On the capacity of bus transit systems

RODRIGO FERNANDEZ and ROSEMARIE PLANZER
Department of Civil Engineering
University of Chile
Casilla 228-3, Santiago - Chile

Abstract

This paper examines the transit capacity problem of bus-based systems. Firstly, it defines the problem of transit operations along a route. This raises the importance of stops on transit capacity and why the analysis and design of stops should be considered in bus traffic schemes. Next, the paper explains the concept of transfer capacity and reviews the work to date on modelling the capacity of stops. Current as well as novel approaches are considered and the advantages and limitations of them are discussed; special attention is devoted to a new simulation model of transfer operations at stops. From that approach, the paper concludes with some examples of capacities of various transit systems and design recommendations for bus transit stations.

1 The transit capacity problem

Buses spend a large proportion of their running time stationary at stops. Lobo (1997) reported that stop time accounts for about half of the journey time between termini. Gardner *et al* (1991) found that the mean bus delay at junctions is 15 s, while for a bus stop range from 45 to 90 s. Stops are, then, the main bottleneck for bus operations.

The reason is simple. Along a route buses spend time on road links, at junctions and at stops. The main task of buses at road links and at junctions is to pass through. By contrast, buses must remain at stops boarding and alighting passengers. As in any other transport terminal (airports, ports, and stations) this is a different kind of activity and requires special arrangements to speed up the process. However, in the case of buses these 'termini' are located on the street and they are frequent along a route.

As an example of the above, let us study the capacity of the public transport system made of the physical components sketched in Figure 1. Some operational characteristics of this system are assumed for the purposes of this example. These can be summarised as follows:

- The system is a segregated way for buses, trolley buses or trams.
- There is no alighting demand of passengers.
- There are no interactions between the stops and the traffic signals.
- C_o = 2,000 pcu/h-lane is the road capacity.
- s_b = 1,800 tcu/h-lane is the saturation flow at junctions.
- u = 0.5 is the green ratio of the traffic signals at junctions.
- x_p = 0.9 is the practical saturation degree for roads or junctions, and 0.6 for stops[1].
- f_b = 2 pcu/bus or tcu/bus is the factor of equivalence for buses.
- t_c = 15 s is the clearance time at stops.
- β_b = 3.5 s/pass is the boarding time per passenger.
- p = is the boarding rate of passengers per bus.
- n = 2.43 is the effective number of berth at stops, if 3 actual berths are provided[2].

As a result of these parameters, the corresponding practical capacities of the various physical elements of this system are the following:

- Road capacity: $$Q_r = \frac{x_p C_o}{f_b} = 900\ (bus/h - lane) \qquad (1)$$
- Junction capacity: $$Q_j = \frac{x_p u s_b}{f_b} = 405\ (bus/h - lane) \qquad (2)$$
- Stop capacity: $$Q_s = \frac{3{,}600 n x_p}{t_c + \beta_b p} = \frac{5{,}249}{15 + 3.5p}\ (bus/h - lane) \qquad (3)$$

According to different values of the boarding rate of passengers per bus (p), the stop capacity has different values, as shown in (3) above (see TRB, 2000). For instance, if, on average, five passengers board each bus Q_s = 162 (bus/h-lane).

[1] This implies less than 60-seconds of stop delay and 0.5-bus queue length (Gibson and Fernández, 1995)
[2] See St Jacques and Levinson (1997).

Therefore, the practical vehicle capacity of the system can be expressed as $min\{Q_r, Q_j, Q_s\} = Q_s \leq 160$ (bus/h-lane). To summarise, if the flow on the corridor is more than 160 buses per hour, special arrangements are necessary at stops to avoid congestion, despite the fact that there is spare capacity at junctions or roads. For example, multiple-berth stops with special layouts are required (Fernández, 1999).

Any stop should be understood as a street space mechanism where vehicles and passengers merge or diverge. It is made of a stop area for vehicles (consisting of berths) and a compatible platform for passengers. Berths and platforms can be arranged in various layouts to cope with passenger demands and flows (e.g., single berth, multiple berth, sawtooth, split stops).

The design of stops is not a trivial issue. Each stop is a particular case of demand structure and external conditions. Hence there is a need to understand the phenomena that occur at a particular stop and forecast performances of alternative arrangements and operations. This requires tools to classify cases and provide design guidance.

Despite this need, currently there are few formal approaches for stop design. Most of the analyses have been oriented to the bus-scheduling problem, addressing the issue of bus movement rather than bus access. Lobo (1997) offers a good review. Only Gibson *et al* (1989) have provided an approach to model stop operations in detail using microscopic simulation. But there is still limited understanding of some issues at stops. For instance, Lobo (1997) appeals for a more realistic replication of bus scheduling and passenger arrivals at stops to model bus operations. Accordingly, Fernández (2001a) carried out research to improve the scope of current approaches and shed light on the understanding of stop interactions. Some of the results of that study are summarised in this paper.

2 Review of transit capacity models

In Section 1 the importance of stops in the capacity of a transit system was shown, implying that the actual bottlenecks for transit operations are the stops. Therefore, the capacity of a public transport system is determined by the capacity of its stops.

Thus, one of the main concerns about stops, when considered as isolated mechanisms, has been the estimation of their capacity to manage passenger transfer operations. From this, some performance indices can be derived for subsequent analysis and decisions, such as queues and delays at stops.

In conceptual terms, a transfer station (port, airport, rail station, bus stop, taxi rank, etc) is the place where transport objects (passengers or freight) and modes of transport (different types of vehicles) meet in order to allow the objects to be loaded onto, and unloaded from, the vehicles. For the purposes of this paper these objects are passengers and the vehicles are road-based public transport vehicles.

The capacity of a transfer station can be defined in terms of the vehicles that can be served, or the passengers that can be transferred. From a traffic point of view the former is more relevant, for it implies vehicles passing the station and hence their passengers moving through the system. This can conceptually be expressed as:

$$C = \frac{\alpha N}{t_o} \tag{4}$$

where C is the transfer capacity of the station, N is the number of loading positions or berths; α is the availability of the loading positions, and t_o is the occupancy time of each loading position.

If each loading position can be assumed to accept one vehicle at a time, then the transfer capacity is expressed in vehicles per unit of time (e.g., buses per hour). The number of loading positions depends on the available space at the transfer station. Normally this is a scarce resource that should be minimised subject to both physical and operational concerns.

The availability of a loading position can be expressed as a proportion of the time that the loading position is free. Availability depends on operational conditions including the way in which the loading positions are allocated to vehicles, the entry and exit discipline to and from a loading position (e.g., FIFO) and the possibility that a vehicle remains at a loading position after the completion of the transfer process;

Occupancy time is a function of the types of vehicles and passengers. For instance, an articulated and high-floor bus could require more time to be accommodated and loaded than a smaller low-floor bus; passengers paying in cash to the driver will require more time to board than people with passes; etc. Occupancy time will also depend on the interaction between vehicles and passengers. This interaction can be described by means of models that relates the occupancy time with the number and type of passengers being transferred.

The factors that affect the transfer capacity can therefore be classified as:

- Physical: number and layout of the loading positions and manoeuvring space, loading and unloading facilities, type of vehicles.
- Operational: arrival of vehicles and passengers, assignment and use of loading positions.
- Behavioural: types of drivers and passengers.

In the case of stops all these factors are present. In the remainder of this Section these and other issues such as the effect of the variations in arrivals and occupancy time and how this has been consider in the modelling, will be introduced using the stop capacity as the basis for analysis. Four approaches to stop capacity are discussed in this section. They correspond to the few formal approaches found in the literature on this matter.

2.1 The Highway Capacity Manual model

Since its earliest version the Highway Capacity Manual (HCM) has dedicated some paragraphs to the performance of on-street transit (see TRB, 1965). The present HCM model of bus stop capacity can be summarised as follows (TRB, 2000):

$$Q_N = \frac{3{,}600(g/C)N_b}{t_c + t_p(g/C) + Z_\alpha C_v t_p} \tag{5}$$

where:

Q_N : capacity of an on-street bus stop (bus/h)

g : green plus amber time at a downstream traffic signal (s)
C : cycle time at the downstream traffic signal (s)
t_c : clearance time between successive buses (s)
t_p : passenger service time at the bus stop (s)
C_v : coefficient of variation of passenger service time
Z_α : one-tail variate for the normal distribution associated with the probability α that a queue will not form behind the bus stop
N_b : effective number of berths for N actual berths

If there is no a traffic signal close ahead, then (g/C) = 1.0, and St Jacques and Levinson (1997) reported a C_v between 0.4 to 0.6 for passenger service times over 20 seconds.

