SIMULATING ADVANCED BUS PRIORITY STRATEGIES AT TRAFFIC SIGNALS

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Abstract

Giving priority to buses at traffic signals is a common form of priority in a busy urban area where opportunities for segregated systems are not available and/or where numerous traffic signals exist. A bus priority system may benefit buses by reducing their journey time and improving their punctuality/regularity. This will result in reductions in passenger waiting time at bus stops and in passenger travel times. With the aid of new technologies and strategies, there are now various priority options which can be used to optimise the benefits possible from this form of priority. In their advanced form, these priority options use an Automatic Vehicle Location (AVL) system to locate buses in the system to give priority based on a combination of the lateness of buses and the permitted level of priority at junctions. The main focus of this paper is to explore these different advanced priority options that are available at traffic signals and to estimate the resulting benefits. Furthermore, the paper also explores the possibility of detecting buses upstream of bus stops to give priority at traffic signals. The work in this paper is based on the combination of PhD research and research being undertaken at the University of Southampton for Transport for London (TfL).

Keywords: Bus priority; Automatic vehicle location systems; Traffic signal control
Topic Area: C3 Traffic Control

1. Introduction

Providing priority to buses is important in protecting bus services from the effects of traffic congestion and in improving route frequencies, speeds and reliability. In the UK, the report ‘Keeping buses moving’ (DETR, 1997) details a number of bus priority measures that can be considered to assist buses. Among these measures, bus priority at traffic signals is the most relevant where opportunities for segregated systems are not available and/or where numerous traffic signals exist. At signalised junctions, priority can be given by altering the signal timing in favour of an approaching bus. For example, this can be achieved by either extending the green period for an approaching bus or recalling the green stage, if the signals are currently red for the bus.

In more advanced forms of priority, an approaching bus is continuously monitored and the priority is given according to its requirement. The monitoring of locations of buses is carried out continuously using an Automatic Vehicle Location (AVL) system which may be based on a satellite global positioning system (GPS). The locational information is used to ascertain the priority requirement of the bus. Priority is determined according to the site-specific criteria, which are commonly based on the lateness of the bus. Depending on the requirement, different levels of priority based on the spare capacity at the junction, defined in terms of degree of saturation (DoS), may be given. The lateness requirements and priority levels may be varied to formulate different bus priority strategies.

The main aim of this paper is to explore the performance of various strategies under different field conditions and operations. The paper includes a brief description of the simulation model used for this exploration, followed by details of the results, from which conclusions and discussion issues are drawn.

2. Methodology

The exploration of the performance of different priority strategies under various conditions has been carried out using a simulation model SIMBOL (Shrestha, 2002), developed by the main author of this paper. This gave a control on the functionality and logic in the model which was not readily available in commercial microscopic simulation models. SIMBOL (Simulation Model for Bus priority at traffic signals) is a microscopic simulation model of bus priority operations at traffic signals. It enables a range of priority strategies to be modelled at traffic signals taking account of the characteristics of buses, bus stop operations, traffic signal operations and the AVL system used to locate buses. It also models general traffic at signals to simulate the impact of bus priority on non-priority traffic. The main modelling features of SIMBOL are summarised in Table 1.

Table 1: Modelling features of SIMBOL

Component	Main characteristics	Methods
Bus system	Bus operation Overlapping services	Timetable, headway Multiple origin-destination
Bus	Generation Movement	Timetable, Distribution Average link journey time
Bus stop	Passenger generation Alighting passenger Waiting time Dwell time calculation Holding early buses	Regular arrival rate % of passenger inside Average, individual basis Alighting and boarding passenger nos. Optional
Traffic signal	Cycle time Bus delays General traffic delays	Fixed time Individual basis By generation and discharge of cars
Bus priority	Priority methods Priority strategies	Green extension and recall Selective detection, Differential and Mixed priority
AVL system	GPS based system Detection	Error sampled from Normal random distribution Virtual detectors, detectors

The main capability of SIMBOL is that it can model a long linear route in a simple way but with specific details of public transport operations and performance. In the model, buses are generated and terminated at multiple origins and destinations within a route according to the services. While on the route, a bus may stop at bus stops and traffic signals depending on their status. At bus stops, the number of passengers boarding and alighting is estimated to calculate bus dwell time. At traffic signals, signal stages are calculated based on the fixed time plan given at the beginning of the simulation. General traffic is generated at a fixed rate on the traffic signal approaches and is used to calculate traffic delay. In non-priority situations, it is assumed that all vehicles generated in a cycle are discharged during the green period (unsaturated junctions). Buses are affected by any traffic queues, according to their arrival time at the junction. They are detected at the traffic signal approaches and their arrival time at the stopline is estimated. Then the signal may be altered in favour of the approaching bus depending on the priority strategy. Priority is given either by extending the present green period or by recalling the next green period earlier with different levels of priority also available. The model gives concise output in terms of journey time, junction delays and passenger waiting time. These are used for the comparison of the performances of the different strategies.

3. The Application

The present application of SIMBOL is based on a corridor bus route in the Portswood district of Southampton, UK. The route has 15 bus stops and 11 traffic signals over a 4.3km length. The route is served by two main bus services with each having a service frequency of 6 buses per hour. These bus services overlap on part of the corridor. Figure 1 shows a visual representation of the route in SIMBOL during a simulation run.

