Centre for Transport Studies
University College London

Working Paper

Study of Passenger-Bus-Traffic Interactions on Bus Stop Operations

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ABSTRACT

Buses are the unsung heroes of public transport in modern cities around the world in high, medium and low income countries. However, the bus system is usually cobbled by poor design which has resulted from poor understanding of how a busThis paper examines the impacts of the interactions between buses, passengers and traffic on bus operations, especially in relation to delays and capacity at bus stops. First, the principles of bus stop operations are presented. Issues like the stages of bus stop operations, the classification of times spent at bus stops, causes of delays, and the interaction between bus flow and stop delays are analysed. This leads to the necessity of microscopic simulation to study stops operations. Then, an illustration of the sort of understanding that can be achieved with a simulation modem is shown. Simulation experiments regarding arrival patterns of buses and passengers, boarding times, difficulties for buses to leave the stop, and vehicle capacity are presented. Results indicate that it is important not to underestimate the real situation found at bus stops, as designing for ideal conditions will be insufficient if the reality is different.

1.   INTRODUCTION

Except in a few cases, buses operate in the general traffic system. Sometimes they have the benefit of bus lanes and other priorities to offset the effects of traffic congestion, but unless they are completely segregated from general traffic, they are subject to congestion. Bus stops constitute one potential interruption to smooth traffic flow. As this could easily affect buses, we need to see how we should examine bus stops for their impact on bus operations in the first instance.

In order to make buses accessible to the people at bus stops, buses need to be able to reach the kerb and to be able to enter and leave the bus stop without the interruption from traffic, parked vehicles or other buses. The bus stop provides a service to the buses that takes a certain amount of time. As the number of buses attempting to use the stop within a given time period increases, a queue will form. We therefore have the problem of bus stop capacity, i.e. the number of buses able to enter the bus stop area in a given time period. This, as with most queuing problems, depends on the service frequency. However, unlike many queuing problems, the service time at the bus stop is also a function of the frequency, because this

affects the amount of passengers at the platform and so the time spent by the bus at a bus stop. Besides, the service time also depends on the arrival of passengers at the bus stop. This generates a concurrent queuing problem in which the service time is a function of both the arrival pattern of buses and passengers. All the models that deal with buses and bus stop operations either ignore this issue or assume either constant arrivals or inter-arrivals taken from a traditional distribution (e.g. exponential). For a discussion on these models, see Tyler[1].

In the following section, we summarise some of the concepts on bus stop operations developed by Tyler[1]. Next, the result of a set of simulation experiments on bus stop operations worked out by Fernández[2] is shown. Then, a summary of the consequences for bus operations derived from simulation experiments is presented. Finally, some concluding comments are stated.

2.   DELAYS AT BUS STOPS

2.1.   Stages of Bus Stop Operations

The easiest way to consider a bus stop when thinking about its functioning is as a one-armed signal-controlled junction. In these circumstances, we imagine a bus stop to contain a fixed location with one berth in which a bus can stop. If a bus is occupying the berth, no other bus can enter. As in a junction, its capacity is determined by the length of time a bus spends occupying the berth and the number of buses that could pass through the berth within a defined time period. The capacity of a bus stop is expressed in terms of the number of buses that can enter the stop area within a specified time period (usually an hour). As with any capacity problem, we compare the flow of buses actually using the bus stop with its capacity to obtain the degree of saturation. Further discussions on bus stop capacity models can be found elsewhere[2,3,4].

To introduce the principle, we will discuss the operational issue with a one-berth bus stop. Figure 1 illustrate the stages of bus stop operations:

(1)   An empty berth awaits the arrival of a bus.
(2)   A bus approaches to the berth.
(3)   The bus decelerates from its running speed and enters the berth.
(4)   The bus comes to a stop in the berth.
(5)   The bus opens its doors to allow passengers to board and alight.
(6)   When all the passengers have board and alight, the bus closes its doors and is ready to depart.
(7)   The bus checks if the exit path is clear, otherwise the bus remains at the berth waiting for an available gap in the traffic stream.
(8)   During the above stages, other buses can arrive and have to queue behind the stopped bus.
(9)   Then, the first bus accelerates away from the berth, permitting the subsequent bus to enter the berth
(10)   The second bus then stops in the berth in the same way as the first bus.

Stages (1) and (2)

Stage (3)

Stages (4) to (8)

Stage (7)

