1}$$

where the total operator cost covers all capital investment by operators of the public transport service, the total user cost includes passenger walking time, waiting time and in-vehicle time converted into money units using values of time and the total external cost accounts for any external impacts such as air pollution and accidents.

There are a number of assumptions made in the TEST model. The TEST model is based on the core operating day time services (07:00 to 18:00). Three time periods have been identified in this model: morning peak, evening peak and off peak period. The lengths of these time sectors are assumed to be 2 hours for each peak time and 7 hours for the off peak and 11 hours of steady operating period in total. The daily passenger demands are split into these time period which is 22.5% for each peak period and 55% for the off peak. Model calculations are based on the input of estimated demand and parameters of the public transport technologies and are either set by the user or use the default values. With initial input data, the model can then obtain the intermediate outputs such as required service frequency and average operational speed which are the two key factors to calculate all the costs. The required service frequency function is defined as:

$$F = \frac{\alpha \times PAX}{VehCap \times MaxLF} \quad \text{Equation 2}$$

where α is the factor to allow for seasonal fluctuations for which the default value is 1.1 and can be modified by the user, PAX is the demand for the time period, $VehCap$ is the vehicle capacity including seating and standing space and $MaxLF$ is the maximum relative load factor at which level a new vehicle is required which is set to 50% as default. The required service frequency is associated with the average operational speed V^{ALL} which is calculated with the speed-flow equation of:

$$V^{ALL} = V^{NoCap} \left(1 - \frac{F}{C}\right) \quad \text{Equation 3}$$

In this equation, V^{NoCap} is the vehicle operational speed calculated by using the default value (or user defined) of acceleration, maximum speed, station spacing, stopping time and passenger boarding/alighting time without considering the capacity of the infrastructure, and the variable C is the infrastructure capacity which is the maximum possible vehicle numbers per lane (for road-based systems) or per track (for rail-based systems). With the restraint of the infrastructure capacity, the average operational speed can then reflect the traffic situation when the congestion of the system due to passenger demand rises. The infrastructure capacity can be defined by users for the technologies which allow overtaking or calculated by the equations as follows for technologies where overtaking is not possible.

$$C = \frac{3600}{H} \quad \text{Equation 4}$$

$$H = T^{Veh} + \sqrt{\frac{2L^{Veh}}{A}} + \frac{L^{Veh}}{V^{Max}} + \frac{V^{Max}}{2A} \quad \text{Equation 5}$$

where H is the safety headways in seconds to calculate the minimum possible service interval without any passenger boarding, T^{Veh} is the vehicle stopping time which includes opening/closing doors and changing shifts for drivers, L^{Veh} is the length of the vehicle, V^{Max} is the maximum possible running speed and A is the acceleration and deceleration of the vehicle.

The speed-flow equation in the spreadsheet model is a linear function (Equation 3). This is because the spreadsheet model assumed the public transport service is on a segregated 12km route and the level of public transport traffic is fixed. However, the advantages of having a segregated road for the public transport technologies such as guided bus and rail-based public transport modes cannot be clearly shown in the cost model. If the service frequency requirement of the public transport service increases which means the passenger demand on the route is increased, the probability increases that not only the public transport vehicles themselves but also other traffic will delay the operating speed of the public transport services, either by causing congestion at the junctions or by blocking access in to or out of the stops.

The speed of the traffic flow can be estimated based on the number of the vehicles entering the route and the capacity of the roadway. As the travel time is highly related to the travel speed, a simple power law function can be used to demonstrate the relationship of traffic volume and travel time, and the power law function is:

$$1/S = T_0 + T_1(V/V_K)^k \quad \text{Equation 6}$$

where T_0 , T_1 , and k are parameters, V is the traffic volume and V_K is the capacity. This power law function is postulated for single links in a network by the U.S Bureau of Public Roads with $k = 4$ and $T_0/T_1 = 0.15$ and widely used in many economic models (Small, 1992). Small (1992) also derived another function to express the travel time over a peak period, which is a piecewise linear function:

$$1/S = \begin{cases} T_0 & V \leq V_K \\ T_0 + T_1(V/V_K - 1) & V > V_K \end{cases} \quad \text{Equation 7}$$

Parameters are estimated for both the power law function and the piecewise linear function and average maximum delay against daily vehicles are plotted, and the piecewise linear function fits slightly better (Small, 1992, page 71-72).