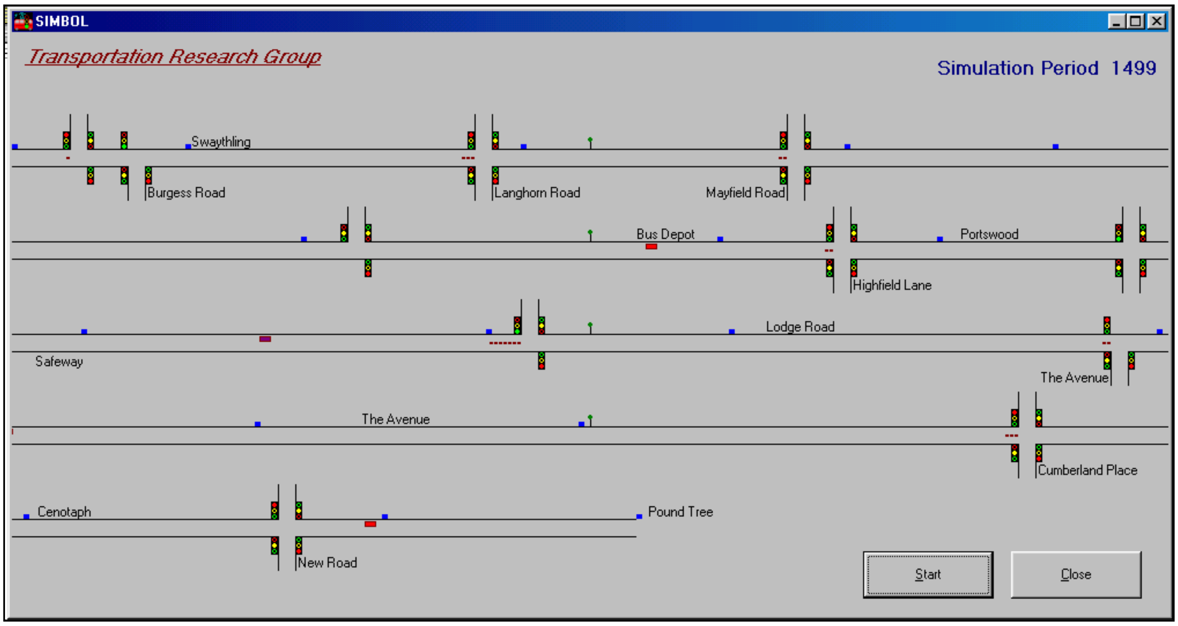

Figure 1: Visual representation of Portswood corridor route in SIMBOL

The model was calibrated using surveyed data to ensure realistic values for passenger boarding times and vehicle delays at junctions. Model validation was carried out by comparing bus journey times in the field situation to those forecast from the model. The modelled journey time for each bus was plotted against field journey times. A close compatibility between journey time in the field and model prediction for the data was found. A paired t-test showed that the difference between these sets of values was not significant at the 5% level. The validated model was then used to simulate 7 different priority strategies as follows:

Here, ‘Normal’ and ‘High’ relate to the target degree of saturation (DoS) for non-priority traffic while giving priority to buses. The higher this target, the higher is the amount of priority available to buses (and the higher would be the disbenefits to non-priority traffic). The ‘All buses’ strategy is the simplest and most common form of bus priority, giving priority to all buses, within the constraints of the traffic signal system. This strategy is commonly referred to by the name “selective vehicle detection” (SVD). The ‘Late buses’ strategies give priority to late buses only and are sometimes referred to by the name “differential priority”. The ‘Late buses (0&60)’ strategy differentiates between buses that more than one minute late, less than one minute late, and buses that are on time or early. It is recognised that in practice, this level of preciseness about the lateness of the bus might not be feasible, but the strategy was considered to be worthwhile examining from a theoretical viewpoint.

Table 2: Different priority strategies under consideration

Strategy name (used for reference)	Part of the route using given priority	Priority level given to the buses		
		Buses more than one minute late	Late buses	On-time or early buses
No priority	Whole route	None	None	None
All buses (Normal)	Whole route	Normal	Normal	Normal
Late buses (Normal)	Whole route	Normal	Normal	None
Late buses (High)	Whole route	High	High	None
Late buses (0&60)	Whole route	High	Normal	None
Mixed (Late&All)	Early part	Normal	Normal	None
	Later part	Normal	Normal	Normal
Mixed (Differ&All)	Early part	High	Normal	None
	Later part	Normal	Normal	Normal

The 'Mixed' priority strategies were developed in the course of this research to give priority to late buses during the earlier part of the route and priority to all buses in the later part of the route. These priority strategies were aimed at:

- improving bus regularity on the earlier part of the route to reduce passengers waiting times at bus stops; the early part of the route had larger numbers of boarding passengers than the later part of the route
- reducing bus journey time on the later part of the route, where there were more travelling passengers and fewer boarding passengers.

The lateness of the bus was calculated with reference to a timetable. It was found that the actual bus timetable used in practice was quite inaccurate in places and also lacked sufficient detail for this application. A more accurate and more detailed bus timetable was derived, based on typical bus running times along the route.

In the following section, the selected priority strategies are first compared for current operational conditions. Further study was then carried out to simulate these strategies under different operational conditions such holding early buses at bus stops, using headway-based bus operations and considering GPS bus detection errors. Performance has been based on the economic evaluation of parameters such as journey time, passenger waiting time and car delays at traffic signals. The economic values for these parameters were calculated as the resource values of time per person from the UK's Highways Economics Note No.2 (HEN2, 1997).

4. Simulation Results

4.1 The base case scenario

In the base case scenario the following assumptions were made:

- buses were allowed to leave early from bus stops, as observed to occur in practice
- passenger arrivals at bus stops were modelled as being random – this was verified in the test site.