The HCM offers different values of N_b for linear berths with no overtaking ('on-line') and overtaking ('off-line') facilities. These come from empirical observations at bus terminals in New York and New Jersey. It also states that all other berth arrangements, apart from linear, produce fully effective berths.

The HCM states that passenger service time t_p can have different expressions according to the number and function of the doors:

- boarding only, one-way flow door;
- alighting only, one-way flow door;
- two-way flow through door.

However, these conditions can be summarised in the following equations:

- For one two-way door:

$$t_p = \beta_a p_a + \beta_b p_b \tag{6}$$

- For two one-way doors:

$$t_p = max\{\beta_a p_a, \beta_b p_b\} \tag{7}$$

where:

β_a : alighting time per passenger (s/pass)
β_b : boarding time per passenger (s/pass)
p_a : alighting passengers per bus in the 15-min peak
p_b : boarding passengers per bus in the 15-min peak

To illustrate this model, data collected during a one-hour boarding peak period at a one-berth bus stop in London (Manor House Station) were used. The average data are:

- Bus flow: 22 bus/h
- Boarding demand: 390 pass/h
- Alighting demand: 67 pass/h
- Boarding time: 2 s/pass
- Clearance time: 5 s

In this case, buses have two one-way doors, so (7) applies for the passenger service time. The number of passengers per bus is much higher than the alighting passengers per bus, consequently only the product $\beta_b p_b$ comes to play to evaluate t_p. Thus, from field observations β_b = 2 s/pass, p_b = 21.3 pass/bus, t_c = 5 s, and C_v = 0.63. The HCM advises that one berth is always fully effective, then N_b = 1, and as there is no downstream traffic signal *(g/C)* = 1.0. In addition, the value $Z_{25\%}$ = 0.675 suggested by St Jacques and Levinson (1997) is used

As a result, a capacity of 55 bus/h is obtained. However, an estimation of the actual capacity derived from field studies is 87 bus/h, which is obtained as the reciprocal of the mean occupancy time of the berth during the peak period. In all cases, the parameters of equation (7) have been obtained from field studies. The difference in the results seems to lie in the steady-state condition of the HCM model. This assumes that the arrival rates of passengers and buses are constant during the 15-min peak period of calculation; any variation in passenger service time is considered only as empirical factors. However, in some cases – as in this example – this is not enough to take into account actual dynamic changes over short periods of time. Therefore, the difference seems to be caused by the way in which the HCM formula deals with variations: constant factors do not always reflect reality.

The HCM formula is plain and pragmatic. However, it rests on empirical evidence coming from limited case studies – such as the values of C_v and N_b obtained at bus terminals – to evaluate stop performance. Therefore, the approach is too simplistic to consider a wider range of operating conditions as found at on-street bus stops. This requires a richer view of bus operations at stops. One approach to solve this problem has been to use microscopic simulation models, either to revise the HCM predictions or to calculate capacities.

2.2 Stop capacity under convoy operation

Convoy operation was studied in Brazil as a way of increasing the capacity of a bus lane where many of the principal arterial streets were totally saturated by large volumes of buses which often use more than one lane for overtaking manoeuvres. This presents the following questions:

- At what point it is advantageous to use exclusive bus lanes when the volume is very large?
- How many buses can reasonably be accommodated in only one lane?

Following Szász *et al* (1978), in a bus lane having no traffic signals one bus may pass a given point each 3.5 seconds, which means a 1,030-bus/h capacity. If there are traffic signals, the above capacity should be reduced by the ratio of the effective green to the cycle time of the downstream traffic signal. For instance, if the green time is equal to 50% of the cycle time, a capacity of 515 bus/h can be obtained, which is higher than the normal flow of buses at almost any corridor. Therefore, if traffic signals were the only point where buses stop, one bus lane would be sufficient.

However, as shown in Section 1, the actual critical points of bus lanes are intermediate bus stops. For example, if four passengers board each bus at a rate of 3 s/pass and each bus takes 12 s entering, opening and closing doors, and leaving the bus stop, a maximum capacity equal to 150 bus/h can be achieved unless some action is taken. This was experimented in Brazil by using convoy operations at bus stops (EBTU, 1982).

Convoy operation consists on operating buses similarly to a train, but without being physically connected. Buses travel in a group with short headways between them and stop all together at the bus stop in the order in which they travel. Buses to specific destinations stop at determined berths, so passengers know where to wait on the platform. As a result, passenger transfers takes place at the same time for all the stopping buses. As this is a parallel transference, the passenger service time for all buses is that of the maximum, instead of the sum as would be in the serial case. Under this form of operation, an empirical expression for the capacity of a bus stop is provided by Szász *et al* (1978):

$$Q_C = \frac{3{,}600 - \beta_b B\left(\dfrac{3}{2+N}\right)}{4 + \dfrac{8}{N}} \tag{8}$$

where Q_C is the capacity of a bus stop under convoy operation (bus/h); N is the average number of buses in the convoy (bus); β_b is the boarding time per passenger (s/pass) and B is the boarding demand at the bus stop (pass/h).

This formula comes from experiences carried out in São Paulo where it was found that each bus takes 12 s to arrive and depart. Of this time, four seconds correspond to the minimum headway between successive buses and cannot be reduced. The remaining eight seconds correspond to lost time for bus deceleration entering the stop area, opening and closing doors, and acceleration while leaving the stop area. In a convoy, these processes are assumed to be simultaneous and so this time is divided by the size of the convoy.

Similarly, in convoy operation passengers can board all buses at the same time, so the total boarding demand at the bus stop should be divided by the size N of the convoy to account for the number of boarding passenger per bus. However, it was found that this number is not the same for all buses, and some buses have to await the departure of the bus with the highest demand. Hence, an effective number of buses in the convoy equal to $(2+N)/3$ was introduced to take this into account.

Equation (8) can also be understood as the capacity of a well-organised stop with N linearly adjacent berths. In this view, it is considered that vehicles arrive and depart according to FIFO discipline, and they occupy all available berths. It is assumed that the berth occupancy time is equal for each vehicle, the boarding demand is evenly distributed through each hour, and buses arrive with minimum headway between them.

In such circumstances the capacity Q_c is a linear decreasing function of the hourly boarding demand B. The slope of the function is given by the boarding time per passenger β_b as the only behavioural variable. In Figure 2 an example of this variation in the bus stop capacity is shown for a 3-bus convoy with three different boarding times per passenger.

The formula for the capacity of a bus stop under convoy operation can be applied for a bus convoy of any size. In particular, if the convoy is made of only one bus (N = 1) the formula should reproduce the capacity of a one-berth bus stop. In that case, the formula considers that each bus takes about 12 seconds to arrive and depart, plus β_b seconds per boarding passenger.

To explain the model, the same data obtained at London mentioned above can be entered into (8). Field data also suggest that β_b = 2 s/pass and B = 390 in this case. Replacing these data and N = 1, indicates an absolute capacity equal to 235 bus/h, compared with the 87 buses/h of measured capacity.

As a result, although illustrative, the model to estimate the capacity of a bus stop under convoy operations does not deliver good results in this case. The reason could be found in the constant 12 s that the formula assumes each bus takes to arrive and depart. It seems that as convoy operations was thought to describes the operation of bus corridors under busy conditions, where there are pressures from buses to use the bus stop, the capacity formula tends to overestimate the capacity of a normal bus stop.

2.3 The simulation model IRENE

This approach considers an isolated bus stop with N linear berths and FIFO discipline (Gibson *et al*, 1989). Under these conditions, a bus can enter the stop area only if the last berth is free. The stop area can be in one of only two states:

- Unblocked: The last berth is empty, and a certain number n ($n \leq N$) of buses can enter the stop area at rate s buses per unit of time. The duration of the unblocked period is then n/s.
- Blocked: The last berth is occupied, and no buses can enter the stop area. The duration of the blocked period is assumed to be t_b.