However, these functions are for calculating the speed and travel time in mixed traffic flow, given the capacity of the roadway. Many innovative public transport technologies tend to operate on either transit lanes (guided bus, light rail etc.) or grade-separated rights-of-way (Personal Rapid Transit, underground etc.) to avoid the delay caused by other vehicles. Facility capacity will vary in different operating environments of the public transport service. For example, conventional bus service may experience congestion and the operating speed will start to decrease at a lower level of passenger demand than those bus services operating on segregated busway such as the guided bus and Bus Rapid Transit. The method of determining the lane capacity of a public transport technology in the TEST project is to consider the minimum headway without any passenger boarding. Therefore a factor should be added to account for the differences between different operating environments.

The impacts of operating environment on capacity have been investigated and reported in Transit Capacity and Quality of Service Manual (Kittelson & Associates, Inc., et al, 2013). There are four types of operating environments which are discussed in that manual, which are: mixed traffic, semi-exclusive, exclusive and grade separated. Mixed traffic operating environments mean the public transport mode has to shared lanes at all times with general traffic, such as the conventional bus technology. Semi-exclusive operating environments will have partially dedicated facilities for transit use, but are also available for other vehicles at certain times, such as buses on bus lane and light rail line with pedestrian access. Exclusive operating environments are defined as the facilities are dedicated for transit use at all times, but there may be some external traffic interaction at controlled locations (for example, guided bus or Bus Rapid Transit). Grade separated operating environments have no at-grade crossings, and facilities are fully dedicated to the transit vehicles (for example, underground). Facility capacity as percentage of base condition for different operating environments has been illustrated in Transit Capacity and Quality of Service Manual (see, Kittelson & Associates, Inc., et al, 2013, page 3-34), as shown in Table 1.

Table 1 Facility Capacity as % of Base Condition in Different Operating Environments

Transit Type	Mixed Traffic (urban street)	Semi-exclusive (transit lane)	Exclusive (street median)	Exclusive (private right-of-way)	Grade-separated (busway or subway)
Bus	38%	52%	61%	57%	100%
Rail	41%	67%	100%	92%	100%

*data adapted from Transit Capacity and Quality of Service Manual (Kittelson & Associates, Inc., et al, 2013)

The facility capacity is defined as the maximum possible service frequency of the public transport services calculated either by critical bus stop capacity (for bus transit) or by safety headways (for rail-based transit). Base condition for bus technologies assumes 30s dwell time, no traffic signals, 10s clearance time and 60% dwell time variation. For rail technologies, base condition assumes 3-aspect train signals, 45s dwell time and 20s operating margin (details can be found in Kittelson & Associates, Inc., et al, 2013, Chapter 6 & Chapter 8).

According to Table 1, facility capacity varies for different transit modes and different operating environments, and the advantages of having a segregated transit lane are shown, for example, the operating speed of the bus service in mixed traffic environment may begin to decrease earlier than the service mode with dedicated transit lanes if we consider with a piecewise speed-flow equation. This facility capacity in different operating environments can be applied in the spreadsheet cost model to represent the advantages in the operating speed and the passengers' waiting time costs of the public transport technologies with higher infrastructure costs.

To take the piecewise speed-flow equation and the facility capacity in different operating environments into account for the spreadsheet model, the speed equation will be:

$$1/S = \begin{cases} T_0 & F \leq C_F (= fC) \\ T_0 + T_1(F/C_F - 1) & F > C_F (= fC) \end{cases} \quad \text{Equation 8}$$

where f represents the capacity percentage as listed in Table 1 and C_F is the critical facility capacity calculated by f times the safety headway capacity C . Since the spreadsheet model calculations use the operating speed of the public transport technology instead of the average travel time as intermediate variable, we have:

$$V^{ALL} = \begin{cases} V_0^{NoCap} & F \leq C_F \\ \frac{V_0^{NoCap} V_1^{NoCap}}{V_1^{NoCap} + V_0^{NoCap} (F/C_F - 1)} & F > C_F \end{cases} \quad \text{Equation 9}$$

This function is derived from the piecewise linear function for travel time and uses the original safety headway capacity in the TEST project multiplied by the capacity percentage in different operating environments. To demonstrate the difference, the relationships between speed and passenger demand of the Single-decker Bus in mixed traffic and the Single-decker Bus on busway from the spreadsheet cost model are shown in Figure 1 and Figure 2.

