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Delay at Bus Stops of Transmilenio Transport System According to Parameters Measured "in situ". Case Study Bogotá-Colombia

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Abstract

Paper proposes a dwell-time model at bus stop that predicts transportation capacity of Transmilenio bus system based on operating parameters measured "in situ". This bus system is in continuous development, is part of the Integrated Public Transport System (IPTS) in Bogotá-Colombia and follows reticular trunks structure that interconnecting important points of city ensuring a wide coverage. Measurements are performed on Troncal Norte that experiment high demand for travelers across network, has an approximate length of 9.7 km and stops located every 687 m on average. Operates with high capacity buses (articulated and bi-articulated) that run along exclusive lanes, through to intersections controlled by traffic signals. Field techniques developed and tested in previous works for evaluation of main parameter (dwell-time) and other parameters are used for achieving good results. Calculation methodology is widely known (Transit Capacity and Quality of Service Manual, TCQSM) and allowed to obtain satisfactory results in bus stop delay and capacity on stretch with more passengers. Data are collected in weekdays on board of different buses and from stops with more demand, being 2013, reference date of the results obtained.

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Keywords: public transport; transmilenio; dwell-time model; delay at bus stop; capacity.

1. Introduction

Public transport systems are a key element to improve mobility in medium and large cities. In many cases, allow to reduce travel time by using for example; a road network particularly suited to the city, as is Bogotá case, where two lanes in each direction are used by high capacity buses. A main parameter used to monitor lines functionality,

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which will maintain an adequate service quality, is the capacity. In other words: maximum passengers number that can be transported with reasonable certainty along a stretch or critical route section, during a given period of time under specific operating conditions, without delays, restrictions or unforeseeable risks are experienced (Kittelson et al., 2003) .

The public transport capacity is affected by boarding and alighting passengers at each stop, bus stop design, and bus interference with other traffic, as aspects of mayor consideration. Transmilenio is part of the Integrated Public Transport System which includes; cycle routes network, train and subway line, projected in the future. The system consists of articulated and bi-articulated buses with stops arranged along exclusive corridor, key elements that make it, a bus rapid transit system. The network is trunk-fed, high bus platform and stops have person access control, which allows ticket payment before boarding. In general, there is double lane in each direction which allows overtaking at bus stop and express service. The capacity calculation methodology used is contained in TCQSM, specifically focused on bus analysis operating in exclusive lane. Collected data in Troncal Norte allows capacity adjustment through of time model by boardings and alightings at stops in peak hours. Thus, new curves specify not only maximum value under high demand, but also variation range associated to other critical parameters that may be useful for study of new routes or similar. Model allows knowing offered capacity and top values according to demand. The values obtained are compared with data from previous research conducted in same transport system and same stretch with more demand (Reilly & Aros-Vera, 2013).

2. Literature Review

Bus operations hit a critical point when demand rises: lower reliability, decreases in speed, and increases of travelers' load (Ryus et al., 2003). When passengers transfer between buses at a bus stop, the buses involved can interfere with other buses in such a way that the capacity of the stops is restricted, a situation that can lower the service quality in bus systems (Fernández & Planzer, 2002; Gibson et al., 1989). The use of articulated buses provides 50% more capacity than conventional buses, and a recent study indicates a capacity of 7200 passengers/h per lane (Martinelli, 1996; Zamorano et al., 2006). However, this capacity is estimated according to available space inside the bus and a minimal interval between vehicles; this capacity ignores the dwell time at each bus stop. This dwell time at stops is a key element when considering bus operations. According to the most widely used methodology, a linear dependency is considered, with a fixed service time per passenger (Kittelson et al., 2003). Gardner et al. (1991) verify that irregularity in the number of boarding passengers causes great dwell time variability; they also use a linear model to confirm that the time for boarding passengers is greater than the time needed for alighting. If passengers pay their fares on board, the delay in the boarding process tends to be even greater. If the number of passengers boarding is low relative to the space available to board the bus, the time needed for boarding will also be low, and it can be considered to be constant. However, if access to the bus is crowded by passengers, the boarding time increases rapidly because of the resulting restriction in the normal entry process. Because of this phenomenon, the dwell-time relation is likely to follow a nonlinear relationship, which justifies this additional research.

Levinson (1983) showed that dwell time was an important parameter that affects service quality, and he developed a linear model using a constant proportion related to the number of boarding passengers in a stop, which seems more consistent. According to Chien et al. (2000), dwell time is determined mainly by the passengers' activities at every bus stop. Lobo (1997) determines that the bus stop time is approximately half of the trip time between terminal points, which represents a considerable value. Fernández and Planzer (2002) confirm that bus stops are where the greatest proportion of trip time is lost, and they conclude that these stops constitute the main bottleneck in bus operations. Bertini and El-Geneidy (2004) consider dwell time to be a parameter that affects trip times in bus routes; they propose to obtain the lost time at stops using a linear model based in boarding and alighting passengers, both in combined and separated form. The dwell-time model used in the estimation of trip time show a low correlation coefficient due to the existing high dispersion.