These two states are cyclical, where the duration of the cycle is equal to $n/s + t_b$. During each cycle a number of buses n can use the bus stop. Then the maximum number of buses per hour that can enter the stop area – the capacity – is given by:

$$Q_B = \frac{3{,}600n}{\frac{n}{s} + t_b} \qquad (9)$$

where Q_B is the absolute bus stop capacity (bus/h); n is the average number of buses that can enter the stop area (bus); s is the saturation flow of the lane prior to the bus stop (bus/s), and t_b is the average duration of a blocked period in the last berth (s).

The main concern of this approach is then to estimate t_b and n. In a multiple-berth bus stop the blocked time t_b has three components: a lost time t_l for acceleration and deceleration manoeuvres, the passenger service time t_p linked with passenger transfer operations, and an extra delay t_e. Then:

$$t_b = t_l + t_p + t_e \qquad (10)$$

The lost time t_l can be obtained from kinematic equations. Hence:

$$t_l = \frac{V_r}{\gamma} \qquad (11)$$

where V_r is the running speed of buses (m/s), and γ the harmonic mean of the acceleration and deceleration rates of buses (m/s^2).

The estimation of the passenger service time t_p can be done with the same type of model (6) and (7) suggested by the HCM. A more general specification of those models after Gibson *et al* (1989) is:

$$t_p = \beta_o + max_m \left\{ \beta_a p_{am} + \beta_b p_{bm} \right\} \tag{12}$$

where:

β_o : dead time per stop -opening and closing doors, etc.– (s)
β_a : alighting time per passenger (s/pass)
β_b : boarding time per passenger (s/pass)
p_{am} : alighting passengers per bus by door *m*
p_{bm} : boarding passengers per bus by door *m*

The extra delay t_e arises when a bus has completed its transfer operations but cannot leave its berth because of restrictions imposed by other vehicles. This could be caused by the blocked time of the downstream berth in a multiple-berth bus stop with no overtaking facilities, or the time searching for a suitable gap in the adjacent lane if overtaking is possible. In the case of a one-berth bus stop it can be the time during which the exit of the stop area is blocked by a downstream traffic signal or by queues of vehicles generated by that signal. Otherwise, if the exit from the berth is free of obstructions t_e is equal to zero.

Values of t_b and n are dependent upon all factors influencing the use of existing berths. Among them, Gibson *et al* (1989) identify the following:

- definition of the stop area and platforms (well-specified or not);
- berth configuration (linear or other layouts);
- use of berths (specific for particular services or not);
- character of the stop (compulsory or request);
- entry and exit discipline (FIFO or overtaking allowed);
- fare collection method (in-vehicle or not, passes or in cash);
- vehicle characteristics (internal space, number and use of doors);
- downstream junction (if it affects the bus stop or not).

In addition, under informal or chaotic operations, a bus can stop more than once inside the bus stop. This can be observed in developing countries where the stop area is not well defined or the capacity decreases in relation to demand. As a consequence, bus queues begin to form and passengers begin to occupy space away from their waiting points and each vehicle could stop more than once in a disorderly boarding area. Therefore, the number of stops inside the stop area is another factor that influences the values of t_b and n.

As a result, Gibson *et al* argue that this is a complex stochastic process as bus and passengers arrivals, as well as the number of stops at the bus stop, are stochastic elements. Therefore, they chose microscopic simulation to calculate Q_B, because analytical models can only be applied to very limited cases, as noted above with respect to the HCM approach. The result is the simulation program IRENE.

Using IRENE the capacity for the London bus stop described above can be obtained. Thus, for the same data and parameters applied before, the resulting capacity is $Q_B = 78$ bus/h. This result is 42% greater than the value obtained from the HCM formula.

However, the result is almost 90 percent of the observed capacity. The reason for this similarity lies in the way in which the simulation considers the bus stop interactions. These are represented in a more flexible way than in the analytical formulae.

2.4 The simulation model PASSION

It can be seen that, for the same data set, there are differences between predicted and observed capacity. The differences can be caused by the flexibility with which each model considers the interactions between buses and passengers. It seems that, in this case, analytical models cannot satisfactory cope with the dynamics or transient effects at stops. Therefore, it is not strange that the simulation approach, which considers many more behavioural factors than steady-state formulae, produces better answers in comparison with measures of the real system. Thus, a new model to describe stop interactions is presented in this Section (see Fernández, 2001b).

2.4.1 Model overview

This model is called **PASSION** for **PA**rallel **S**top **S**imulat**ION**. It should be noted that the expression ‘parallel’ in the name of the program does not mean any particular computing architecture, but the concurrent nature of the interactions that are modelled. PASSION is an elemental simulator built as a virtual laboratory to experiment with a simplified version of the system under study: **a one-berth stop area, its adjacent platform, and its immediate traffic restraints**. The aim of PASSION is to reproduce the behaviour of this system under different cases of vehicle and passenger arrivals, and exit conditions. Figures 3 and 4 show the flowcharts of the main parts of the model. It is postulated that the fundamental nature of PASSION will act as the base for modelling more complex cases, such as multiple stops and transit corridors.

PASSION is able to provide information about the occupancy of the berth and the platform due to various causes. This can allow the modeller to obtain a proxy of the capacity of the stop, delays to vehicles for different reasons (passengers, internal congestion, queues), and upstream queues. For the platform, it is possible to obtain the number of passengers waiting for different services and their waiting times. These outputs should enable the user to discover the influence of diverse external conditions on the performance of stops. Then, this knowledge can be used to derive operational rules to improve the stop efficiency.

To meet these requirements the program is able to support many arrival patterns of vehicles and passengers, and exit conditions. For example, constant headways, random headways, scheduled arrivals, several lines with different frequencies, and vehicle bunching. For the passengers, distinct patterns of arriving passengers could be generated. For instance, uniform arrivals, random arrivals, or following a certain order set by other activities (e.g., arrivals from other stops or stations). In addition, the exit from the stop area can be completely free or partially obstructed by traffic conditions. In the latter case, the exit can be controlled by a traffic signal or blocked during a certain time by other vehicles ahead or in the adjacent lane,

The data for simulation consist of a list of the parameters for the simulation (simulation period, clearance time, and dead time), arrays of arrival times of vehicles and passengers at the stop, plus other characteristics. These are, for each vehicle and passenger, the following:

- vehicle route;
- number of passengers alighting from the vehicle;
- marginal alighting times for the vehicle;
- spare capacity of the vehicle
- blocking times of the stop area (if any).
- desired route of each passenger; and
- marginal boarding times of each passenger.

The user generates these arrays in a spreadsheet, which is the input file for the program. The proper use of a spreadsheet allows the user to test any combination of vehicle and passenger arrival patterns and sequence of characteristics, without limiting the inputs to a random generation with a particular distribution.

With the data supplied in the input file the program sorts the arrivals and calculates the mean values of flow and demands resulting from the arrivals during the simulation period. Deviations from these mean values are also computed. Deviations and means are used to show the behavioural irregularities of operations at the bus stop and how busy the bus stop is, on average, during the simulation period. For example, a mean flow can indicate that buses arrive every three minutes, but a deviation of two minutes in the headways indicates that bus bunching is probable. Equation (13) shows the way in which PASSION calculates the deviations of bus and passenger arrivals.

$$SD_k = \sqrt{\frac{\sum_{i=1}^{N_k}\left(\bar{h} - h_k\right)}{N_k - 1}} \qquad (13)$$

where:

SD_k : standard deviation of inter-arrival times of entity k (buses or passengers)

N_k : number of entity k present in the simulation

h_k : inter-arrival times of entities k (s)

$\bar{h}$: mean headway of entity k (s), where

$$\bar{h} = \begin{cases} \dfrac{3{,}600}{q_b}, & for\ buses \\ \dfrac{3{,}600}{B}, & for\ passengers \end{cases}$$

q_b : average stopping bus flow during the simulation period (bus/h)

B : average boarding demand during the simulation period (pass/h)

Next the program estimates the effects on buses and passengers by matching the sequence of bus and passenger arrivals. For passengers, every time that a bus arrives the number of waiting passengers is computed from the sorted sequence of arriving passengers. Then, the bus route for which each passenger on the platform is waiting is checked. This determines the number of boarding passengers for that bus and the waiting times for these and the remaining passengers.