The bus delay saving per bus per junction and the passenger waiting time savings per passenger from different strategies are shown in Figure 2.

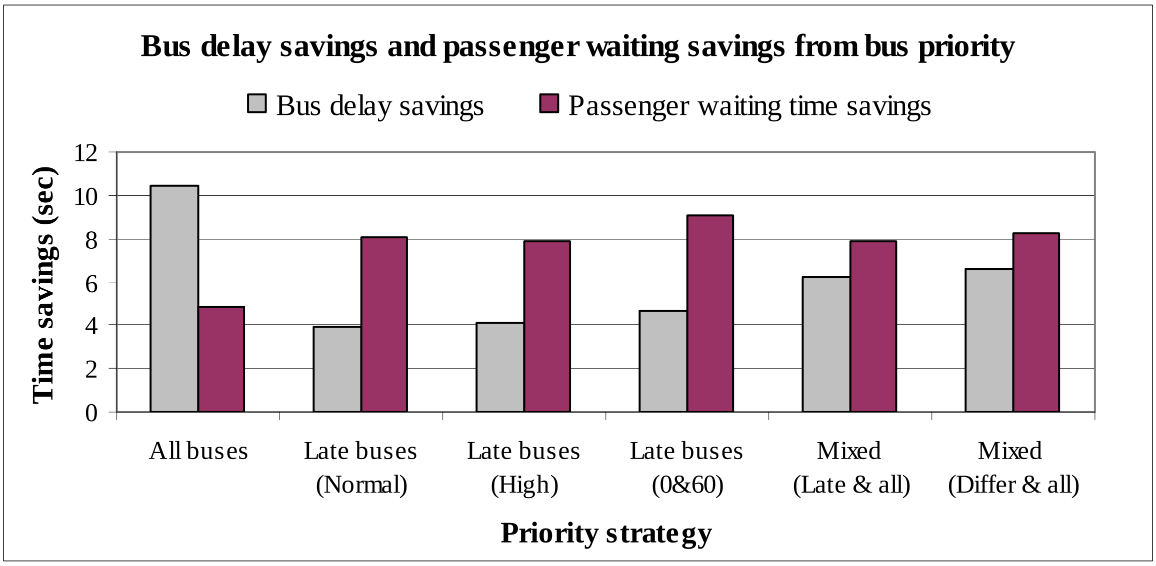

Figure 2: Bus delay savings and waiting time savings from different priority strategies

The bus delay savings from different priority strategies were found to be in the range of 4-10 seconds per bus per junction. The maximum bus delay saving was found for the ‘All buses’ strategy, giving priority to all buses without any restriction. All differential priority strategies and mixed priority strategies gave much higher passenger waiting time savings than this strategy. Among them, ‘Late buses (0&60)’strategy gave the maximum passenger waiting time savings. The result highlighted the fact that different strategies give priority benefits in different ways. To compare these strategies overall, an economic assessment of the priority benefits was carried out. This was based on passenger waiting time, journey time and delays to general traffic. Table 3 shows the economic benefits for each parameter per hour after deducting from the no priority case.

Table 3: Economic benefits from different priority strategies

Priority strategy	Priority benefit per hour for whole route (in €)			
	Passenger waiting time	Journey time	Car delay	Total
All buses (Normal)	2.29	19.87	3.03	25.19
Late buses (Normal)	3.84	8.38	0.58	12.80
Late buses (High)	3.74	9.40	-0.39	12.75
Late buses (0&60)	4.29	10.63	-1.75	13.17
Mixed (Late & All)	3.74	12.11	2.15	17.99
Mixed (Differ & All)	3.93	15.04	2.54	21.50

The following observations are drawn from Table 3:

- all strategies provide an overall benefit compared to the no priority case
- the greatest overall benefit was provided by the ‘All buses’ strategy, due to the high journey time benefits; this result was gained despite the strategy having the lowest passenger waiting time saving and the highest disbenefit to non-priority traffic
- the greatest passenger waiting time benefit was gained by the ‘Late buses (0 &60)’ strategy; this strategy would be recommended if bus regularity was considered to be more important than bus journey time
- the ‘Mixed (Differ and all)’ strategy gave a good overall performance in terms of both journey time and waiting time benefits.

Journey time savings were found to be the main contributor to overall economic benefits. The economic benefits from waiting time savings were smaller than the journey time savings here because of the random arrival of passengers assumed in the model, which meant that waiting times were not greatly affected by buses that departed early from bus stops. It is interesting to note that some waiting time savings were accrued by the 'All buses' strategy. This is due to the fact that, without bus priority, bus regularity tends to deteriorate along a route due to some buses being stopped at a red signal. The results also showed that the strategies using 'Normal DoS' give benefits to cars while giving priority to the buses. The reason for this was that the availability of spare green time at the under-saturated junctions on the route made it possible to give priority to buses without having a severe effect on the side road traffic. Also, cars on the main road would benefit from the increased proportion of green time occurring with the priority strategies. Similar benefits to cars at junctions with lower saturation levels in London were found in an earlier study (Hounsell *et al*, 1996).