Highway Capacity Manual (HCM, TRB, 2010) defines the capacity in the access to an intersection as maximum number of vehicles per hour that can traverse and this represents the inverse of average interval between vehicles when there is queue at the access, being implanted thus a specific model of capacity. Gibson et al. (1989) indicate that bus stop capacity is determinant in the performance of public transport, and they express, a similar definition as “maximum number of vehicles per hour that can enter to loading area”. However, this capacity is not associated only to an average interval between vehicles in queue at the bus stop entry, but must consider the dwell time due to passenger transference at bus stops. Levinson (1983) suggested that public transport system performance could improve if a minimal number of stops were designed. Another interesting study of the bus dwell-time is realized by Jara and Gschwender (2003b), who take in account the passengers' congestion to estimate the time at bus stop.

Analytic tool for performances analysis of BRT systems had been carried out, where dwell time at bus stops includes both lost time for doors to open and close and lost time for passengers to alight and board. Instead, vehicle’s waiting time at traffic light approach ends when signal turns green. It is assumed that a bus stop platform allows one vehicle’s operation at a time to happen. Therefore, if the platform is already occupied by a vehicle, the following must wait. Alighting and boarding time has been set to one second per passenger (Ancora et al., 2012). Li et al. (2012) introduce the conflict between passengers boarding and alighting into your model and conclude that the proposed nonlinear model can better predict the dwell time at BRT stations.

Zhang and Teng (2013) explain that the dwell time usually takes a large part of bus travel time and the large variability in dwell time always makes accurate prediction of arrival time difficult. The dwell time model established in this paper not only includes the number of passengers boarding and alighting, but also considers secondary factors like crowding and fare type. Collection method, service mode, capacity restriction and occupancy of the vehicle are all taken into account in the model. However, inclusion of other factors like service type, capacity limits, fare collection methods, crowdedness in-vehicle, will increase the Accuracy of the bus dwell time prediction. Better representative distributions of passenger arrivals at bus stops could be attempted instead of the implied uniform distribution. What’s more, according to the characteristic of different stations, the parameters of stations can be set separately. And in the observation, other factors such as bunching phenomenon can affect the dwell time. The modify items for these factors can be added in the model in the future research.

3. Public transport system tested

Transmilenio is a widely known system in the world. On 18 December of the year 2000, begins operations and since then its new trunks and high capacity, it has become in the largest Bus Rapid Transit. Today is a world reference and has made that bus is considered a mode that can carry lots of passengers in urban areas. Transmilenio connects neighborhoods and main roads in the Bogotá city and its infrastructure consists in: *main routes* of two exclusive lanes inserts on major roads; *stations or stops*, designed to facilitate quick and easy access to passengers, only points of passengers transfer, closed and covered spaces that has lockers for sale ticket before boarding. Pedestrian accessibility to the stop is secured with traffic signals, bridges or tunnels. Stop platform is over-high to level of the bus floor, allowing fast operation, especially for person with low mobility. Some stops have been adapted to bi-articulated bus used in express service. The fare is integrated with feeder services and has different means of payment; *Infrastructure*, allows to monitor permanently the operation of each bus, making it possible to control speed, frequency, schedules and itineraries, allowing adequate provision service in each trip. Each vehicle is equipped with three key elements: GPS receptor that reports bus location, on board computer to transmit operating information to the control center, and a communications system (Terrestrial Trunked Radio) by which sends and receives information to better operation control. This monitoring is based not only on operational control but also provides statistical parameters for helping to the management.

4. Stretch with more demand

It has an approximate length of 9.7 km, consists of 13 single stations; a line header "Portal del Norte" and the other extreme, station intermediate "Los Heroes". Stops are spaced 687 m on average, there is only one level intersection controlled by fixed time traffic signal between station "Los Heroes" and "Calle 85". It has two u-turn; located in "Alcalá" and before "Portal del Norte". See Fig. 1.

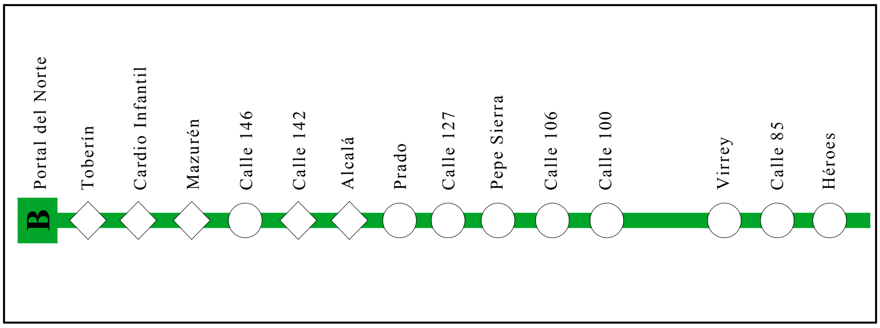

Fig. 1. Study stretch in Transmilenio, Troncal Norte green line.