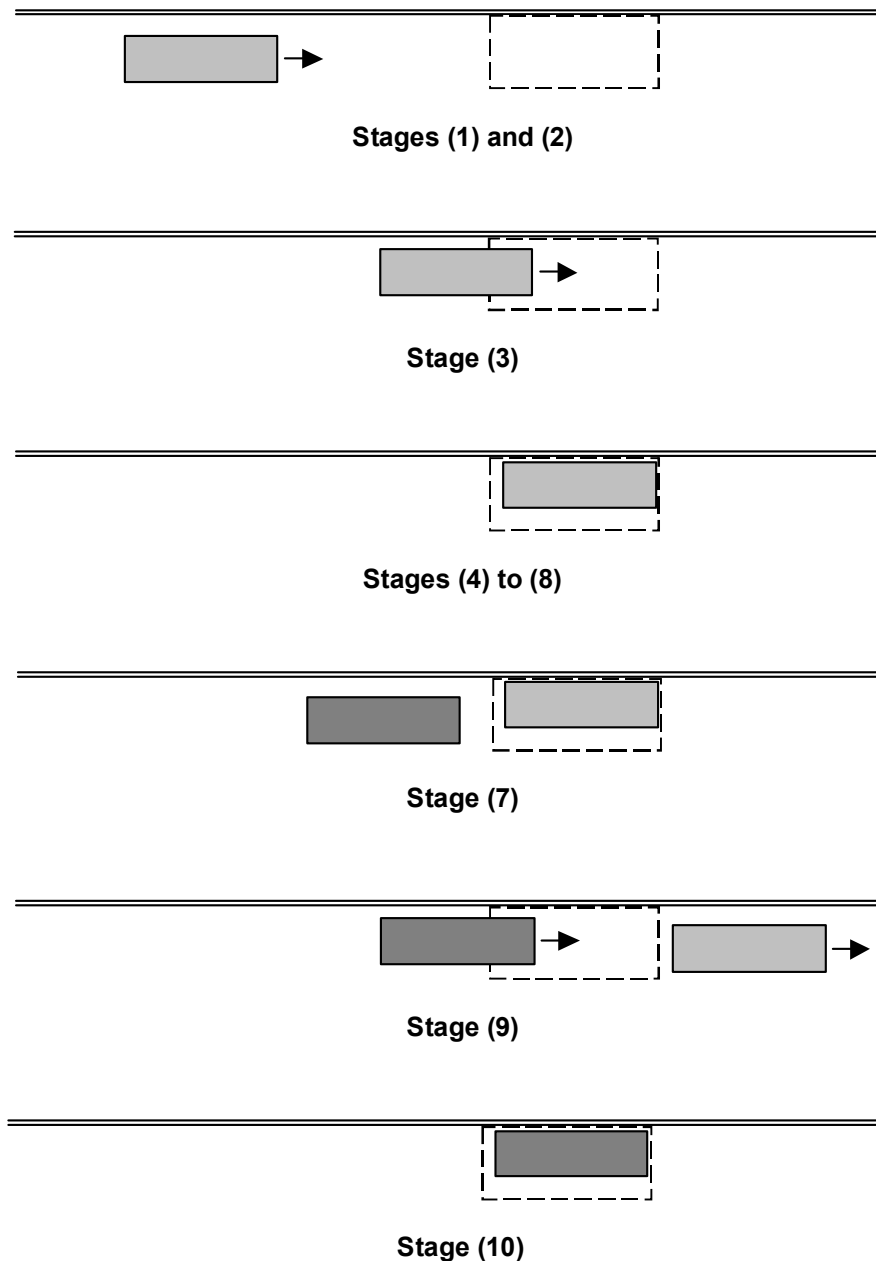**Stage (9)**

Stage (10)

Figure 1: Stages of bus stop operation

We can define six time periods which we can use to analyse how the operation – and hence the capacity – might be affected by changes to bus stops:

(a) *Queuing time* (t_q). The time spent in the queue prior to entering the bus stop.
(b) *Passenger service time* (PST). The time for passengers to board and alight, plus any time to permit the boarding and alighting to occur or *dead time* (time to open and close doors, lower the bus, etc).
(c) *Internal delay* (t_i). The time waiting to leave the bus stop, when the bus is ready to leave but is obstructed by other buses in the stop area.
(d) *External delay* (t_e). The time waiting to leave the bus stop, when the bus is ready to leave but is obstructed by other traffic outside the stop area.
(e) *Dwell or occupancy time* (t_o). The total time spent by a bus at a bus stop, which is the sum of time periods (c) to (e).

(f)   *Clearance time* (t_c). The minimum time between the departure of one bus and the arrival of a subsequent bus in the berth.

The clearance time (t_c) has to be added to the dwell time (t_o) to take into account the time taken to enter and leave the berth, which includes the time periods spent decelerating, accelerating, and travelling down the bus stop. In some cases, the internal (t_i) and external (t_e) delays are concurrent, in which case the greater of the two is used in the estimation of the dwell time and capacity. As in a junction, the queuing time (t_q) is a useful indicator of the adequacy of the bus stop capacity.

Apart from the direct effects on the capacity, it should be noted that the sum of all these time periods shows the delay imposed on a bus by a bus stop. This in turn affects the commercial speed of the bus service – the distance divided by the total travel time between any two points of the route – because it adds to the time taken to operate from the start to the end of a bus route.

2.2.   Time Allocation to Space

We need to design a bus stop so that it can accommodate the number of buses wishing to use it in such a way that they can perform properly. This means to stop as close and parallel to the platform as possible. In this case, the service being provided by the bus stop is time. Time is related to space in the sense that these operations need to take place in space and thus the time is allocated to the utilisation of a defined amount of space. In most urban areas, such space is a scarce resource. Therefore we need to know how much space is required in order to obtain an accessible bus stop under local operating conditions such as bus flow and passenger demand. Only once this has been achieved can we consider the detailed position of the bus stop and its accessibility. This is because a bus stop with insufficient capacity will be incapable of delivering buses close enough to the kerb to provide acceptable accessibility for the passengers.

Some of the time periods described above can be considered to be constant – for example, clearance time. However, other periods depend strongly on the actual arrival times of the individual buses and the number of passengers boarding and alighting as a consequence. For example, a bus arriving after an interval of several minutes following the departure of the previous bus can expect to pick up more passengers than one that arrived after only a few seconds. The latter would benefit from a very short PST, but possibly suffer an increased internal delay as the previous bus could obstruct its departure. Instances of such time-dependent obstructions can only be analysed through the use of microscopic simulation models, and this is the reason why such models have been developed (see Tyler[1] for further discussion).

2.3.   Operational Issues at Bus Stops

2.3.1 Passenger service time (PST)

From the point of view of the operation of a bus stop, PST is the most obvious time period to consider first. A passenger takes a certain amount of time to board and alight. This can be averaged to give a marginal boarding time per passenger; the effect of variation in boarding times per passengers is an important issue (and discussed hereafter). The ticketing system has an enormous effect on the marginal boarding time. First, if all passengers must pass the driver

in order to show a pass, pay a fare or – even worst – cross a turnstile, this places a constraint on how many doors could be available for boarding and increases the PST. Secondly, passengers have to pass the driver and/or a turnstile in more or less a single file. This reduces the rate at which people can enter the vehicle and thus increases the marginal boarding time and so the PST.

PST must include time for boarding and alighting passengers and must consider all the doorways of the bus. There are many specifications of the PST as a function of the number of boarding and alighting passengers. For example, Fernández[2] quote a working paper by Gibson and Fernández proposing the following general model found in Santiago de Chile:

$$
\begin{aligned}
PST = \beta_0 + \beta_0'\delta_1 + \\
+ \max_j \left\{ \left[\beta_b + \beta_b'\delta_1 + \beta_b''\delta_2 \right] p_{bj} + \left[\beta_a \exp\left(-\beta_a' p_{aj}\right) + \beta_a''\delta_3 \right] p_{aj} \right\}
\end{aligned}
\tag{1}
$$

where
p_{ij} : boarding (i=b) and alighting (i=a) passengers per bus by door j
$\{\beta_i\}$: vector of parameters to be calibrated
$\{\delta_k\}$: vector of dummy variables

Parameters β_0 are dead times, β_b are fractions of the marginal boarding time per passenger, and β_a are parameters related to the marginal alighting time per passenger. Table 1 shows the values of the parameters. The dummy variables are $\delta_1 = 1$, if the platform is crowded; $\delta_2 = 1$, if boarding passengers are 4 or more per bus; and $\delta_3 = 1$, if the bus is crowded (e.g. aisle is full). Otherwise, $\delta_k = 0$ in all cases (with k = 1, 2, 3).

The dummy variable δ_2 is active for a boarding rate of 4 or more pass/bus, because in Santiago passengers must pay the driver; so only 3 passengers can be stored in the entrance. If there is a fourth passenger wishing to board, the queue will reach the platform and the bus must wait at the berth. As can be seen in the table, in such a case a single boarding file would increase the PST by 15 to 23% at each bus stop.