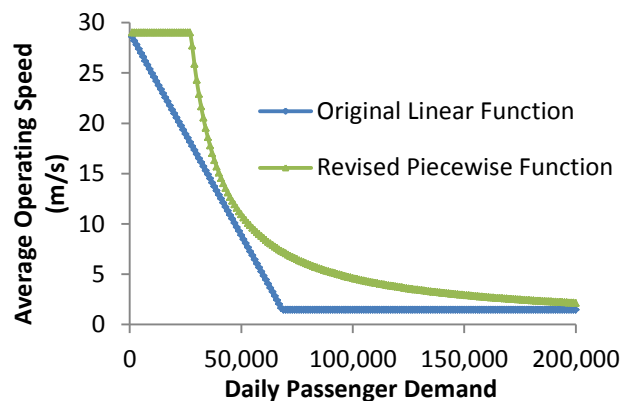


Figure 1 Average Operating Speed of Singler-decker Bus in Mixed Traffic

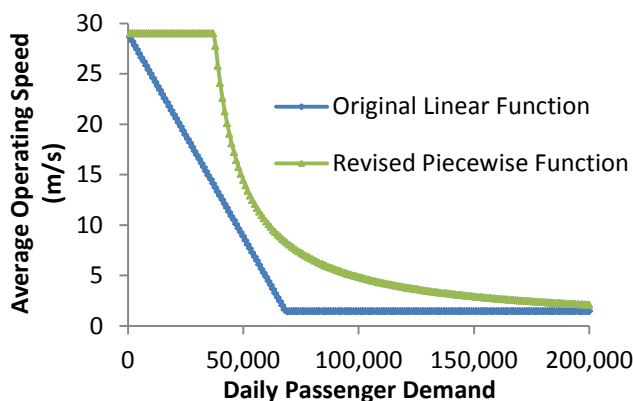


Figure 2 Average Operating Speed of Singler-decker Bus on Busway

From Figure 1 and Figure 2 we can see that, with the original linear function indicated as blue lines in the graphs, the average operating speed is the same for both technologies, as their lane capacities (safety headways) are the same. The green curves indicate the revised piecewise speed-flow function for average speed as shown in Equation 9 with the application of a facility capacity factor to account for the operating environment. For both bus technologies, there is no speed reduction until they reach the critical facility capacity, and then the travel time starts to increase linearly which means their average speeds decrease as a reciprocal function of flow, as shown in the graphs.

3. Passenger waiting time Equation in the Spreadsheet Model

Passenger waiting time is one of the most important constituents of the total user cost for all public transport technologies. The calculations of the passenger waiting time in the original spreadsheet model assumed a classic formula for the mean waiting time, due to lack of information and the notably strategic nature of the model version, and the formula is:

$$T^{wait} = \frac{H^{freq}}{2} + \frac{T^{Stop}}{3600} \quad \text{Equation 10}$$

where T^{wait} is the mean waiting time for each passenger, H^{freq} is the service headways and T^{Stop} is the vehicle dwell time for each stop. This formula assumes all passengers at the stop have to wait half of the service headways plus dwell time in average before they start their journey. Suppose all public transport passengers are evenly distributed and the service capacity can always meet the demand, this equation can correctly represent the passenger waiting time. However, passenger demand level varies at different stops for different time periods in reality. The distribution of passenger demand is cumulative and depends on the location of stops. The number of passenger loading at the stops close to the central business district could be much larger than other stops in peak time periods. There will be a probability that passengers at these stops find the incoming public transport vehicles full or with not enough space to take all waiting passengers, even though the overall capacity of the public transport service may still higher than the total demand of the route. This situation may occur more often when the demand level is high because the vehicle capacity is fixed except for some rail-based technologies that able to operate multiple car-units, and passengers who use lower vehicle capacity public transport services may have higher possibility to wait longer than the expected service frequency in the busiest public transport stops.