4.2 Effect of holding early buses

Buses may arrive early at bus stops due to changes in passenger demand, traffic conditions, bus driver behaviour or poor timetabling. The field data showed that many bus drivers did not wait at bus stops other than for boarding/alighting and sometimes departed early. For example, at a major bus stop on the route (Portswood), only half of the early buses stopped to match their timetable. If passengers arrive near the scheduled time, an early departure of a bus can cause some of them to miss the bus and have to wait for the next bus to arrive. This increases passenger waiting time and deteriorates passenger confidence in the bus timetable. One simple method of avoiding early running buses is by holding them at a bus stop until their scheduled departure time. Though holding early buses improves the punctuality, it increases the journey time of the passengers already inside the bus. The effects of this scenario are explored in this section.

The simulation was carried out for all 7 different priority strategies. Any buses that arrived early at the Portswood bus stop were forced to wait until their timetabled departure time. The holding improved the punctuality of the buses which resulted in the improvement of passenger waiting time. However, this also increased the journey time due to the stoppage. The change in waiting time and journey time costs as a result of holding, for different priority strategies is shown in Figure 3.

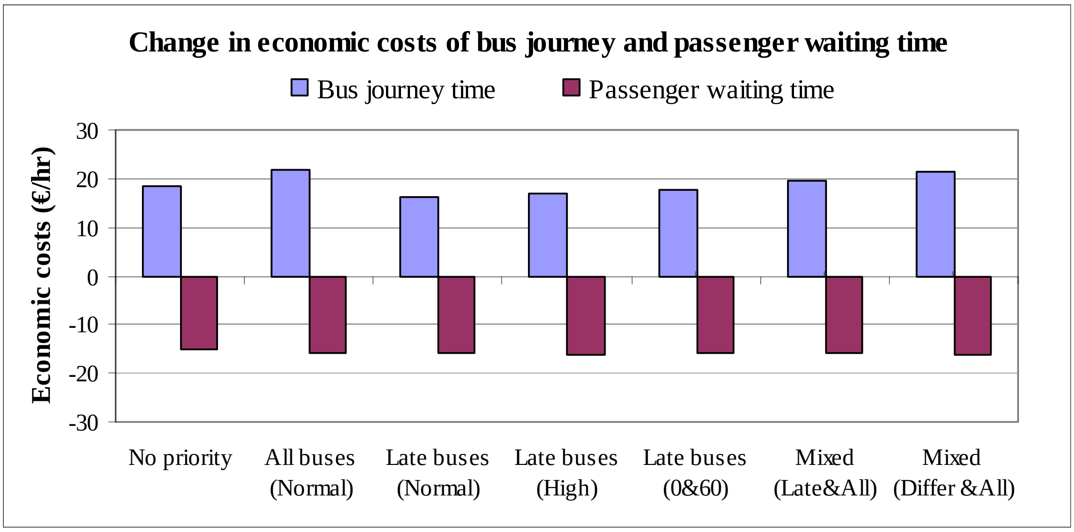

Figure 3: Change in economic costs of main parameters while holding buses

Figure 3 shows a decrease in passenger waiting time costs and an increase in journey time costs across all of the priority strategies considered. The extent of improvement in waiting time (decrease in cost) is fairly equal across all the strategies. However, the extent of increase in journey time cost varied between the strategies. The 'All buses' strategy suffered the most and the 'Late buses (Normal)' strategy suffered the least. This implies that better passenger waiting time savings and punctuality can be achieved by holding early buses, in the case of the 'Late buses (Normal)' strategy, without increasing total cost. It should be noted that passenger arrivals at bus stops were modelled as being random here, as observed in the field. Improved results would be expected for this strategy for a scenario where there were more passengers timing their arrivals at the bus stop to match the timetable.

In conclusion, holding early buses can be an effective measure in improving punctuality and reducing passenger waiting time. This measure is particularly effective when combined with the strategy of giving priority to late buses. However, the results here also highlighted the negative impact on journey time. This suggests that even though holding is useful, in terms of punctuality and waiting time considerations, long delays at bus stops to match the timetable should be avoided as far as possible, especially when the bus occupancy is high. A better way to achieve good punctuality is to build a more accurate and flexible timetable that is adaptive to journey time changes observed in the field. Changes in bus journey time can be due to various reasons such as time of day, seasonal variations, holiday periods. A good timetable should be one of the key requirements for implementing an effective advanced bus priority system at traffic signals.

4.3 Effect of changes in operations

This section considers bus operations that are based on maintaining regular headways between buses rather than trying to run buses to a timetable. This form of bus operation is commonly used for high frequency bus services, where it is more important, from the bus passengers' point of view, that buses arrive at regular intervals, so that they never have long to wait for the next bus. For high frequency bus operations passengers tend to arrive at bus stops at random. Random passenger arrivals were observed for the bus services modelled here. Although the bus services being modelled actually operated to a timetable, the bus service frequency was relatively high at six buses per hour or more. In practice, random passenger arrivals can also occur due to other factors, such as passengers having an insufficient knowledge of the timetable or service punctuality being poor so that the timetable becomes less relevant.

For the headway-based bus operations investigated here, a bus was defined to be late if its headway to the bus in front was greater than the average headway. The comparison of simulation results for both timetabled and headway operation is shown in Table 4.

Table 4: Priority benefits for timetabled and headway-based bus operations

Priority strategy	Total priority benefits per hour (in €)		
	Timetable	Headway	Change
Late buses (Normal)	12.80	18.08	+41%
Late buses (High)	12.75	14.30	+12%
Late buses (0&60)	13.17	14.21	+8%
Mixed (Late & All)	17.99	23.53	+31%
Mixed (Differ & All)	21.50	21.66	+1%

Table 4 shows an increase in priority benefits for the headway-based operation. Here, the biggest changes in priority benefit are for the 'Late buses (Normal)' and 'Mixed (Late

& All)' strategies. These strategies were analysed further to explore the reasons behind the large increases in priority benefits, as illustrated in Figure 4.