Table1: Values of parameters of the PST model

Parameters (units)		Type of bus stop	
		Kerb bus stop	On a dedicated island
β_0	(s)	1.17	0.00
β_0'	(s)	0.00	2.34
β_b	(s/pass)	3.48	2.99
β_b'	(s/pass)	0.34	0.40
β_b''	(s/pass)	0.78	0.43
β_a	(s/pass)	1.44	2.00
β_a'	(pass)$^{-1}$	0.00	0.035
β_a''	(s/pass)	0.76	1.14

2.3.2 Queuing time

Queuing time is another important way in which the design of a bus stop can affect the way in which a bus service operates. It is also an outcome of a bus stop with insufficient capacity. If a bus cannot enter the stop area it must wait in a queue before the bus stop until a berth is

available. This causes delays to passengers in the vehicle and creates problems for passengers wishing to board the bus. The length of this queue and the time a bus has to spend in it indicate the extent to which the stop is lacking in capacity.

One way of increasing the capacity of a bus stop would be to increase the number of berths, as this would allow more buses to call at the stop at the same time. Let us consider the case where the new berth is immediately adjacent to the current one. In this case, the berths are not independent: a bus in the rear berth would not be able to leave if there were a bus occupying the front berth. Under these conditions, the additional berth does not double the capacity of the stop: there will be periods when only one bus can be accommodate at the stop; e.g. when the front berth is unoccupied and a bus is stopped in the rear berth. As a result, the addition of a second berth would increase the capacity by about 50%. Similarly, a third berth would add a further 30%, a fourth 20% and so on[1, 16]. Even these increases only apply when drivers stop as a matter of course in the berth nearest to the exit. Poor performance in this respect will further reduce the capacity of the stop.

2.4. Flows and Delays at Bus Stops

Just taking the PST and the queuing time into account, the overall delay to a bus at a bus stop is the sum of these two times (in section 2.1 we have mentioned the other elements of delay at bus stops, but for the purposes of simplification in this illustration we are only using these two). Each is affected by bus frequency and thus by the bus flow but in different ways. Figure 2 shows a simple example of the nature of the effects that arise. As the bus flow increases, the amount of time spent serving passengers falls because each bus serves fewer passengers. As the congestion increases the amount of time each bus spends in the queue before the bus stop increases. The total time has a minimum between the lowest and the highest flow values. If the frequency of a service were low, the best way to improve PST would be to deal with the boarding process (including ticketing system, use of doors, design of the entry hall of the bus, and design of the entry and exit path of the bus stop). Where frequency is high, a better course of action would be to resolve the capacity problem at the bus stop so that it could cope with the large number of buses trying to use it; for example, by means of multiple two-berth bus stops[4].

One interesting outcome is that the total delay is insensitive to the actual flow of buses for much of the range. However, we can see two points at which the slope of the total delay changes markedly: in this example these points are found at bus flows of about 70 and 160 buses per hour. These figures correspond to the degrees of saturation of about 40% and 80%, respectively. This effect is quite common and gives rise to the suggestion that a reasonable *design flow* for a bus stop is approximate 60% of its theoretical capacity[5]. In fact, in this example the design flow (120 bus/h) produces the minimum total delay (42.75 seconds).

If we wish to design bus stops with appropriate capacity and buses able to take full advantage of them, we need to understand these arrival-dependent processes in considerable detail. Calculations based on average arrival rates are not sufficient for the analysis and so we have turn to microscopic simulation to study operations at bus stops.
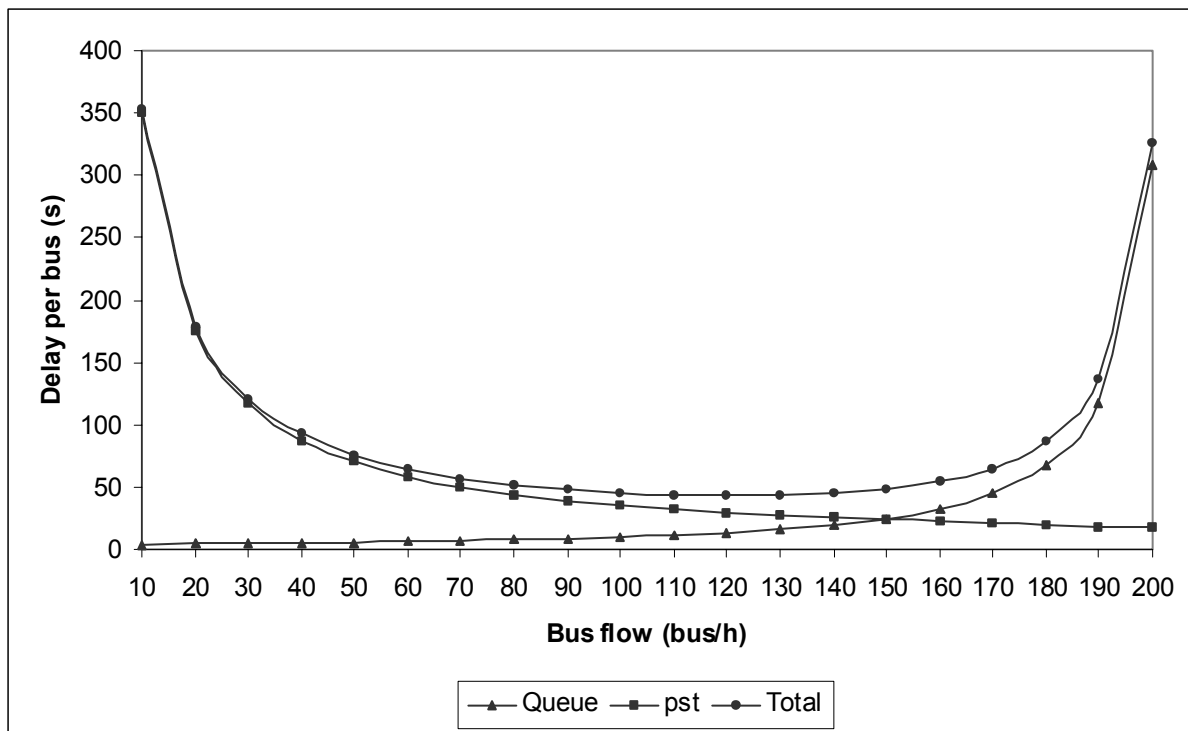
Figure 2: Flows and delays at bus stops

3.   A SIMULATION ILLUSTRATION

3.1.   A Simulation Model and Experiments

The simulation model used in this study is called PASSION (PArallel Stop SimulatION) and has been described elsewhere[2, 3, 4]. This model was developed as part of our research at the Accessibility Research Group, University College London and allows us to see what would happen at a single berth bus stop under a variety of operating conditions. The complexity of the problem is such that the development of the model required a parallel computer to represent all the various concurrent processes. Once we could understand what was going on at the bus stop, it was possible to represent the problem in a serial form and accordingly a PC-based simulation model was written. In order to illustrate the sort of information provided by the model, an example of a PASSION output file is shown in Figure 3. The model is now being translated into visual C++ for a friendlier interface.