Every time that a bus arrives, the existence of other buses at the stop area is checked. If another bus is found, the bus remains in a queue without transferring passengers until the berth is cleared and the queue length and delay in queue are calculated. Otherwise, the bus occupies the berth and the passenger transfer operations take place. Each bus brings its corresponding number of alighting passengers (as generated in the input file). This number can be the mean alighting rate per bus or a variable number around this rate randomly generated in the input spreadsheet. The number of boarding passengers is taken from the passenger function matching the bus and passenger route.

a) The passenger service time model

The interactions between buses and passengers at a bus stop are represented by the passenger service time (t_p). This is the time that takes a bus to perform the boarding and alighting operations. Many authors have found that a linear relationship between the passenger service time and the number of boarding and alighting passenger per bus fit well field observations (Cundill and Watts, 1973; TRB, 2000; Pretty and Russell, 1988; Gibson *et al*, 1989; Tyler, 1992; York, 1993; Lobo, 1997):

$$t_{pi} = \begin{cases} \beta_o + max\left\{ \sum_{j=1}^{p_{bi}} \beta_{bj} ; \beta_{ai} p_{ai} \right\}, \text{parallel operations} \\ \beta_o + \left\{ \sum_{j=1}^{p_{bi}} \beta_{bj} + \beta_{ai} p_{ai} \right\}, \text{sequential operations} \end{cases} \tag{14}$$

where:

- t_{pi} : passenger service time of the bus *i* (s)
- β_o : average dead time per stop (s)
- β_{bj} : marginal boarding time of passenger *j* (s)
- p_{bi} : boarding passengers to the bus *i*
- β_{ai} : marginal alighting time from the bus *i* (s)
- p_{ai} : alighting passengers from the bus *i*

In (14) two sources of variability in the boarding time are introduced, per passenger type and per bus type. The first source of variability can, for instance, be included in the input file generating a boarding time for each arriving passenger from a distribution (e.g., uniform). The second source of variability can be incorporated through the bus route, assuming a homogeneous fleet for each route; this can provide the range of the aforementioned distribution. Other ways of providing the β_{bj} values could also be used, such as the mean marginal boarding time for all passengers, producing a total boarding time equal to $\beta_b p_b$, as in (6) or (7).

The alighting time, on the other hand, supports only one source of variation. This is by bus type, because the model does not consider each alighting passenger as in the case of boarding passengers. This is done in the input file through the bus route, using the same average value for each bus of the same route (same fleet). As the alighting operation is easier than the boarding one, this assumption infers that all the difficulty rests in the features of the alighting facilities of buses. Otherwise, a constant average value for all buses can be assumed, given a total boarding time equal to $\beta_a p_a$, as in (6) or (7).

Other times generated by the bus-bus and bus-traffic interactions are added to the passenger service time to compute the occupancy time; i.e., the total time spent at the berth. This is shown below.

b) The occupancy time model

The occupancy time model is applied to calculate the bus delay at the berth. The occupancy time model is made of a constant clearance time, a deterministic passenger service time model as shown above, and an extra delay model based on the state of the exit from the stop area. The latter can be deterministic or stochastic depending on the type of phenomenon that controls the exit.

The extra delay model computes the time during which a bus, having completed its transfer operation, cannot leave the berth because of restrictions imposed by other traffic. Three mutually exclusive exit conditions from the berth are considered; these are:

- the exit is free;
- the exit is controlled by an immediate downstream traffic signal; or
- the exit is temporary blocked by other vehicles.

In both cases, free exit and traffic signal, the extra delay model is deterministic. In the first case, the extra delay will always be constant and equal to zero. For the traffic signal case, the time at which the bus is ready to leave is compared with the state of the traffic signal, given the timings supplied as data. If at that time the signal is red the bus remains in the berth until the green time starts, and the corresponding extra delay is computed. Otherwise, the extra delay is set to zero.

In case that the exit is temporary blocked by other vehicles, a blocking time can be randomly generated using any distribution describing the time that takes the blocking vehicle to complete its task. Law and Kelton (1991) offer a summary of such distributions (e.g., Gamma, Weibull, Lognormal, and Pearson). This is the case when the exit is temporarily blocked by another bus transferring passengers ahead or due to junction tailback. The probability of the downstream obstruction and the average blocking time, are data that can be obtained from field information or from a previous run of the model.

There is another case for the occurrence of obstructing exits. It is the case when a bus is trying to pull out from an off-line bus stop (a bus bay stop or a kerbside stop between parked cars). In that case, the obstruction is produced by the traffic in the adjacent lane while the bus is waiting for a suitable gap to re-enter to the traffic stream. An approach to estimate this suitable (critical) gap to perform this procedure can be found in Armitage and McDonald (1974) and McDonald and Armitage (1978). The gaps in the adjacent lane can be randomly obtained from an assumed distributions of headways (see Plank and Catchpole, 1984; Hagring, 1998; or Brilon *et al*, 1999 for a review). Thus, every time that the headway is less than the critical gap of buses, a blocking time until the next suitable gap is produced. The model uses an internal procedure to replicate this with the following Cowan's M3 distribution (Cowan, 1975):

$$F(h) = \begin{cases} 1-(1-\theta)e^{-\gamma(h-\tau)}, \text{ if } h \geq \tau \\ 0 \qquad\qquad\qquad\quad, \text{otherwise} \end{cases} \tag{15}$$

where:

F(h) : distribution of headways
h : headway

γ : arrival rate of vehicles
τ : minimum headway between vehicles
θ : proportion of vehicles arriving in batches

c) The bus stop capacity model

Bus stop capacity is obtained from the previous models. Capacity is calculated as in the IRENE model for a one-berth bus stop, according to (9) and (10); that is:

$$Q_b = \frac{3{,}600}{\frac{1}{s} + t_l + t_p + t_e} = \frac{3{,}600}{t_c + t_p + t_e} \tag{16}$$

where Q_b is the bus stop capacity (bus/h); $t_c = t_l + 1/s$ is the clearance time (s); t_p is the passenger service time (s), and t_e the extra delay (s).

According to other authors (Szász *et al*, 1978; TRB, 2000; Gibson *et al*, 1989), the clearance time t_c (the average minimum time between one bus leaving the berth and the following bus entering) can be deemed to be made of the time spent decelerating and accelerating at the bus stop (t_l) plus the time needed to run through the bus stop ($1/s$). Both components are functions of the vehicle type. The acceleration and deceleration processes depend on the average running speeds and the acceleration and deceleration rates (see 11), and the time needed to run through the bus stop depends on the minimum headway between vehicles (the inverse of the saturation flow of the bus stop lane). Thus, for a bus stop serving similar types of vehicles (e.g., double-deckers), it can be consider a constant during simulation. Therefore, PASSION calculates the capacity of a one-berth bus stop as:

$$Q_b = \frac{3{,}600 N_b}{t_c + \sum_{i=1}^{N_b}\left(t_{pi} + t_{ei}\right)} \tag{17}$$

where:

Q_b : capacity of the bus stop (bus/h)
N_b : number of buses present in the simulation
t_{pi} : passenger service time of the bus i (s)
t_{ei} : extra delay for the bus i (s)
t_c : constant clearance time (s)

It should be noted that the capacity estimated with (17) is an approximation of the absolute capacity of the bus stop. It is generally agreed in the traffic-engineering field that the capacity is the inverse of the minimum headway between vehicles *when there is a queue trying to use a road device*. However, in our case queues are not a common situation, unless the bus stop is saturated during the whole simulation period. If that were the case, the estimation of the capacity would be reduced to a few observations. Therefore, it was decided to estimate the capacity with all the buses present in the simulation, representing the particular structure of bus and passenger arrivals. This strategy is similar to that used in the HCM via the factor C_v that reduces the capacity to account for variations in passenger service times at the bus stop (St Jacques and Levinson, 1997). However, if the absolute capacity is wanted, the bus flow and passenger demand can be scaled until full saturation is achieved for the whole simulation period; i.e., the resulting mean queue length is grater that one.

From the estimation of capacity in the above manner, the degree of saturation of the bus stop can be obtained as:

$$x_b = \frac{q_b}{Q_b} \tag{18}$$

where x_b is the degree of saturation of the bus stop; Q_b is the average capacity of the bus stop during the simulation period (bus/h), and q_b is the average stopping bus flow during the simulation period (bus/h).