The public transport service can be regarded as serving seats to passengers (customers) and each arrival vehicle means a bunch of customers are served. Therefore, passenger waiting time can be calculated by using queueing theory for the time spent by the queueing customers. In order to use the queueing theory for passenger waiting time calculation, we have to define the utilization rate of the system as:

$$\rho = \frac{\lambda}{\mu} \quad \text{Equation 11}$$

where ρ stands for the utilization rate of the system, λ is the passenger arrival rate and μ is the service rate. In the queueing theory calculation, the utilization rate is less than 1. This is because when the incoming passenger number is higher than the facility capacity, the equilibrium queue length becomes unbounded and the waiting time of the late arrived passengers could be infinitely high. As this equation uses the same unit for the arrival passengers and the incoming public transport vehicles, we can assume the boarding passengers as a group by dividing a percentage of the vehicle capacity:

$$\rho = \frac{Q/aC_{veh}}{F} = \frac{Q}{aC_{veh}F} \quad \text{Equation 12}$$

where Q is the average demand per hour, C_{veh} is the vehicle capacity and a is the boarding/alighting rate to calculate the available spaces left for each incoming vehicle. To apply the queueing theory, specifications of the system have to be made for: the arrival process, the service mechanism and the queue discipline. The arrival process and service mechanism should be defined as either deterministic flow or some other random distribution for the way which passengers and the public transport services arrive at the stop, respectively. The queue discipline defines the method to handle the incoming customers,

which can be “first come first served” or “last come first served”. Glaister (1981) demonstrates the method of calculating passenger queues of travel by any mode. By assuming a “first come first serve” rule of service and a Poisson process of both the passenger arrival process and the bus service mechanism, Glaister (1981) gives the probability of having to wait longer than W^* as:

$$P = \rho \exp[-(\mu - \lambda)W^*] \quad \text{Equation 13}$$

By substituting the service interval and Equation 12 into Equation 13 we have the probability of having to wait longer than one service headway as:

$$P = \frac{Q}{aC_{veh}F} \exp\left[-\frac{(F-Q/aC_{veh})}{F}\right] \quad \text{Equation 14}$$

The parameter W^* has been substituted by $1/F$ which is the service interval, and the probability of having to wait for at least the third incoming vehicle can be calculated by simply replacing the W^* as $2/F$. To illustrate the result, the probability that the Single-decker bus passengers in the peak period have to wait longer than the expected service headways at demand level of 50,000 per day is shown in Figure 3.

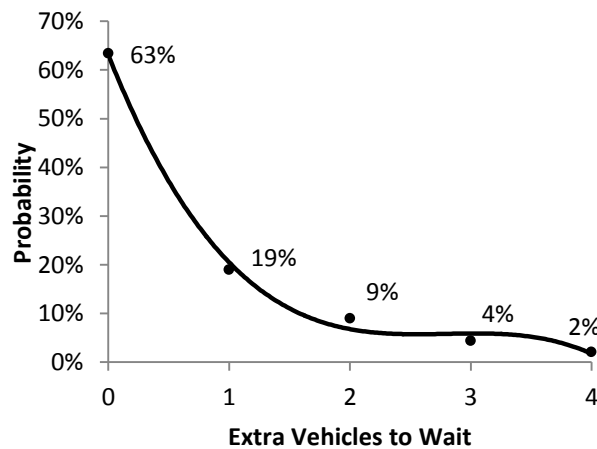


Figure 3 Probability of Having to Wait Longer than Service Headways

Note that all parameters are using the default value in the spreadsheet cost model which can be modified by the user to incorporate different public transport technology characteristics. Although the public transport passengers along the corridor still have to be assumed evenly distributed, this equation considers the passenger arrival process as Poisson distribution. With the assumption that the spare capacity is 30% of vehicle capacity, 39% of passengers have to wait for more than one service interval of the bus service. To apply this probability into the spreadsheet cost model calculation of passenger waiting time, the average waiting time for each passenger at each stop will be:

$$WT = \sum_{i=0}^{\infty} T^{wait}(i + 1)P_i \quad \text{Equation 15}$$

where WT is the average waiting time for each passenger at each stop, i is the extra vehicle numbers to be waited and P_i is the probability of having to wait more than i numbers of the public transport vehicle.

If we consider the previous Single-decker bus example, the passenger waiting time calculated by using the original method is:

$$T^{wait} = \frac{65.45}{2} + 23.64 = 56.36s$$

Therefore the average passenger waiting time if we use the queueing theory will be:

$$WT = T^{wait} \times 63\% + T^{wait} \times 2 \times 19\% + T^{wait} \times 3 \times 9\% + T^{wait} \times 4 \times 4\% + T^{wait} \times 5 \times 2\% \\ \Rightarrow WT = 86.79s$$

This means in the passenger demand level of 50,000 per day on the 12km corridor, each passenger may have to spend approximately 30 more seconds because of the queue length.