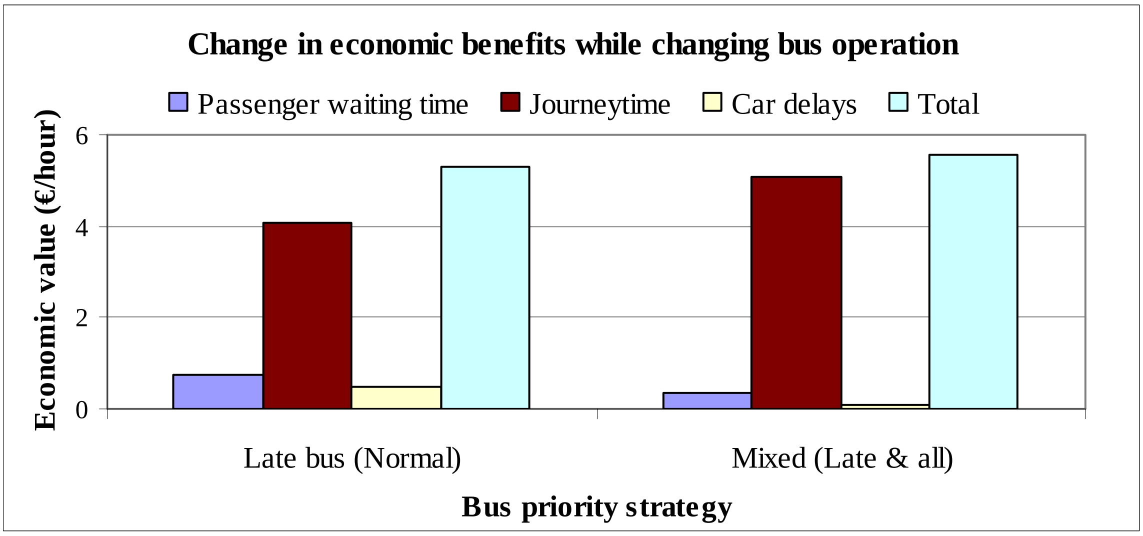

Figure 4: Change in economic benefits while changing bus operation

Figure 4 shows that the increases in priority benefits are gained mainly through improved journey times and partly by passenger waiting times. Since the two strategies considered here give priority to buses with the biggest headways, regularity and, consequently passenger waiting time, will tend to be improved. The buses with the biggest headways will also tend to be carrying the most passengers, as the larger gaps imply more passengers waiting to get on the bus when it eventually arrives at the bus stop. Targeting these buses for priority is therefore good, in terms of reducing overall passenger journey time.

The results here have shown that headway-based priority strategies tend to be better than timetable-based priority when passengers arrive randomly at bus stops. This is intuitively sensible, as if passengers arrive at random then the timetable becomes irrelevant and regular headways become more important to achieve. Headway-based operation also saves regular updating of the timetable to address variations in field conditions and avoids any issues concerning early buses and related passenger confidence in the system. However, it should be noted that bus priority implementation is easier to achieve using a timetable. With the use of an on-board timetable, a bus can assess its own lateness without referring to any other system/bus. This self-assessment is not possible for headway-based operations where (at least) the headway to the bus in front must be known in each case.

4.4 Effect of GPS error

The use of GPS as an AVL system for bus priority purposes has been growing in recent years. However, the random error associated location derived from GPS systems creates an uncertainty in the predicted position of a bus. The uncertainty in the position of a bus would have an impact on the effectiveness of a bus priority system. For example, small positional errors could lead either to the signals being held on green for too long or, worse, for too short a period of time, so that buses might miss the priority extensions awarded. Additionally, when a priority activation point is located downstream of a bus stop, GPS error could result in priority being activated when the bus is actually stopped at the bus stop. This would tend to lead to wasted priority actions. To avoid this possibility of detecting buses while being at a bus stop, it is necessary to place the virtual detector(s) at a 'safe' distance(s) downstream of the bus stop. Typically this safe distance will depend on the maximum locational error that is anticipated for the GPS system used. This requirement for a safety margin reduces the distance between the virtual detector and the traffic signals and so reduces the opportunities for providing green extensions for buses.

In analysis described here, the simulated GPS error was sampled from a normal random distribution, with a mean of 0 metres, standard deviation 3.3m and a maximum assumed error of ±10m (Rupprecht, 2001). The virtual detectors were placed 10m downstream of the existing bus detectors, which were downstream of bus stops. The results of simulation runs modelling 6 different priority strategies are given in Table 5.

Table 5: Change in total priority benefits after introduction of GPS error

Priority strategy	Total priority benefits per hour (in €)		
	No GPS error	GPS error	Change
All buses (Normal)	25.19	24.35	-3%
Late buses (Normal)	12.80	12.19	-5%
Late buses (High)	12.75	11.90	-6%
Late buses (0&60)	13.17	12.43	-6%
Mixed (Late & All)	17.99	17.76	-1%
Mixed (Differ & All)	21.50	20.46	-5%

The results show that the error in GPS reduces the bus priority benefit by around 5% on average across the strategies when compared with a bus priority system having accurate bus detection. Despite this disadvantage, GPS is becoming more widely used for bus priority purposes for various reasons, such as:

- avoiding the need for installation and maintenance of costly infrastructures
- bus detector positions can be more readily moved, as the changes are made within software rather than on street
- bus detection is not compromised by roadworks
- there is the potential for multiple detector configurations to be used to provide confirmation of the priority needs for buses at different points on their routes, e.g. upstream of a bus stop, on leaving the bus stop and on passing through the traffic signals, to cancel the priority action
- GPS can also be used for other applications.