The degree of saturation is used to estimate how busy is the bus stop and it is a key index to design bus stops; i.e., to estimate the number of stop points and berths required for a given combination of bus flow and passenger demand.

d) Models for other performance indices

Having finished the analysis of the interactions between buses, passengers, and traffic, the program calculates some statistics derived from the simulation, as depicted in Figure 5. The mean queue length at the bus stop is calculated in the traditional traffic-engineering manner; i.e., it is equivalent to the rate of delay per time unit:

$$L_q = \frac{\sum_{i=1}^{N_b} L_{qi} d_{qi}}{T} \tag{19}$$

where:

L_q	: mean queue length at the bus stop in (bus-s/s) or (bus)
L_{qi}	: number of buses in queue found by the bus *i* (bus)
d_{qi}	: time in queue experimented by bus *i* (s)
T	: simulation period (s)
N_b	: number of buses present in the simulation

In this case, the maximum queue length during the simulation is given by $max\{L_{qi}\}$ and the standard deviation is calculated in the traditional manner.

The mean queue delay of buses has different components, but all of them have similar expressions for calculation. The components are delay for passengers, extra delay, delay in queues, and total delay. Thus, the mean delay for any of the aforementioned causes is given by:

$$D_k = \frac{\sum_{i=1}^{N_b} d_{ik}}{N_b} \tag{20}$$

where D_k is the mean delay to buses for cause *k* (s/bus); d_{ik} is the delay of bus *i* for cause *k* (s), and N_b is the number of buses present in the simulation.

The average waiting time of passengers has the same sense as that used for many authors to describe the level of service of a public transport system (see for instance Holroyd and Scrags, 1966). In the case of PASSION, this is obtained from the simulation as:

$$AWT = \frac{\sum_{j=1}^{N_p} w_j}{\sum_{i=1}^{N_b} k_{pi}} \quad (21)$$

where:

AWT : average waiting time of passengers (s/pass)
w_j : waiting time of passenger j (s)
k_{pi} : number of passengers on the platform when the bus i arrives (pass)
N_p : number of passengers present in the simulation
N_b : number of buses present in the simulation

The mean number of passengers on the platform is different to the traditional average number of customers in a queue waiting for service. On the contrary, it is the average number of passengers on the platform when a bus arrives and it is calculated as an approximation of the platform density, if the area of the platform is known, for design purposes. Thus:

$$K_p = \frac{\sum_{i=1}^{N_b} k_{pi}}{N_b} \quad (22)$$

where K_p is the average number of passengers on the platform (pass); k_{pi} is the number of passengers on the platform when the bus i arrives (pass), and N_b is the number of buses present in the simulation.

For all the above performance indices the maximum value is given by $max\{x_i\}$, where x_i are the observed values of index x during the simulation, and the standard deviation is calculated in the traditional manner.

Finally, the deviation of the exit times of buses from the bus stop is calculated in the same way as in (13), but for inter-departure times. The objective is to have an equivalent of the perturbation that the bus stop produces on the average bus headway.

2.4.2 Application of the model

The same data and parameters used before were applied to PASSION in order to estmate capacity. As a result, the estimated capacity was 86 buses per hour, which is almost the same as that observed. This is not extraordinary, as PASSION is replicating exactly the actual sequence of bus and passenger arrivals at the stop – and therefore the interactions at that stop – at the cost of a detailed description of the input data.

To summarise, Table 1 shows the predictions from the different models discussed above for the same data set and parameters collected at the one-berth bus stop at Manor House Station in London. This example shows good agreement between capacity predictions from the simulation models (IRENE and PASSION) in comparison with those coming from analytical formulae. Obviously, this only example is not enough to validate the simulation models. However, this has also been done elsewhere (Gibson *et al*, 1989; Gibson, 1996a, b; Fernández, 2001a).

2.5 Integration to transit corridors

The corridor models of the kind discussed in Section 1, can be considered as a supplementary question of the stop operation problem. In fact, while a more precise stop interaction picture is provided, a more accurate representation of the progression of a transit vehicle along its route can be obtained, and vice versa. Indeed, as Tyler (1992) first and later Dextre (1992) and Lobo (1997) suggest, a better modelling of stop interactions would facilitate the evaluation of the performance of a transit system.

How might a better understanding of stop interactions improve a corridor model? It has been argued above in this paper (Section 1) that stops are the main bottlenecks for transit operations. As a result, a transit progression model can be represented as shown in Figure 6. There, the delays d_s at the nodes – stops – are a function of the capacity Q_s of those nodes, which in turn is a function of the boarding and/or alighting number of passengers per vehicle (p). In addition, this boarding or alighting number p depends on both the passenger demand B for the transit system at each node and the flow q_b on the network. So, $p = B/q_b$. Therefore, an accurate representation of the patterns of demand and flow and the consequences of their interactions at the nodes (d_s) will improve the modelling of a network (or corridor) as shown in Figure 6.

The approach presented in Section 2.4 could supply the aforementioned representation of bus stop interactions. For instance, the possibility of using richer representations of the interaction between passenger demand and bus flow at nodes allow the construction of a detailed exit pattern from each node to be used as the arrival pattern at the following node. This pattern, combined with the passenger pattern at the downstream node, will produce the new exit pattern, and so on. Nonetheless, it would be the scope of further research how to incorporate these and other findings (e.g., junction or link interactions) into a comprehensive transit progression model. A detailed modelling of interactions considering some of these elements has being explored by Silva (2000).

As an example of these extensions, an elemental representation of a bus corridor was developed in a spreadsheet. The system is made of upstream and downstream bus stops, a bus lane connecting the bus stops, and a traffic signal in between, as shown in Figure 6. Each bus stop was modelled with PASSION as suggested above.

The bus lane and traffic signal were modelled in a simpler way for this extension. Thus, the movement through the bus lane is made at a specified uniform acceleration rate until buses reach a given constant speed. Similarly, buses stop at another specified uniform deceleration rate from that constant speed. A fixed-time traffic signal is assumed at the junction with some appropriate cycle time and green ratio.

As a way of illustration, the effect of different boarding times on a bus corridor might be studied with such an extension of the model. This is shown in Table 2 for a bus corridor with 30 bus/h, a boarding demand equal to 300 pass/h at the upstream bus stop and 150 pass/h at the downstream bus stop. The traffic signal has 60-second cycle time and 0.8 effective green ratio for buses. Parameters for the simulation were taken from real data in Santiago, Chile. These are: acceleration and deceleration rates equal to 1.5 and 1.7 m/s^2, respectively; cruise speed of buses equal to 45 km/h; distance from the upstream bus stop to the traffic signal of 235 m, and from the traffic signal to the downstream bus stop of 74 m.

As shown in this example, there was a marked drop in commercial speed of buses as the boarding times increased. The distribution of travel time also changes from a condition in which most of the time (55%) is spent in movement to another in which almost 90% of the time buses are stationary at bus stops. In addition, the congestion at the bus stops – represented as capacities and queue lengths – worsens. All this, despite the most advantageous signal timing for buses suggested by some authors (short cycle time and high green ratio, see Gibson, 1996a). These findings demonstrate the advantages of having a good representation of stop interactions in transit progression models and the contribution that PASSION or IRENE can make to that objective (see Fernández and Peñailillo, 2000; Fernández *et al*, 2000).

3 Example of capacity of different transit systems

In this Section, a comparative analysis based on the passenger capacity (for a reasonable level of service) of two technologies of public transport is presented. The technologies compared are a bus lane or busway for conventional buses, and a LRT system consisting of articulated trams. The data come from a study case in Santiago. These are based on an engineering study for the extension of the only busway in the city. The data can be summarised as follows:

- Bus flow on the corridor : 140 bus/h
- Average boarding rate of passengers : p_b = 4 pass/veh
- Average alighting rate of passengers : p_a = 2 pass/veh
- Running speed between stops : V_r = 40 km/h
- Acceleration rate of vehicles : a = 0,9 m/s^2
- Deceleration rate of vehicles : f = 1,2 m/s^2
- Dead time per stop : β_0 = 1,0 s
- Marginal boarding time : β_b = 3 s/pass
- Marginal alighting time : β_a = 2 s/pass
- Saturation flow of the busway : s = 900 veh/h
- Vehicles have one-way doors.