One hypothetical example was defined for this illustration. The operational characteristics of this example are shown in Table 2. Specific experiments were performed to test operational impacts of bus stops. The objective is to provide a *ceteris paribus* analysis of the results due to changes of some isolated factors The factors to be analysed are arrival patterns, boarding times, obstructing exits, and bus capacity. The same set of variables and parameters was used for all the experiments, unless otherwise is stated. The initial conditions assumed an empty bus stop and the event that terminates the simulation was the departure of the last bus that arrives during one-hour simulation period.

```
****************************************************************
*  PASSION 4.2 : PArallel Stop SimulatION - R.Fernandez (2000)  *
****************************************************************

Data  of  this  run:
====================
Stop identification   : My_example_run
Routes using the stop :   1 routes
Simulation period     :  52 min
Bus flow              :  22 bus/h  (sd bus headways: 122.13 s)
Boarding  demand      : 390 pass/h (sd pas arrivals:  14.82 s)
Aligthing demand      :  67 pass/h
Two doors, parallel boardings and alightings...
Free exit...

Results of this run:
====================
Mean pas waiting time :   1.63 min   (max:   6.12 sd:   1.46)
Mean pas on platform  :  17.79 pass  (max:  49.00)

Mean bus pas   delay  :  37.11 s/bus (max:  99.34 sd:  29.44)
Mean bus extra delay  :   0.00 s/bus (max:   0.00 sd:   0.00)
Mean bus queue delay  :   5.62 s/bus (max:  69.42 sd:  17.66)
Mean bus total delay  :  47.73 s/bus (max: 104.34 sd:  31.24)

Berth capacity        :  85.50 bus/h (sat:   0.26)
Mean bus queue length :   0.03 buses (max:   1.00)
Exit time deviation   : 151.24 s

Queue characteristics :
----------------------
Queue Freq Q.Time
(bus) (%)  (s)
  0    89    0
  1    11   53

Bus characteristics:
--------------------
Bus   Route Arriv Board Aligt Platf Queue Q.Del P.Del E.Del T.Del Exits A.Time Bus Cap
(no)  (key) (s)   (pas) (pas) (pas) (bus) (s)   (s)   (s)   (s)   (s)   (s/pas) (pas)
  1    1    227    33     1    33     0     0    69     0    74    301   1.3      50
  2    1    578    28     6    28     0     0    60     0    65    643   1.3      50
  3    1    646     4     1     4     0     0     9     0    14    660   1.3      50 etc.

Passenger characteristics:
-------------------------
Pass Route Arriv Wait  B.Time
(no) (key) (s)   (s)   (s/pas)
  1    1     1    226   1.9
  2    1     2    225   2.3
  3    1     3    224   1.6 etc.
```

Figure 3: Example of a PASSION output

Table 2: Operational characteristics for the experiments

Variables and parameters	Assumed values
Stopping bus flow (bus/h)	50
Boarding demand (pass/h)	100
Alighting demand (pass/h)	50
Clearance time between buses (s)	10
Dead stopping time (s)	1.0
Marginal boarding time (s/pass)	2.0
Marginal alighting time (s/pass)	1.5
Number and use of doors	2 one-way doors

The operational conditions tested were the following:
1) Distributions of inter-arrivals. These can be either:
   a) Exponential distributions; or
   b) Actual inter-arrivals in a real case.

2) Boarding times. Three cases were examined:
    a) Quick boarding (e.g. using passes);
    b) Normal boarding (e.g. pay to the driver); and
    c) Slow boarding (e.g. a cash-operated turnstile).
3) Exit modes from the stop area. Three possibilities were studied (see Figure 4):
    a) Unobstructed path from the bus stop;
    b) The exit is controlled by a traffic signal; and
    c) The exit is partially obstructed by other vehicles.
4) Capacity of vehicles. Two conditions were tested, either:
    a) There is no restriction to board the bus; or
    b) Buses have a limited capacity for boarding passengers.

(a) Free exit

(b) Traffic signal ahead

(c) Partially obstructed
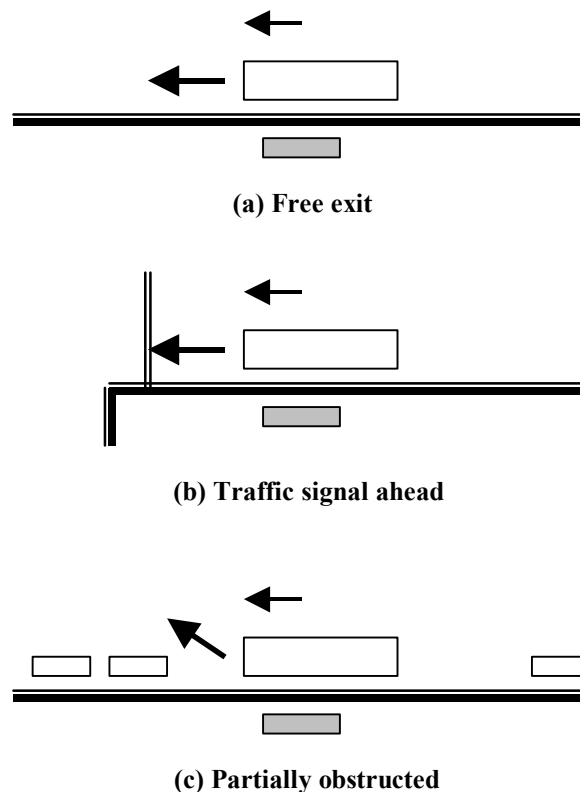
Figure 4: Exit conditions tested in the experiment

The result of the aforementioned experiments with the simulation model PASSION are summarised next.

3.2. Arrival Patterns

In a discrete event simulation much of the model behaviour depends on the statistical distributions that are chosen to model the objects of the system. The distributions are used to model uncertain or indeterminate behaviour, such as the varying intervals between successive arrivals at a queuing system. As Pidd[6] suggested, they are appropriate when the process that produces this behaviour cannot be understood in any deterministic sense. However, evidence indicates that outputs obtained under the assumption of Poisson arrivals of buses and passengers at bus stops do not agree with those obtained if the actual sequence of arrivals is used[2]. This was tested with data collected at bus stops in London and Santiago. Two analyses were made. These are described next.