4.5 Effect of upstream detection

The results in Sections 4.1 to 4.4 were based on the usual practice in the UK of detecting buses downstream of a bus stop to avoid having to estimate the amount of time spent at the bus stop. This practice tends to result in priority benefits being limited where bus stops are close to the stopline, since the opportunities for providing signal extensions are much reduced and recalls are less effective. In such a situation, it could be beneficial to detect buses upstream of the bus stop (see Figure 6).

With upstream bus detection it is necessary to estimate the bus dwell time at bus stops. This dwell time can be quite variable between buses, depending mainly on the number of boarding passengers. This variability can be reduced in various ways, including:

- allowing passenger boarding and alighting using more than one door; in the UK, articulated buses, with three entry/exit doors, are becoming more widely used
- purchasing of tickets before boarding; in the UK it is still possible on most bus services to pay the bus driver directly, which tends to increase the boarding time; this

practice is being replaced in with pre-paid ticketing arrangements in some cities, including London. Contact-less smart card 'ticketing' could also be effective here.

If the dwell time variability at bus stops can be reduced then more accurate predictions of the stopped time can be made. This section of the paper investigates the circumstances under which there could be benefits in detecting buses upstream of bus stops.

A study was carried out using SIMBOL with using the following modelling parameters and assumptions:

- Bus stop positions - 20m, 40m or 60m from the traffic signal stopline
- Bus detector positions – 30m, 50m, 70m or 100m from the traffic signal stopline
- Average dwell time at bus stop – 14 seconds
- Standard deviation of dwell time at bus stop – 5s, 10s, 15s or 20s
- A single junction with two conflicting approach roads: a main road and a side road, with buses on the main road only. The traffic signal is operated under a two-stage fixed time signal plan
- The modelled bus stop dwell time for each individual bus was sampled from a Normal distribution using the mean and standard deviation values as specified above
- The estimate of the arrival time of an individual bus at the traffic signals included an estimate of the dwell time based on the mean dwell time plus a safety margin to account for the dwell time variability. The optimal safety margin was found to be equal to the dwell time standard deviation value. A longer safety margin value would tend to get more buses through on signal extensions but would be less efficient, particularly for non-priority traffic. Conversely, a shorter safety margin value would be more efficient for general traffic but would tend to result in more buses missing signal extensions.

An example of how bus priority delay savings vary for different detector positions and different bus dwell time standard deviation (SD) values is given in Figure 5, based on the simulation results. In this example the bus stop was placed at 40m from the traffic signal stopline.

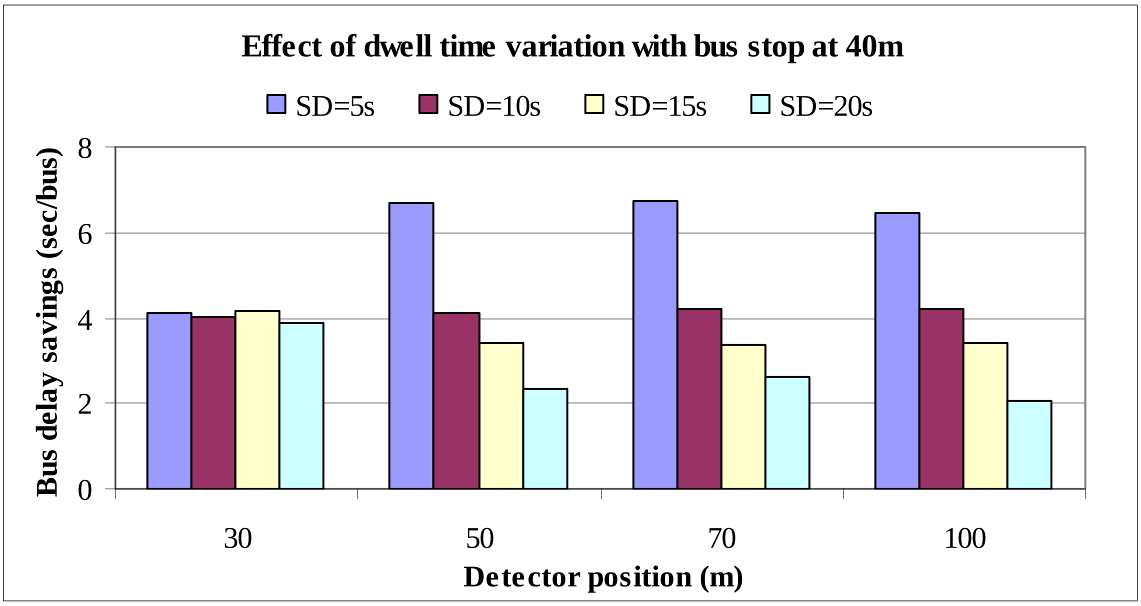

Figure 5: Bus delay savings using detector at various locations

Figure 5 shows that the bus delay savings are influenced by the dwell time variation and the position of the detectors. The increase in dwell time standard deviation considerably reduces the bus priority benefits. This is due to dwell time estimation errors for individual buses, which can result in:

- buses missing the signal green window provided for the bus by the priority system
- wasted signal green time when the signals are held on green and the bus has already passed through them

In addition, the larger dwell time variability requires a longer safety margin parameter to be used in the bus priority system, which leads to inefficiency, particularly for non-priority traffic.