This extra wait time will increase with the level of demand because the remaining capacity of the system is getting lower.

4. Demand Supply Relationship

To investigate the results after applying the revised speed-flow and waiting time equations, the final cost results of the Single-decker bus in mixed traffic with both endogenous demand and exogenous demand are compared in this section. In the spreadsheet model, daily passenger demand level is changed in the calculation procedure for every 1,000 passengers, which means the demand is assumed to be exogenous – externally fixed by the spreadsheet model. This is because the supply requirement calculation model has to assume the level of passenger demand as externally fixed in the first place to obtain the total costs. However, it cannot reflect the situation that passengers' willingness to use the service varies according to the quality of service. As a result of that, a further analysis of demand and supply relationship must be conducted to obtain the actual average costs. The endogenous passenger demand in reality is closely related to the performance of the technology such as the service frequency, passenger waiting time and in-vehicle time for the whole journey.

In order to investigate the internal impact of the users' waiting time and in-vehicle time on the current demand level, the demand elasticity concept is introduced. The elasticity of demand can be defined as:

$$E_x = \frac{\text{The proportional change in demand}}{\text{The proportional change in the variable of interest}} = \frac{\Delta Q/Q}{\Delta x/x} \quad \text{Equation 16}$$

where Q is the demand, ΔQ is the change in the demand, and Δx is the change in the variable x which we are interested in (e.g. service headway). In this definition, the variable x can be any factor that would affect the demand level.

Time is one of the most important factors that impacts on the service quality of public transport, especially journey time and waiting time. Based on the elasticity definition, the endogenous passenger demand level can be calculated as:

$$Q_1 = Q_0 \left(\frac{T_1^{wait}}{T_0^{wait}} \right)^{E_1} \left(\frac{JT_1}{JT_0} \right)^{E_2} \quad \text{Equation 17}$$

where Q_1 is the endogenous demand level, Q_0 is the input exogenous demand level from 1,000 to 200,000 per day, T_1^{wait} is the passenger waiting time at exogenous demand level of the public transport mode, T_0^{wait} is the average passenger waiting time frequency at a fixed demand level for all modes (= 10,000 passenger trips per day), JT_1 is the journey time at exogenous demand level of the public transport mode, JT_0 is the average journey time at a fixed demand level for all modes (= 10,000 passenger trips per day), E_1 is the elasticity of demand with respect to waiting time, E_2 is the elasticity of demand with respect to journey time.

The demand elasticity of passenger waiting time was estimated by Preston and James (2000) based on an analysis with bus data in 23 urban areas in the Great Britain. These waiting time elasticities for UK cities analysis are reported by Balcombe et al. (2004), and the average elasticity is calculated as -0.64. This elasticity value of -0.64 means every 1% of increasing or decreasing wait time will have an effect of a 0.64% decrease or increase in the demand level. For the elasticity of the passenger in-vehicle time, less journey time is always preferred. So for any increment in the time spent on board, passenger demand level will fall, which means the journey time elasticity is always negative. Review studies have been done all around the world for different cities. The in-vehicle time elasticity for buses is estimated to be approximately -0.4 by Daugherty et al. (1999) after reviewing the bus priority schemes in Great Britain. So in the spreadsheet model, the waiting time elasticity for buses would then use -0.64 and an elasticity value of -0.4 would be adopted for bus journey time.

This equation uses elasticities of waiting time and journey time to calculate the difference between the fixed demand level and the endogenous demand level when the public transport technologies are operating on road. By applying this equation to the spreadsheet model for every step of the exogenous demand from 1,000 to 200,000, the original average

demand level would change due to the elasticity factor, and then the graph of the endogenous demand against the original exogenous demand can be produced. To compare the difference of applying the endogenous demand, Figure 4 is plotted according to the spreadsheet cost model results of the Single-decker bus in mixed traffic (before applying the revised speed-flow and waiting time equations).