3.2.1 Analysis of field data

In current descriptions of bus operations, arrivals at bus stops are represented as stochastic phenomena where the particular interval between pair of events is chosen from a distribution. Thus, Gibson et al[7] assume Cowan's M3 shifted negative exponential distribution[8] to describe the headway between buses. Similarly, other authors[9,10] state that passenger arrivals follow a Poisson distribution; therefore, the inter-arrivals should follow a traditional negative exponential distribution[6]. In Figures 5 and 6 the frequency comparison of actual bus headways and passenger inter-arrivals with exponential distributions for the case of London are shown. A chi-square test was applied to compare the theoretical negative exponential distribution with the sample data[11]. The null hypothesis to be tested is: data are IDD random variables with negative exponential distribution. The results of this test are shown elsewhere[2]. In all cases the test rejects the null hypothesis. Therefore, despite the resemblance of the data to the exponential distribution, the statistical test indicates that a negative exponential distribution would not represent the arrival process of buses and passengers at bus stops.
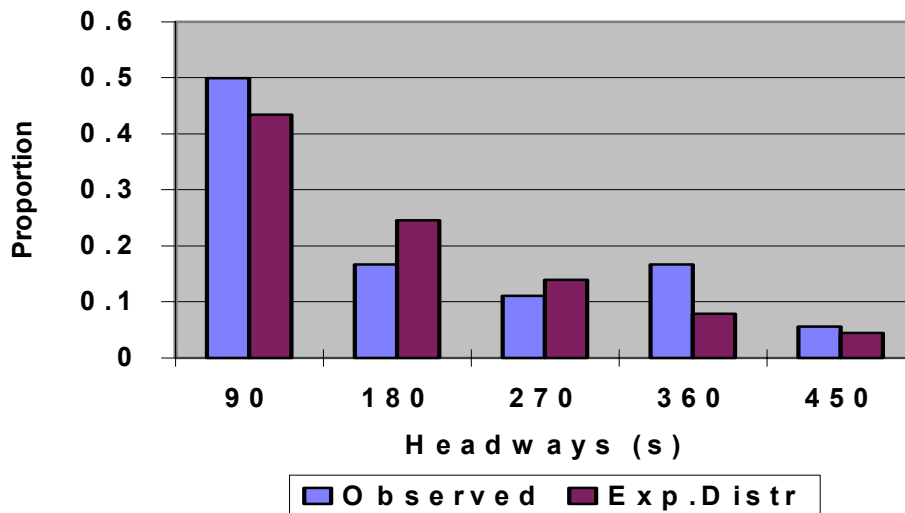

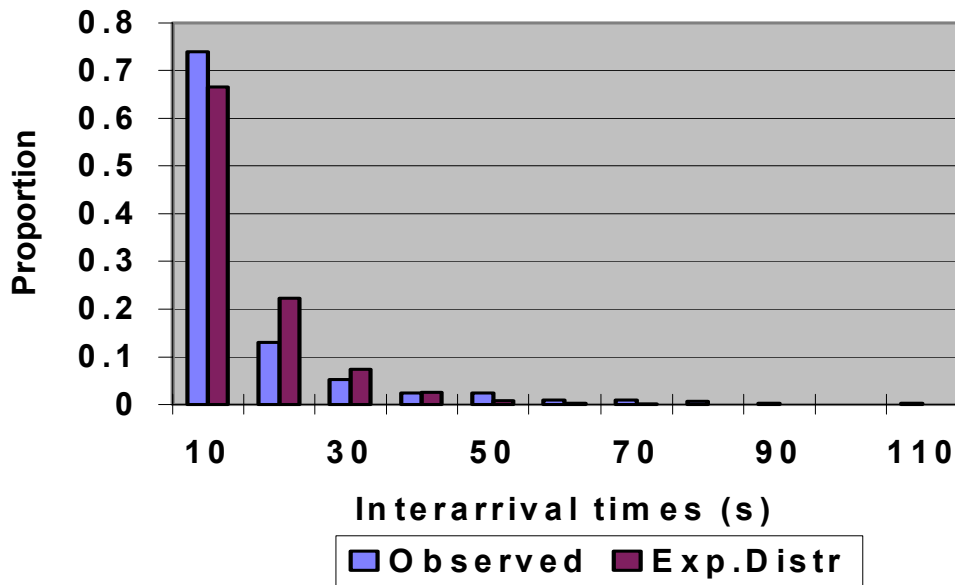Figure 5: Distribution of bus headways at Manor House Stn bus stop

Figure 6: Distribution of passenger inter-arrivals at Manor House Stn bus stop

3.2.2 Analysis of output sensitivity

The question then arises: Are the outputs sensitive enough to the hypothesis of exponential arrivals? In order to test the significance of the differences Fernández[2] performed a hypothesis test for the mean outputs based on the t-student distribution. Results indicate that in some cases model outputs obtained with the actual sequence of arrivals are statistically different to those assuming exponential arrivals.

In the case of Santiago, the queue and total delay to buses were statistically different. This can be explained due to the scattered behaviour of passenger demand, for which exponentially distributed arrivals can be assumed. However, the existence of an upstream traffic signal in conjunction with the high bus flow makes the assumption of exponential arrivals of buses unrealistic. Indeed, buses tend to arrive in pairs in this case. As a consequence, the interaction between an almost Poisson arrival of passengers with a batch arrival of buses makes statistically different the delay to buses at this bus stop. In the case of London, batch arrivals from a metro station makes relevant the use of the actual sequence of passenger inter-arrivals at this bus stop, for the waiting time was statistically different if Poisson arrivals are assumed. However, in terms of the other outputs, the assumption of Poisson arrivals would be reasonable from a statistical point of view, at the cost of a less thorough estimation of the bus stop performance.

In summary, it was shown that the use of some standard distributions for modelling bus stop interactions is valid only for that subset of cases for which the assumption of Poisson arrivals seems reasonable. Otherwise, we could be modelling any bus stop, but none in particular, which could lead to errors in design and evaluation of bus services.

3.3. Boarding Times

It is widely accepted that boarding times of passengers have a large impact on bus operations. Therefore, in order to explore this phenomenon changes in the marginal boarding times were

made. Three values were tested, named quick (1.5 s/pass), normal (3.0 s/pass) and slow 6.0 s/pass) boarding times. In addition, the effect of the variability in boarding times was investigated. To that end, the feature of PASSION that allows the user to specify a different boarding time per passenger was used. Thus, boarding times between 1.5 and 6.0 s/pass were allocated to each boarding passenger.