Figure 5 also shows that when the dwell time variability is low and the bus stop is close to the traffic signals (SD=5s, bus stop at 40m here), it is better to detect the bus upstream of the bus stop. The main reason for this is that the opportunities for providing signal extensions increase greatly with upstream detection, as the effective detection distance, in terms of time, is increased substantially. Figure 5 also shows that there is no further benefit to be gained by placing the detector further upstream: the results for the 50m, 70m and 100m detector positions are similar.

Further simulation results showing the bus delay savings obtained for different combinations of dwell time standard deviation values, detector positions and bus stop locations are given in Table 6.

Table 6: Comparison of bus delay savings from upstream and downstream detection

Dwell time standard deviation (seconds)	Bus delay saving (seconds/bus)					
	Bus stop at 20m		Bus stop at 40m		Bus stop at 60m	
	Downstream detector	Upstream detector	Downstream detector	Upstream detector	Downstream detector	Upstream detector
5	3.4	6.6	4.1	6.7	4.9	6.7
10	3.0	4.3	4.0	4.1	4.6	4.2
15	3.1	3.5	4.2	3.4	4.7	3.4
20	3.1	2.6	3.9	2.3	4.6	2.6

Table 6 shows that upstream detection of buses is beneficial when the dwell time standard deviation is low (5 seconds) for all bus stop locations. When the dwell time standard deviation increases to 20 seconds, upstream detection becomes beneficial only in the case of a bus stop at 20m. This shows that upstream detection is beneficial when the bus stop is close to the traffic signals and/or the dwell time standard deviation is low. This provides an opportunity to implement bus priority at traffic signals where the bus stop is close to the stopline. The benefits may be further improved by using additional detectors downstream of the bus stop to enhance the awarded priority.

5. Discussion

The simulation results showed how the different priority strategies considered varied in their performance. The ‘All buses’ strategy gave the largest journey time benefits, whereas the differential priority strategies gave better passenger waiting time savings. When compared in terms of total economic benefits, the ‘All buses’ strategy gave the best overall result.

Bus journey time was found to be the major contributor to overall performance, with around 50%-70% share of the total performance cost, whereas the waiting time’s contribution was in the range of 10%-25% only. This was the main reason for the ‘All buses’ strategy achieving the best overall performance. However, it will often be a matter of policy as to the weight given to bus service speed compared to reliability in terms of quality of service.

Based on the simulation results, it is clear that the field characteristics greatly influence the outcome of a priority strategy, in terms of journey time and waiting time savings. The main characteristics that have an influence are: the passenger arrival pattern, junction characteristics, timetabling and bus punctuality. The effects of these are discussed below.

5.1 Passenger arrival pattern

Bus passengers tend to arrive at bus stops either at random or to time their arrival according to a particular timetabled bus. Where random passenger arrivals are more prevalent, any bus timetable becomes less relevant, as do any priority strategies that are based on bus lateness according to the timetable. The more effective bus priority strategy here is to try to improve bus regularity. This is best achieved by trying to identify buses with big headways and giving them priority to try to reduce the size of the gaps between buses. Giving priority to all buses can also improve regularity to some extent, as traffic signals can cause irregularity due to some buses being caught by a red signal.

Where the tendency is for passengers to arrive at bus stops according to the timetable then it becomes more important that buses arrive at bus stops on time (i.e. good punctuality). Priority strategies that target buses that are running late are then most effective and it is also good practice to hold any buses that are early.

5.2 Junction characteristics

Under the signal priority system operational with the SCOOT UTC system in the UK, the saturation level of a junction determines the ability of the signal to give priority and the impact of priority on non-priority traffic. Under-saturated junctions have more spare green time available for bus priority, resulting in higher bus delay savings and lower disbenefit to non-priority traffic. Priority strategies that give priority to a larger number of buses can be implemented at under-saturated junctions and give the greatest overall benefits. Conversely, if the junction is close to saturation then it becomes more important to constrain bus priority to avoid unacceptable delays to non-priority traffic. In this situation, priority strategies that select lower numbers of buses for priority are required.

5.3 Bus punctuality and passenger confidence

For timetabled bus services, bus punctuality (adherence to the timetable) is a key performance criterion. Good punctuality is helpful in developing passenger confidence in the timetable and reduces average passenger waiting times. However, the ‘value’ of improved passenger confidence developed from this is generally not considered in the economic evaluation of the priority benefit. If this is taken into account, it may make advanced priority strategies more attractive, particularly those strategies that target late buses.

5.4 Bus timetable

For timetabled bus services, the design of the timetable is very important. An unrealistic timetable could result in buses consistently running either early or late at points on the route. Proper regulation of the timetable is necessary to improve passenger confidence in it and to reduce passenger waiting time. An accurate timetable is also a requirement for those priority strategies that seek to improve bus punctuality.

5.5 Alternative detection locations

The simulation results showed that, in some cases, there are benefits from implementing bus priority at traffic signals by detecting buses upstream of a bus stop. Bus detection upstream detection of a bus stop is particularly important where the bus stop is close to the traffic signals (<50m), where the bus priority benefits from downstream detection are likely to be low. Further study has shown that the benefits can be improved by using additional detectors: a secondary detector downstream of the bus stop to update the priority requirement once the bus has left the stop, and an exit detector close to the stopline to terminate priority when it has achieved its purpose. A typical layout of these various detectors is shown in Figure 6.