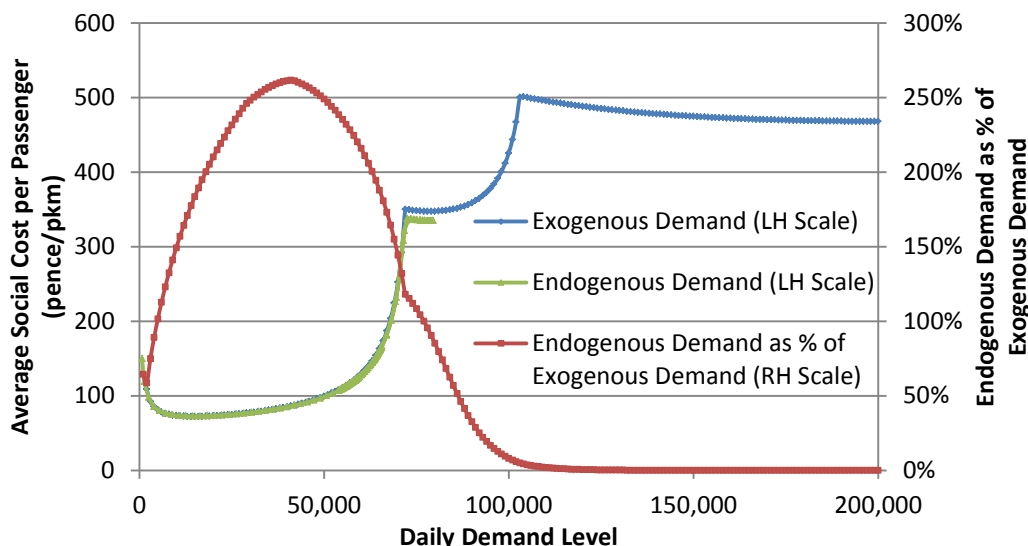


Figure 4 Average Social Cost of the Single-decker Bus in Mixed Traffic with Exogenous Demand and Endogenous Demand

The red line indicates the calculated endogenous demand as a percentage of the given exogenous demand by using Equation 17. The calculated endogenous demand represents the impact of the quality of service to the attractiveness of the public transport service. For example, when the provided journey time and waiting time of the Single-decker bus in mixed traffic are low (from demand level of 9,000 to 68,000 passengers per day), more passengers are willing to use the service (more than 150% of the exogenous demand); when the demand is higher than 85,000 per day, the deterioration in service will bring the demand level down. There are two inflection points at the demand level of 72,000 and 103,000. The safety headway capacity for peak period and off-peak period are reached at the demand level of 72,000 and 103,000, respectively. This is because the public transport services reach the safety headway capacity and the service frequency cannot be increased, and therefore the average costs for the vehicle are reduced. After applying the endogenous demand, the social cost curve stops at the daily demand level of 76,700. This result means any increase in demand will lead to a service which will bring the level of demand back to the maximum level calculated by the elasticity analysis. With the limited quality of service for the Single-deck bus in mixed traffic, the actual level of demand cannot accumulate up to 200,000 passengers per day.

For some public transport technologies, the total operator costs will be much lower than the exclusive facility technologies with higher infrastructure costs while the total user costs are very high due to the congestion time costs. By considering the impacts of journey time and waiting time cost to passengers, the advantages of these high infrastructure costs can be demonstrated in the spreadsheet cost model.

With the application of endogenous demand, the effects of the revised speed-flow and waiting time equations on the total social costs can be assessed. Figure 5 shows the average social costs of the Single-decker bus in mixed traffic and the Single-decker bus on busway with endogenous demand from the spreadsheet cost model.

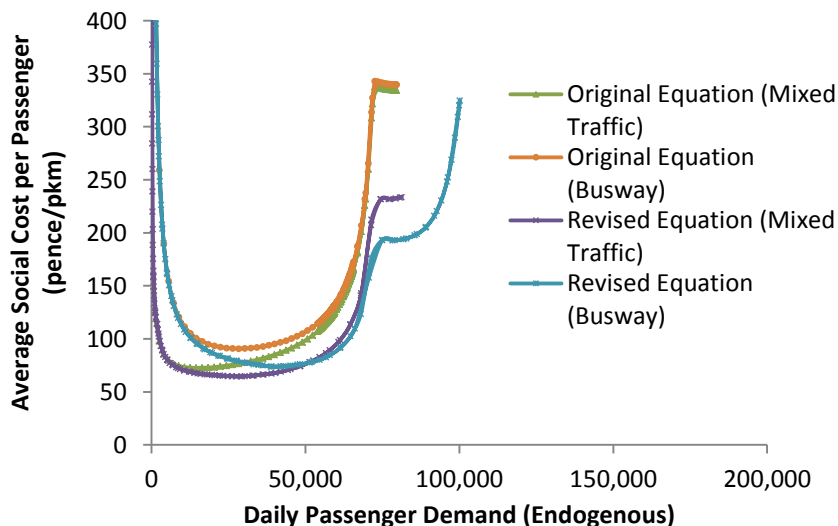


Figure 5 Average Social Cost of the Single-decker Bus in Mixed Traffic and on Busway