Figures 7, 8 and 9 summarise the results for the different arrival patterns considered. As can be seen in the figures there is a sharp drop in capacity as the PST increases as a consequence of the increase in the boarding time. The relationship, however, is less than proportional. On average, a rise in the mean boarding time from 3 to 6 s/pass produces a 23% drop in capacity. This implies, however, an acute increase in the mean queue length (two or three times) coupled with a 40% increase in the delay. It should be noted that average boarding times of nearly 3 to 6 s/pass have been reported elsewhere for various bus types[12, 13]. Thus, the scenario is not unrealistic and demonstrates that different boarding times at the same bus stop have important repercussions, whatever the arrival pattern of buses assumed.

In contrast, it would seem that the sole variability in boarding times does not produce more repercussions than the increase in its average value. In fact, as can be seen in the figures, if boarding times vary between 1.5 and 6.0 s/pass the results are similar to those obtained for a 3.75-s/pass average. Lobo[13] who studied the effect of the number of old-aged persons in boarding times had already suggested this outcome; the conclusion was the same as here: the average is a good indicator.

To summarise, the great influence of boarding times in the bus stop efficiency was corroborated in the case where passengers have to pass the driver on entry to the bus, as was the feasibility of capturing this influence by means of an average value to be used in a PST model. Therefore, the management of stop operations must consider this behavioural variable in order to accommodate the demand. Thus, changes in the design of vehicles and stops can be decided; e.g. door width, steps height, internal bus space, ticketing system, use of doors, raised platforms, etc.
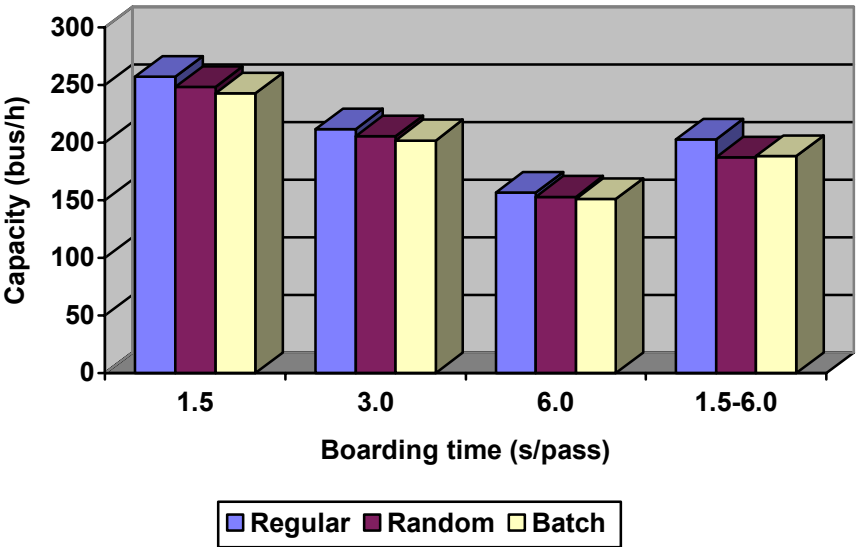

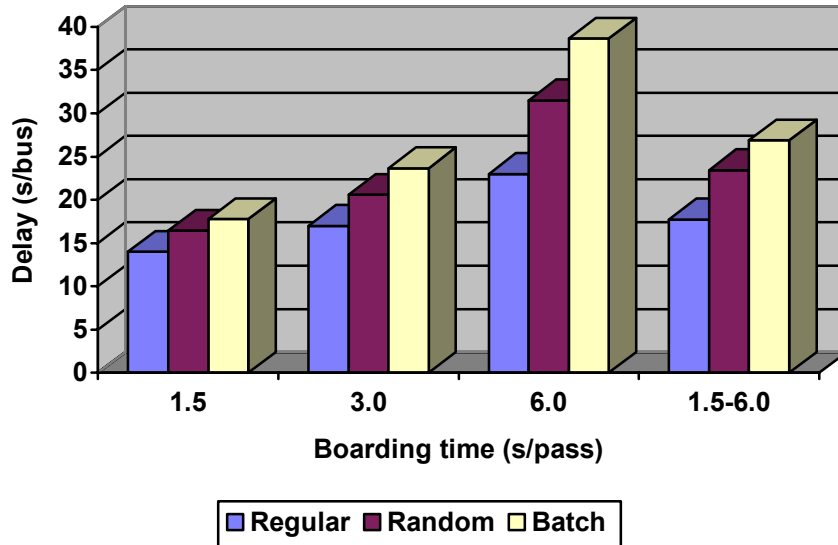Figure 7: Effect of boarding times on bus stop capacity

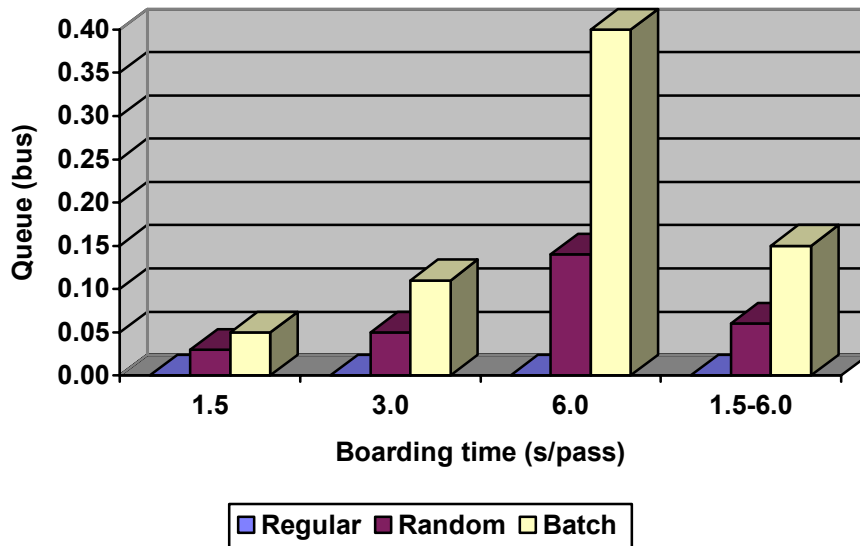Figure 8: Effect of boarding times on bus delay

Figure 9: Effect of boarding times on bus queue

3.4. Obstructing Exits

According to an analysis of variance made by Fernández[2], this was the main influential factor on delays at bus stops. Its effect should be studied according to the type of phenomenon that produces the obstruction. Two possibilities were explored: obstructions due to traffic when a bus is trying to re-enter to a traffic lane from an off-line bus stop (e.g. bus bay) and obstructions due to the operation of a traffic signal in the same lane of an on-line bus stop.