3.1 Buses on bus lanes or busways

The mean boarding and alighting rates at the corridor and the application of IRENE suggest that a 2-berth stop can provide an absolute capacity equal to 174 vehicles per hour. However, as the bus flow on the corridor is 140, the saturation degree is 0.81 and a mean queue of 1.8 buses will develop upstream the stop area. On the other hand, a 3-berth stop provides an absolute capacity of 225 bus/h with a saturation degree equal to 0.62, so some possibility of queues is still possible (one bus 40% of the time). However, in the instance that a multiple-berth stop is supplied, no more than two adjacent berths are recommended because the gain in efficiency of each additional berth drops sharply (see Tyler, 1982; TRB, 2000). As a consequence, a multiple station made of two 2-berth split stops is preferred. In such a station each stop can easily accommodate almost 105 veh/h for a practical degree of saturation equal to 0.6 (i.e., 0.6 times 174 bus/h); therefore, the whole capacity of the station will be 210 veh/h.

The busway will operate with 12-m conventional 2-door buses with a seat capacity equal to 44 passengers. It is assumed 25% standees; therefore, the mean occupancy of vehicles is 55 passengers. According to the HCM this means a level of service D, for it states that this level is based on local bus operations where short trips at relatively slow speed allow standees. However, the same source states that express bus services on expressways and busways should not allow standees (TRB, 2000).

As a result, the passenger capacity of the busway for conventional buses with 2-berth split stops will be 11,550 pass/h per direction (210 veh/h times 55 pass/veh). Under the same operational assumptions, a bus lane – so that buses cannot overtake at stops – with 2-berth single stops can accommodate almost 6,000 pass/h per direction (105 veh/h times 55 pass/veh). These results broadly agree with Gardner *et al* (1991) and TRL (1993) in which several bus corridors of developing cities where studied. Thus, TRL (1993) states that a standard 2-berth bus stop can accommodate up to 111 bus/h or 7,400 pass/h-direction. However, 4-berth high capacity bus stop can accommodate more than 161 bus/h or 10,600 pass/h-direction.

3.2 LRT with articulated trams

The capacity of an LRT system will depend on the capacity of the transfer stations and the characteristics of the vehicles. For the latter, we assumed the CITADIS 202 of ALSTOM. This consists of a 22-m articulated tram with a seat capacity equal to 44 passengers, the smallest vehicle available in this system, to be compared with a bus. Similar to buses, it is assumed that 25% are standees; therefore, the mean occupancy of these vehicles is 55 passengers.

The capacity of the stop will depend on the number of trams that can simultaneously be attended. In contrast with the busway, it is not practical to provide multiple-berth or split stops along the route, due to the difficulties in overtaking manoeuvres that are common to all rail-based vehicles. Therefore, the system should operate as a one-berth stop station serving one articulated tram each time (as a metro system). However, as the trams have 4 doors, it is assumed that 2 doors are used for boarding and the other 2 for alighting. Thus, the boarding and alighting rates per vehicle will be half of the corresponding to buses.

The application of IRENE to this system indicates an absolute stop capacity of 147 vehicles per hour. This means a practical capacity of 88 veh/h (0.6 times 147 veh/h). Therefore, the whole capacity at the station will be almost 90 veh/h.

As a result, the passenger capacity of the LRT with 22-m articulated trams will be almost 5,000 pass/h per direction (90 veh/h times 55 pass/veh). However, as multiple-berth or split stop stations are not feasible along a tram route (except at terminal stations), the capacity can be increased with longer vehicles. Thus, the transport capacity can be up to 7,500 pass/h if a 43-m long tram is used (see Fernández, 2000).

To summarise, the transport capacity under identical operational assumptions for the bus and LTR systems is shown in Table 3.

4 Design recommendations of transit stations

In this Section, some recommendations for the design of transit stations are given. They come from various simulation analysis made with IRENE and PASSION under different operational conditions (see for instance Gibson and Fernández, 1995; Gibson, 1996a; Fernández, 1999).

Simulation experiments with IRENE have provided capacity values for various combinations of operational variables and number of berths (Gibson and Fernández, 1995). The capacity values derived from these combinations are shown in Table 4 for 2-door vehicles. As can be seen in the table, for given operational parameters, the practical capacity of a multiple-berth stop ranges from 60 to 130 vehicles per hour for 2 berths and 80 to 160 for 3 berths. This confirms that the sole increase in the number of berths does not bring in much benefit. It also shows that disordered behaviour produces a loss in capacity in relation to an ordered operation.

Therefore, as a general rule the practical capacity ranges from 25 to 50 veh/h-berth, tending towards the lower values for higher passenger demands or batch arrivals of vehicles, and vice versa (Fernández, 2001a). This offers a criterion to decide when split stops are required: at that combination of bus flows and passenger demands when a single 2-berth stop ceases to cope. According to this, if a single stop does not provide sufficient practical capacity for the actual flow, a split stop will be required. In such a case, the flow and demand will be split into a number of stop points so that each one has adequate capacity.

This, in some way confirms the London Transport recommendation (LT, 1996) which states that if the flow is greater than 25 veh/h, a split stop should be provided. London Transport, however, does not relate this limit to passenger demand, the probability of queues, or the arrival pattern. However, PASSION suggests that if a split stop is supplied a queuing space of 2 or 3 buses (≥ 24 m) should be provided to avoid eventual obstructions between stop points (instead of the 18.5-m gap recommended by LT, 1996 or IHT, 1997). The layout in this case is shown in Figure 7. This will ensure the independent functioning of each stop point, which are assumed working at half the load.

If a multiple-berth stop is supplied, no more than two adjacent berths are recommended, for the gain in efficiency of each additional berth drops sharply (see Tyler, 1982 and TRB, 2000). In such a case, the possibility of overtaking inside the stop area supplies additional capacity to this layout. This can be provided by means of a short separation between berths. Some engineers suggest (EBTU, 1982) that a distance of 3 to 6 m could help to achieve that objective (see Figure 8).

The application of IRENE (see Gibson, 1996a) and PASSION (see Fernández, 2001b) suggest that vehicles should be able to leave the stop area without interference to attain the above performances. Otherwise, losses in performance of 50% on average can occur. Special facilities should be provided to that end. These can take the form of a boarder, a front-open bay, an overtaking lane, and/or adjusting the timings of the downstream traffic signal. In the latter case, a cycle time of less than one-and-a-half minute and an effective green ratio over 0.6 must be provided according to these authors.

Fernández (1999) suggests that platforms should be able to accommodate the expected maximum number of waiting passengers to avoid interactions with other traffic (pedestrian and vehicles). In IHT (1991), a comfortable density of one passenger per square metre is recommended, because people tend to accept less crowding outside a vehicle than inside. Thus, an area – in square meters – equal to four or five times the number of boarding passengers per vehicle is recommended for the platform. Similarly, shelters should be able to contain at least a number of passengers equal to the boarding rate per vehicle, as this is the mean number of waiting passengers reported in many design runs with PASSION. It is also widely accepted that seating should be provided at bus stops and tram stations. Therefore, it is recommended to provide a number of seats equal to the mean number of waiting passengers; that is, equal to the boarding rate per vehicle. Whatever the size of the stop area, the shelter should be located at the head of the platform to encourage the use of the first available berth.

Finally, a well-designed stop is useless if it is not possible to reach it. Consequently, access facilities should be complemented with accessibility facilities. Among the main components of the accessibility to stops are footways and pedestrian crossings. As an aid to provide fully accessible stops there exist some useful guidelines (see for example IHT, 1991; Tyler and Caiaffa, 1999).

5 Concluding remarks

It has been argued in this paper that the capacity of any transit system depends on the capacity of its bottlenecks. Thus, it was demonstrated that the active constraints in terms of capacity for transit operations are the stops, as junctions and link provide, in general, more capacity than stops. Therefore, as TRL (1993) states, for a occupancy k_b of the vehicles, the transport capacity of a transit system should be evaluated as $Q_s\ k_b$ instead of $Q_j\ k_b$ or $Q_r\ k_b$, where Q_s is the capacity of the stops; Q_j and Q_r are the capacity of junctions and roads, respectively.

The capacity of stops depends on the particular conditions at each stop. Within these. the most important are: frequency of vehicles (flow) and arrival pattern of vehicles; passenger demand and arrival pattern of passengers; and facilities to leave the stop once the transfer operations have finished. Thus, the behaviour of the vehicle flow and passenger demand define the boarding and alighting rates per vehicle. These rates, in turn, determine the capacity and performance of the stop. As a consequence, the capacity of the system will be limited by the capacity of the critical stop at the critical period; that is, the stop in which the boarding or alighting rate is the highest.