The x-axis in the graph indicates the demand level when it is influenced by the supplied public transport services. The average social costs calculated by using the original equations for different bus operating environments are shown as the green and orange lines. Before they reach the safety headway capacity, the cost for the bus service in mixed traffic is lower because of the higher infrastructure costs of busway. Without considering the advantage of having an exclusive transit lane in the original equations, the average social cost of the Single-deck bus on busway is always higher than the cost in mixed traffic at all demand levels.

The purple and blue lines indicate the average social costs calculated by using the revised speed-flow and waiting time equations. At low demand levels, the Single-decker bus in mixed traffic still stands out because of its lower infrastructure costs while their speed differences are not obvious. When the demand level reaches 51,400 per day for the 12km corridor, the advantages of having exclusive transit facilities make the Single-decker bus in busway have the lowest average social costs. This is because high passenger demand level would cause traffic congestion which lowers the operating speed especially the services in mixed traffic and eventually make the in-vehicle time higher. Passengers' waiting time would also be affected as the vehicles have to spend more time at stations/stops for those boarding/alighting passengers. The result of this demand and supply relationship analysis shows how the actual public transport performance would affect the passenger demand in reality as well as the results of applying the revised speed-flow and waiting time equation. Although the amendments have led to broadly similar shaped average social cost curves, they have led to changes in the cost minimising choice of technology.

5. Conclusions and Future Work

This paper reassessed the spreadsheet cost model developed in the TEST project and improved the model by adding the probability of having to wait longer than the expected service headways to the passenger wait time calculation and by considering the advantages in speed for different operating environment technologies. Parameter values in the model are able to be modified according to any update of resources to fit the characteristics of the selected public transport technology.

The speed-flow equation takes the advantages of different operating environments into account after applying the piecewise linear function of the average travel time proposed by Small (1992). The speed of different public transport technologies can now represent the situation when they operate in different environments (mixed traffic, semi-exclusive, exclusive or grade-separated). According to the piecewise linear function, operating speed will start to decrease when the demand level reaches the facility capacity which is defined by the operating environment factor and the safety headways. For the technologies with dedicated facilities, this factor would be higher and thus their operating speeds are higher at

the same level of demand compared to the technologies in mixed traffic environment. Passengers have to spend extra time in waiting because the capacity of public transport vehicles is fixed and the probability of being full for the incoming vehicle is getting higher at high demand levels. This has been calculated by using the queueing theory for the probability of having to wait longer than the expected service headways. As an illustration of the queueing theory application, the waiting time calculated by the spreadsheet model was 50.91s in peak period for Singler-decker bus passenger at the demand level of 60,000 per day, and becomes 70.76s if we considered their probability of having to wait longer than the expected service intervals. An investigation of the effects of endogenous passenger demand has been presented to evaluate the revised equations. Exogenous demand is replaced by endogenous demand in order to highlight the advantages of different operating environments. The infrastructure costs are relatively fixed for a public transport technology, the vehicle number required is associated with vehicle capacity and therefore the waiting time and the in-vehicle time would change for different demand levels. According to the comparison result graph, the revised equations demonstrated a lower average user cost for the technologies with exclusive transit facilities.

Due to the size, location and other situations of different public transport corridors in different cities, the demand level would vary. The spreadsheet model can help to assess the choice of choosing a most suitable public transport in different cities. Further work for this model would be focused on the improvement by simulating the operations of these public transport modes in a selected urban area using the transportation analysis software VISSIM. Microscopic simulation would be adopted in order to observe the characteristics of the individual vehicles for different public transport technologies in an urban network in order to consider the performance in mixed traffic flow. The urban area for simulation has been identified to be the main corridor in Nanning, China, where the passenger demand level is about 90,000 ~ 100,000 per day. The current government decision is to build underground to meet this high passenger demand in Nanning. However, other new intermediate public transport technologies would also be a competitive choice in that demand range. A complete traffic network would be built in the future work to analyse the costs for all road users and compared between different public transport technologies.

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