3.4.1 Effect of exit controlled by gaps in the adjacent lane

As a way of illustration of this effect, Figure 10 shows the average bus stop performance as a function of the flow in the adjacent lane derived from the result of the experiments. To summarise the results, the figure shows the bus stop capacity in tens of buses per hour, the total delay in seconds per bus, and the mean queue length in hundredth of buses.
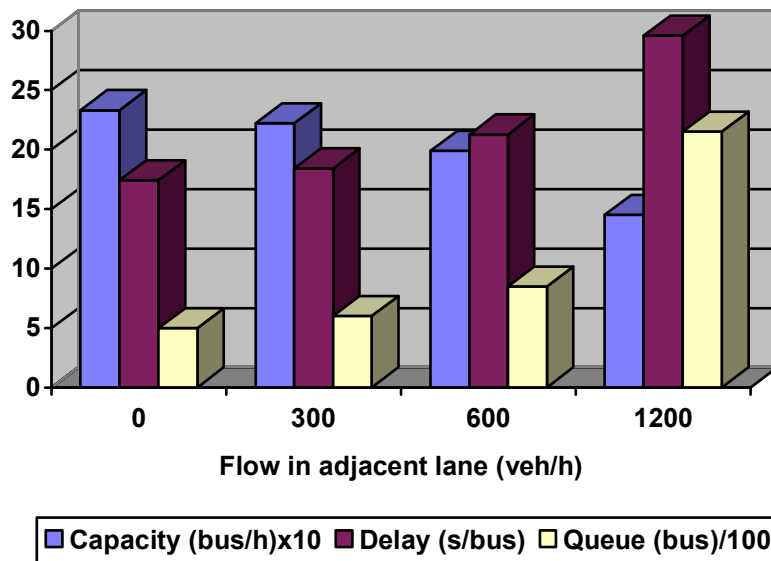
14

Figure 10: Effect of exit controlled by gaps

As can be seen in the figure, there is a gradual deterioration in the performance of the bus stop as the adjacent flow increases in relation to the possibility of unobstructed exits (represented in the figure a zero flow in the adjacent lane). However, this does not affect the waiting passengers in terms of their waiting time or platform density. Compared with unobstructed exits, the main impacts are a reduction in bus stop capacity from up to 40%, an increase in bus delays from up to 70%, and a rise in queue lengths of up to 5 times as large.

These results imply that the provision of overtaking facilities at bus stops is necessary. It should be noted that flows of nearly one thousand vehicles per hour per lane are common in many roads where buses operate. In those cases, a significant drop in bus stop performance is expected if buses have to re-enter to the traffic stream. Thus, bus boarders should be preferred to bus bays if the improvement of bus operations is sought, even if the frequency and demand seems relatively low – less than one bus per minute and just 2 boarding passenger per bus in our example.

3.4.2 Effect of exit controlled by a traffic signal

The analysis of the influence of a traffic signal controlling the exit from the bus stop indicates a decrease in capacity and increases in delays and queues compared with unobstructed exits. An average reduction in bus stop capacity of 50% and an average increase in delay of more than two times are observed when unobstructed exits are compared to an exit controlled with a traffic signal with a 100-second cycle time and 0.4 green to cycle time ratio. The same comparison indicates that queues up to 5 times as much can be develop. Two factors have influence in this situation: the cycle time and the green ratio. In fact, the lower average impact occurs in the case of short cycle time (50 s) and high green ratio (0.6). Gibson[14] had already reported a reduction in bus stop capacity induced by the existence of a nearby downstream signal of up to 40%.

Results of further experiments produced with PASSION are shown in Figure 11. These show the reduction of the base bus stop capacity (unobstructed) as a function of the green ratio for a long and short cycle time, under the hypothesis of random arrivals of buses and passengers. It

can be observed in the figure that for long and short cycles a significant lost in capacity is obtained as the green ratio decreases. On average, this means a 22-bus/h lost in capacity per one-tenth decrease in the green ratio. In addition, it seems that over a green ratio of 0.4 the cycle length has a negligible effect.

To summarise, the presence of a traffic signal controlling the exit from a bus stop always brings a reduction in performance. If this situation cannot be avoided, the signal timings must seek to maintain this drop in performance as low as possible. The experiments performed with PASSION give information about how this could be achieved. For instance, a green ratio above 0.6 produces a reduction in bus stop capacity of less that 20%, irrespective of the cycle time.
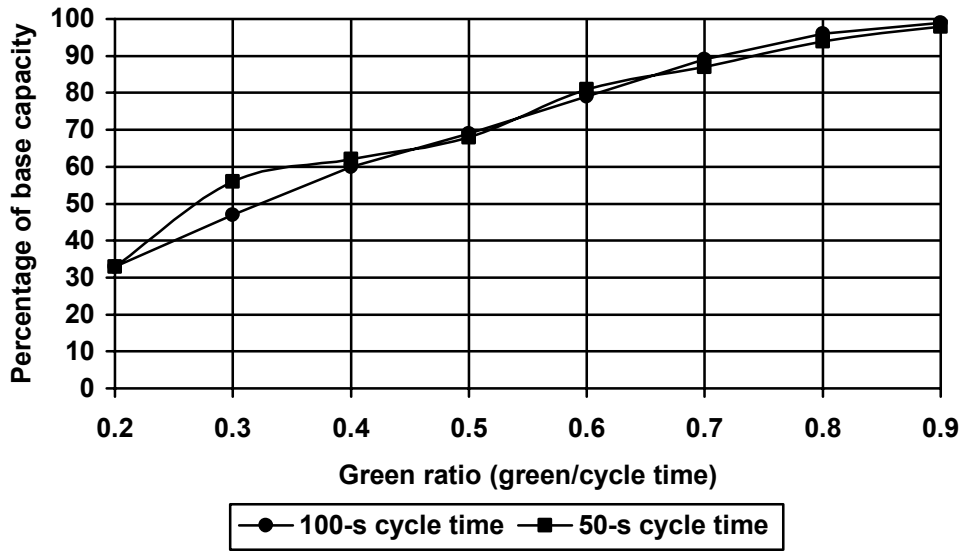

Figure 11: Effect of a traffic signal on bus stop capacity

3.5. Bus Capacity

Previous researchers have studied the issue of the bus capacity on bus operations along a route. For example, Oldfield and Bly[15] postulated the following functional forms of the Average Waiting Time (AWT) as a function of the load factor of the vehicles:

$$AWT = \begin{cases} \dfrac{\varepsilon}{f} \\[2mm] \dfrac{\varepsilon}{f}\left(1 - z\phi^{\gamma}\right)^{-1} \\[2mm] \dfrac{\varepsilon}{f} + z\phi^{\lambda} \end{cases} \tag{4}$$

where
$\phi = k/K$: load factor of vehicles
k : load of vehicles
K : capacity of vehicles
f : frequency of vehicles

ϵ, z, γ : parameters

These authors state that ϵ depends on the level of ϕ; however, they postulate that if ϕ is low enough and passengers arrive at random, ϵ is around 0.5. They also indicate that there are few empirical evidences about the values that should take the parameters z and γ. In addition, they state that if the demand is not homogeneous in time and space, the impact of bus capacity will be concentrated at some few stops. Therefore, the impact over the entire route will be reduced. However, those passengers that cannot board some of the overloaded vehicles will increase in their waiting time, with consequences on the perceived level of service.