The capacity of critical stops can be improved with appropriate design and this paper has provided some recommendations based on simulation studies. However, this design should respond to the particular operational conditions at the stop. These particular conditions will determine physical issues such as:

- the number of berths at the stop;
- the need of single or split stops;
- platform space for passengers and cage dimensions for vehicles;
- overtaking and exit facilities from the stop; and
- comfort, accessibility, and information for passengers.

In summary, the design of stops must regard every physical and operational detail to provide an effective public transport system. Otherwise, the system will not be attractive enough to their potential users

It has been shown that simulation models of stop operations are useful both to estimate stop capacity and as design tools. These models are more flexible to represent particular conditions, so they provide a better estimation of stop capacity than analytical formulae. In addition, simulation models of stop operations can be combined with traffic progression models to simulate route operations. In conclusion, estimating the capacity of transit system should be based on thorough simulation of stop operations, as has been the case of junctions in the arterial design for cars.

This paper has mentioned two simulation models of stop operations (IRENE and PASSION). These models are among the few detailed approaches found in the literature, as scarce attention has been put on stops when designing road-based transit systems. The simulation models discussed in the paper have different scope and have some limitations, but are available to study stop operations within their experimental frame (Law and Kelton, 1991). As a result, the integration with traffic models and with design software seems to be the next necessary step in the analysis of public transport operations on the streets.

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Biographical note

Rodrigo Fernández (CEng, DIC, MSc, PhD) is Assistant Professor at the Transport Division, Department of Civil Engineering, University of Chile since 1992. Previously, he held a similar position at the University of Concepción since 1986. His main research area is Traffic Engineering and within it he has been interested in two topics: (a) modelling and design of public transport facilities (priorities, stops, etc); and (b) estimation and mitigation of the urban impacts of traffic (risk, pollution, noise, severance, etc). He teaches the courses *Traffic Flow Theory* and *Traffic Engineering* to graduate and undergraduate students of the Faculty of Mathematical and Physical Sciences, University of Chile.

Table 1 Bus stop capacities from different methods

Method	Convoy Operation	HCM Formula	IRENE Simulation	PASSION Simulation	Field Observation
Capacity (bus/h)	235	55	78	86	87

Table 2 Simulation of a bus corridor with PASSION

Board Time (s/pass)	Comm Speed (km/h)	Time spent at (%)				Absolute Capacity (bus/h)		Queue Length (bus)	
		Up Stop	Down Stop	Traffic Signal	On the Move	Up Stop	Down Stop	Up Stop	Down Stop
1.0	21	26.8	17.2	0.6	55.4	248	368	0.02	0.01
2.5	15	40.7	22.0	0.4	36.9	123	211	0.12	0.06
3.5	12	45.1	26.1	0.4	28.4	92	162	0.23	0.15
5.0	9	49.4	30.2	0.2	20.2	67	121	0.53	0.44
7.0	6	56.6	29.6	0.3	13.5	49	91	1.33	0.70

Table 3 Transport capacity of transit systems

Transit System	Transport Capacity[1] [pass/h-direction]
Bus lane with 2-berth single stops	6,000
Busway with 2-berth split stops	11,500
LRT with 22-m articulated trams	5,000
LRT with 43-m articulated trams	7,500

[1]: for 25% standees

Table 4 Stop capacities as function of passenger demand[1]

Type of Operation	ORDERED[2]				DIS-ORDERED[3]
Board Rate (pass/veh)	12	8	4	2	8
Alight Rate (pass/veh)	6	4	2	1	4
Number of Berths	PRACTICAL CAPACITY[4] (veh/h)				
2	60	80	100	130	70
3	80	105	125	160	80

[1] Adapted from Gibson and Fernández (1995).
[2] First-in-first-out discipline; vehicles stop once at the berth closest to the exit.
[3] Overtaking allowed; many stops at any place within the stop area.
[4] Estimated for a degree of saturation x = 0.6.