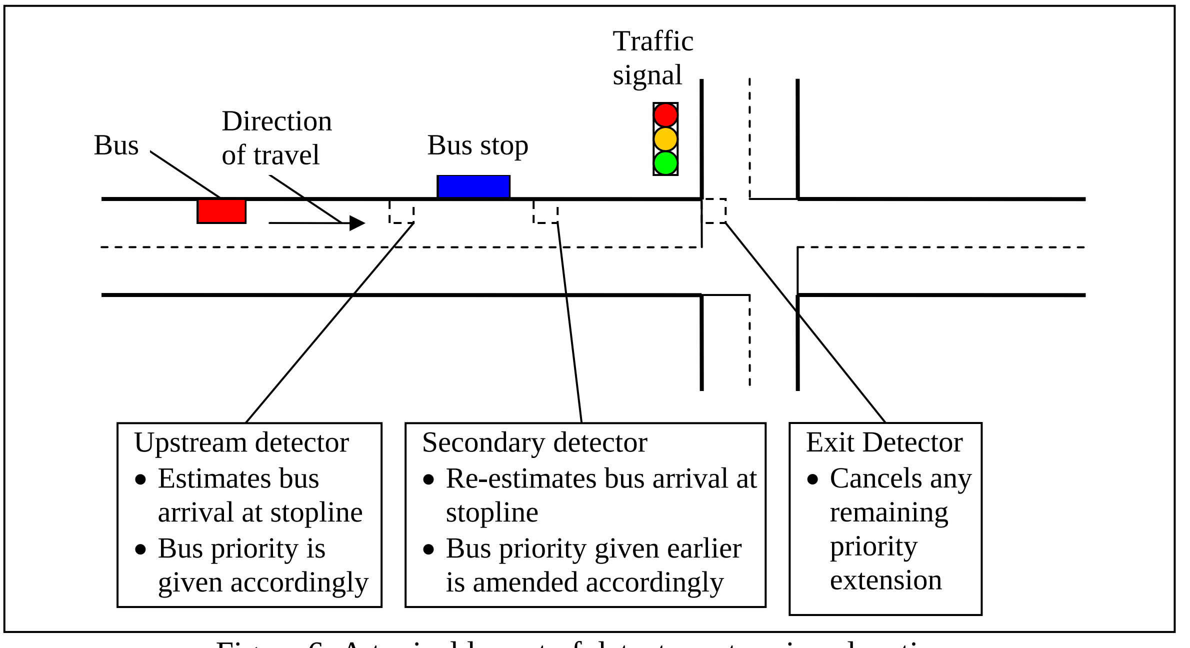

Figure 6: A typical layout of detectors at various locations

The layout of detectors in Figure 6 would be relatively complex and costly with fixed infrastructure systems, but it is much easier in principle using a GPS system to locate buses in the network. A GPS system allows many ‘virtual’ detectors to be placed at the required locations without the need for physical detectors on site. Buses can be detected once they reach these virtual detector locations and priority can be activated. With the growing use of GPS in most parts of the world, a system using detectors at various locations becomes a realistic option and is demonstrated here to increase the benefits from bus priority in some situations.

6. Conclusions

This study has demonstrated the relative performance of different priority strategies in terms of effects on bus journey time, passenger waiting times at bus stops and impacts on general traffic, through the use of a detailed simulation model. The strategy of giving priority to all buses resulted in the greatest journey time benefits, however, this strategy was the least preferred in terms of bus punctuality and passenger waiting times. Giving priority to late buses improved passenger waiting times but bus journey time benefits were reduced. Good overall performance was achieved by hybrid priority strategies that aimed to maintain good bus punctuality towards the start of the route but then reverted to maximising bus speed later in the route.

Holding early buses at bus stops is a simple measure that improves the punctuality of buses and waiting time of passengers. However, it also reduces priority benefits by increasing the journey time by stopping buses at bus stops. The holding practice should be minimised with the use of an accurate and flexible bus timetable reflecting the variability in the bus journey time.

Shifting from a high frequency timetabled bus service to a headway-based service is beneficial where passengers tend to arrive at bus stops randomly. Headway-based priority is aimed at making buses more evenly spaced, which will tend to reduce passenger waiting times at bus stops. A headway-based priority strategy is also good in terms of overall passenger journey time, as priority is often given to the buses that carry the most passengers.

The effects of using GPS for bus detection were studied. The positioning error associated with GPS, assumed here to be ±10m, reduced the overall bus priority benefits by around 5% on average, across all the priority strategies. Despite this reduction in benefit, the use of GPS for bus priority applications is increasing due to its flexibility and versatility.

The paper has also shown that the outcome of a priority strategy is heavily influenced by the field conditions. It has highlighted that the field conditions should be carefully considered when selecting a bus priority strategy, as illustrated in Table 7.

Table 7: Field conditions favourable to different priority strategies (timetabled services)

SVD (All buses)	Advanced (Differential/Mixed)
Random passenger arrival	Passenger arrival at specified time
Junctions at lower DoS	Junctions at higher DoS
Punctuality issue not very important	Punctuality issue is very important
Poor timetable design and regulation	Proper timetable and strictly regulated

The paper also described recent work into bus priority with detection of buses upstream of bus stops. Upstream detection was found to be beneficial when the bus stop is very close to the traffic signals and/or the dwell time variability at the bus stop is low. Further enhancements to the priority system can include use of a secondary detector downstream of the bus stop and an exit detector close to the traffic signals to cancel priority actions once the bus has passed through the traffic signals.

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