At an isolated bus stop two outcomes are expected from a reduction in bus capacity: (a) an increase in the number of waiting passengers at the platform and their waiting times, for not all of them can board the first bus that arrives if this is overloaded; and (b) a reduction in the passenger service time (PST) as a consequence of the smaller number of boarding passengers per bus. These potential outcomes were examined in our experiments. To that end, two cases of spare capacity were considered: buses arriving with limited spare capacities (from 0 to 10 passengers) and buses with virtually unlimited spare capacity (50 passengers). The results show a minimal fluctuation on the performance of the bus stop due to the spare capacity of buses. The outcome (b) was only a slight reduction in PST, which in turn meant a negligible benefit on bus stop delay and capacity. The outcome (a) was an increase of the platform density of about 10 to 20%, but the effect was not enough to change the maximum values of the waiting time and platform density. There was, however, one exception: the case of regular arrivals of buses and passengers in which the maximum figures of waiting time and platform density were double those of unlimited capacity of vehicles. It seems in this case that the introduction of the only random perturbation (the variation in capacity of vehicles) produces important effects on passengers.

In summary, it would appear that the capacity of the vehicles has more influence on bus stop performance if regular arrivals are considered; that is, if frequency of buses and demand rate of passengers are assumed constant. This is a simplifying assumption in analytical models of bus operations along a route like those of Oldfield and Bly[15], and may have an effect on other questions of bus operations such as route demand, line-haul capacity, vehicle scheduling, and operating cost. Therefore, the relaxation of some assumptions used in analytical models which is provided by our simulation approach could also shed light on these issues.

4.   SUMMARY AND CONCLUSIONS

The results and conclusions from our work can be summarised in the following main points.

First, it is shown that the actual arrivals at bus stops do not always follow a Poisson process, as is usually assumed. It was also stated when and why the differences in model outputs coming from Poisson and actual arrivals are statistically significant. In that case, a general-purpose distribution cannot be used to model bus stop interactions. This leads to the necessity of microscopic simulation of bus, passenger and traffic interactions at bus stops to understand this seemingly simple problem. We postulate that the oversight of this fact has led, in many cases, to ill-designed bus stops. For example, the capacity at bus stops is rarely considered in the UK because the view is that buses are relatively few in number. However, bus flows, although low, are not regular and thus are characterised by very high flow rates over short periods of time, in particular in London where bus frequencies have been increased as part of

the congestion charging initiative. In this case, oversaturation is expected during those periods. The visible outcomes of this are queues of buses at bus stops. One effect of this is that buses stop away from the berth and passengers must walk towards them, often into the roadway and into what can be a difficult and confusing traffic environment around the bus stop. As a consequence, poor accessibility to public transport is provided.

Secondly, the arrival patterns of buses and passengers have their prime impact on the passenger service time (PST) of which the boarding time is the principal component. Once a number of boarding passengers interact with a bus, the boarding time is greatly affected by the fare collection system. Thus, the worst condition is an on-board collection mechanism for which a single door and a single line must operate. In such a condition, the number of passengers that the entrance hall of the vehicle can store plays an important role. In addition, according to the PST model, no only the fare system affects boarding times, but also the crowding conditions at the platform. Both conditions – a small entrance hall and a crowded platform – may increase the boarding time in about 30-40%; so the PST and the delay at the bus stop of *each* stopping bus is increased. This in turn has a damaging effect on route performance.

Thirdly, it was shown that any obstruction in the bus exit from the stop has a negative impact on bus stop operation – and so on bus route operation. Conventionally, however, it is considered legitimate to consider that the less a bus stop affects private cars the better. The problem is that this is usually the main – and sometimes the only – criterion to define how a stop will be located and built, and the common perception is that the impacts of bus stops on private car are very bad. Even worse, most tools for traffic analysis end up reinforcing these views, prioritising the circulation of cars over the accessibility of the bus system. Nevertheless, buses need sufficient road space near the bus stop so that they can leave and enter the traffic stream and not be obstructed by other vehicles. Therefore, bus stops need to be located in such a way that they are not adversely affected by traffic management measures such as traffic signals, car parking, or off-line bus bays. As the overriding need is to make bus stops accessible, we have to decide where the priority lies: a bus stop which is inaccessible prevents some people from boarding, so we should only move away from the accessibility requirement in extreme circumstances.

Fourthly, the effect of buses arriving with limited capacity is not so important as to change the performance of a bus stop. Our experiments showed that in only two cases the restriction in bus capacity might affect the bus stop operation: (a) under the assumption of regular (constant) inter-arrivals of buses and passengers; and (b) if the spare capacity of buses is similar to the mean number of boarding passengers per bus. In the rest of the cases, other effects are more important. The assumption (a) is common in analytical models and this seems to be the reason why it has been a matter of concern in the literature. When this assumption is released, however, the real-world issues for bus stop operation are unveiled.

Finally, the discussion in this article suggests a number of issues that need to be addressed before we can begin to design a bus stop to allow greater accessibility to the bus system. It seems clear that a bus stop with insufficient capacity will be unable to deliver an accessible interface between buses and passengers. Therefore, it is an essential prerequisite that bus stops are constructed so that they can accommodate the number of buses *and* passengers that will be using the stop. To that end, the analysis of bus stop operations requires the use of specialised microscopic simulation models. These models must incorporate the possibility of allowing exact arrival and departure data for both buses and passengers so that different bus

stop designs can be tested against real and repeatable situations; we have given one example of detailed analysis of different effects in order to detect and analyse these problems. As a last word, it is important not to underestimate the real bus flows in the bus stop – designing for a regular bus service and passenger arrivals will be insufficient if the reality is different.

ACKNOWLEDGEMENTS

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