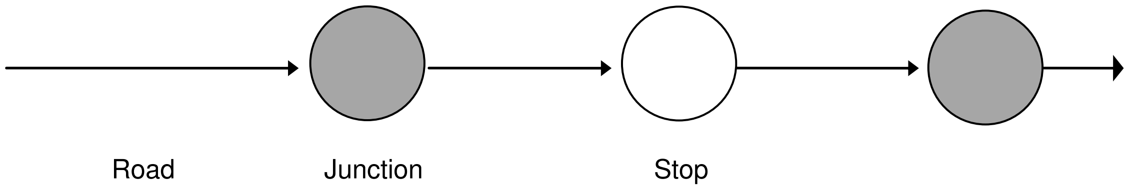

Figure 1 Sketch of physical elements of a public transport system

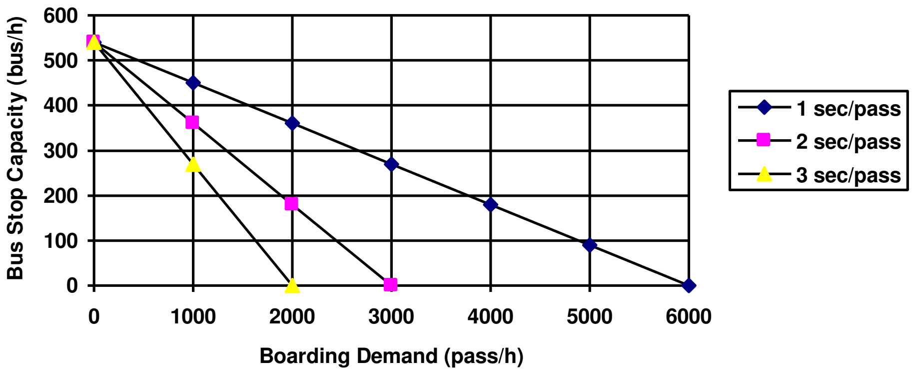

Figure 2 Bus stop capacity for a 3-bus convoy and different boarding times

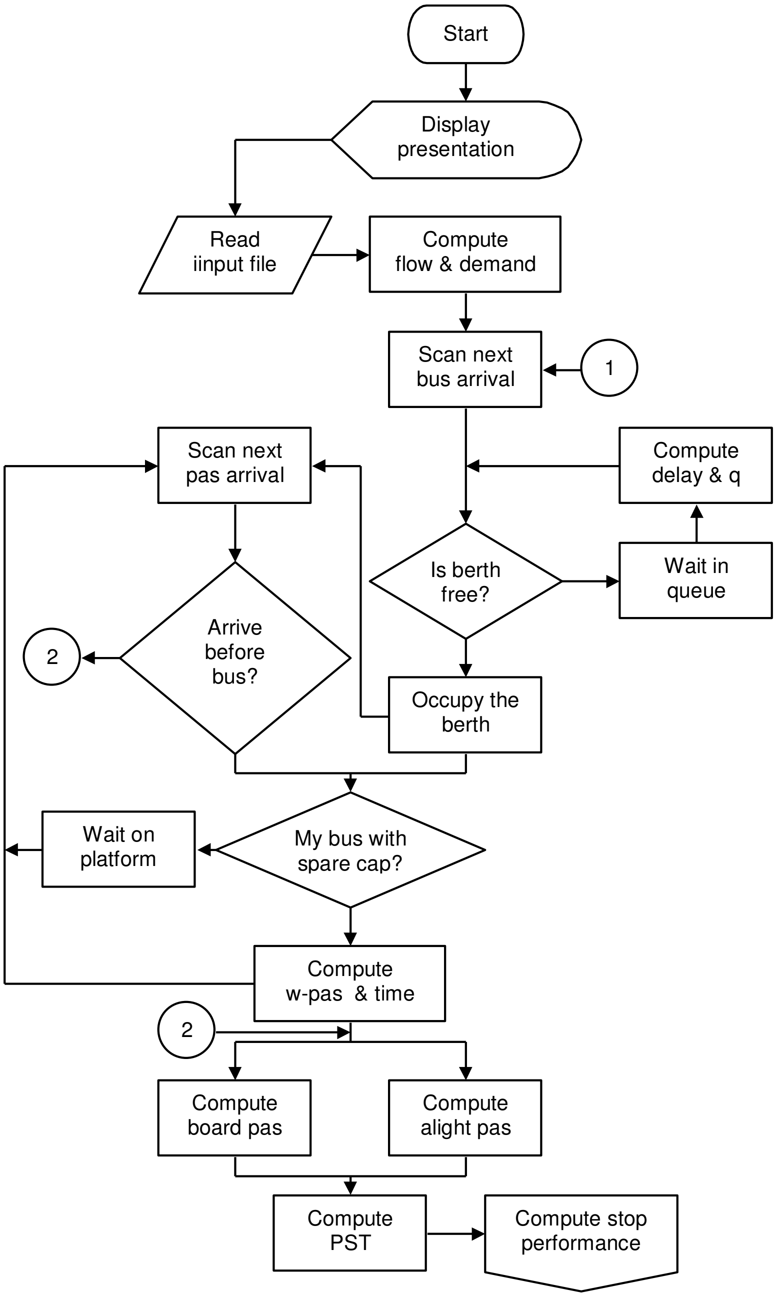

Figure 3 Flowchart to compute Passenger Service Time (*PST*) in *PASSION*

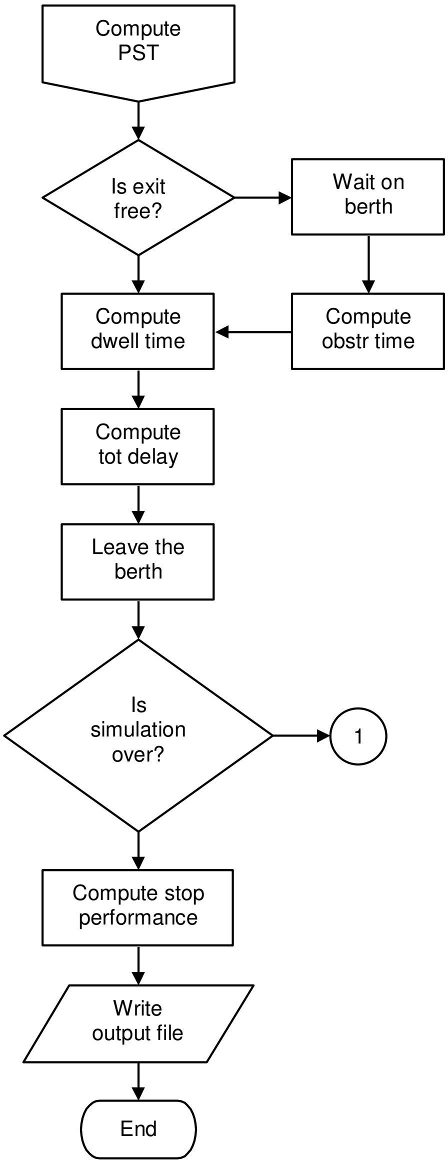

Figure 4 Flowchart to compute bus stop performance in *PASSION*

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

Data  of  this  run:
============
Stop identification            :  xyz_bus-stop
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)
Alighting demand               :   67 pass/h
Two doors, parallel boardings and alightings...
Free exit...

Results of this run:
============
Mean pas waiting time          :    1.62 min   (max:   6.12  sd:    1.46)
Mean pas on platform           :  18.26 pass  (max:  49.00)

Mean bus pas   delay           :  37.01 s/bus (max:  81.23  sd:  28.03)
Mean bus extra delay           :    0.00 s/bus (max:    0.00  sd:    0.00)
Mean bus queue delay           :    4.66 s/bus (max:  69.32  sd:  16.27)
Mean bus total delay           :  46.67 s/bus (max:  86.23  sd:  29.65)

Berth capacity                 :  85.70 bus/h (sat  :    0.26)
Mean bus queue length          :    0.03 buses (max:    1.00)
Exit time deviation            :149.02 s

Queue characteristics:
-------------------------
Queue Freq Q.Time
(bus)   (%)   (s)

   0      89       0
   1      11      44

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 . . .

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 . . .
```

Figure 5 Example of PASSION output

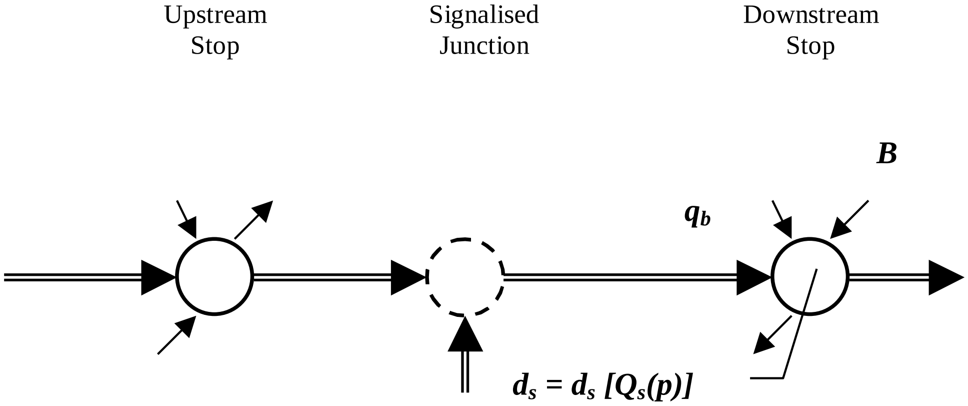

Figure 6 Representation of a corridor model

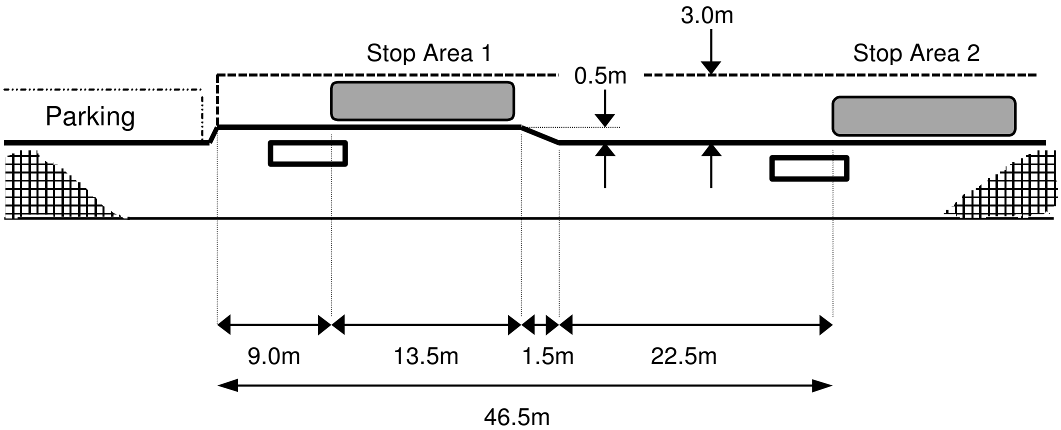

Figure 7 Recommended layout for multiple one-berth bus stops

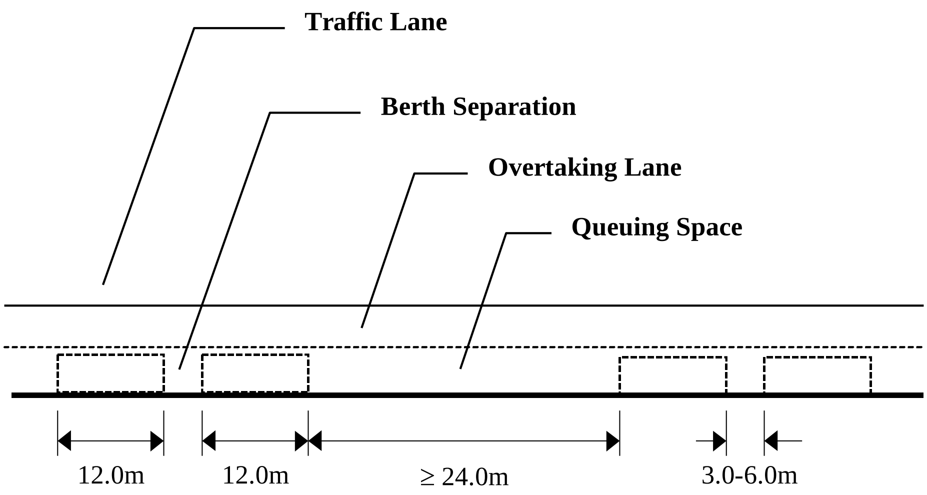

Figure 8 Recommended layout for multiple two-berth bus stops