Transmilenio combines the use of bi-articulated and articulated buses along their lines depending of peak hours, where increases the count and its frequency, the express lines come into operation with bi-articulated buses with capacity up to 250 passengers. Each stop has information service to help you choose best trip and reducing the transfer time, the station staff assists persons with reduced mobility. The bus driver is trained and at each station there is a guidance system that allows the parking maneuver, ensuring fit perfect of bus to the platform without using another accessory for quick passenger access to the vehicle and safe form.

5. Methodology and data capture

The calculation methodology is widespread, has a greater scientific support that can be seen in TCQSM and is developed from basic capacity model obtained at intersection approach (HCM, 1985 and 1994). Thus, the load area capacity can be calculated. See Equation 1. If increases effective green time ratio, stop capacity augment too. For exclusive lanes this effective green time ratio takes value one. According to literature 25 % of failure rate is recommended for estimating capacity (Jacques & Levinson, 1997), and this probability is function of admitted failure rate if data fits a normal distribution. Variability coefficient is determined as the standard deviation over average dwell-time.

$$B_s = B_l \cdot N_{el} = \frac{3600 \cdot \left(\frac{g}{C}\right)}{t_c + \left(\frac{g}{C}\right) \cdot t_d + Z \cdot C_v \cdot t_d} \cdot N_{el} \qquad (1)$$

Nomenclature

Bs	bus stop bus capacity (bus/h)
Bl	loading area bus capacity (bus/h)
g/C	effective green time ratio
tc	clearance time (s)
td	average dwell-time (s)
Z	standard normal variable corresponding to a desired failure rate
Cv	coefficient of variation of dwell-time
Nel	number of effective loading areas

For data collection were necessary using field techniques, in order to obtain actual delay by boardings and alightings at stop, taking into account through visual observation parameters that may affect capacity calculation and thus better understand behavior. We designed forms in order to collect the passengers number that boarding and alighting at a certain time, and took note of all spent time in the process; doors opening, doors closing, arrival and departure of the bus, and other data required, in particular incidents. Typical bus stop it shows in Fig. 2. For data registration was necessary two people who are located within the stop in front of the doors, the objective is to see in more detail the passengers number in each operation, to capture disruptions and the all process time.

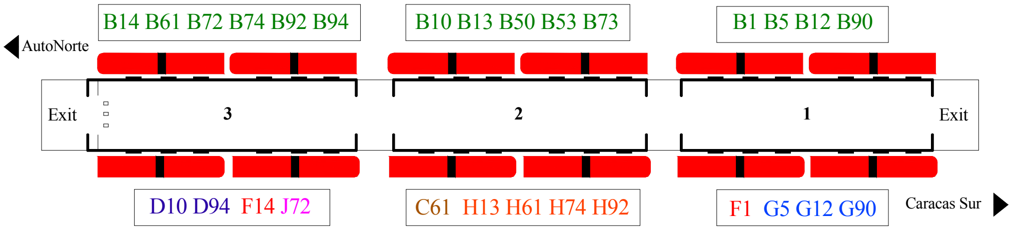

Fig. 2. Typical bus stop in Calle 100 (AutoNorte - Caracas Sur), two berths available by line.

6. Sampling and statistical analysis

In order to obtain highly representative data and a good result in the general model determination, was carried out sampling in order to save time and costs. Equation 2 is applied and the sampling was done in two phases: first, to define dispersion of the main parameter, and second, bring the error to acceptable values by expanding sample. Minimum size “n” and maximum error “e” are obtained by applying normal distribution for a 95% confidence level, considering a good percentage of observations. See Table 1.

$$n = \frac{3{,}84 \cdot S^2}{e^2} \tag{2}$$

Table 1. Sampling in two-phase.

Description	Troncal Norte	Phase
Parameter	td (s)	
Maximum error "e"	± 4,4	1
Observed deviation "S"	± 8,9	1
Minimum size "n"	16	1
Final sample "n"	565	2
Deviation "S"	± 5,99	2
Absolute error "ea"	± 0,5	2
Relative error "er"	± 0,02	2

The quadratic model represents best the net time by passenger flow that the linear model, under normal operating, i.e., without outliers. The p-value less than 0.05 in the quadratic coefficient thus determine it, there is a statistically significant relationship between the net time by boardings / alightings and number of passengers in transfer with a confidence level of 95 percent. See Fig. 3 and Table 2. R-squared indicates that the model explains 64.57% of the variability in the net time by boardings and alightings. Statistical adjusted r-squared, which is more appropriate to compare models with different number of variables is 64.44%. Estimated standard error shows that the standard deviation is 2.66, within tolerable limit. The mean absolute error is 2.14, and the Durbin-Watson statistic explores the residuals to determine significant correlation based on the order in which they are presented.

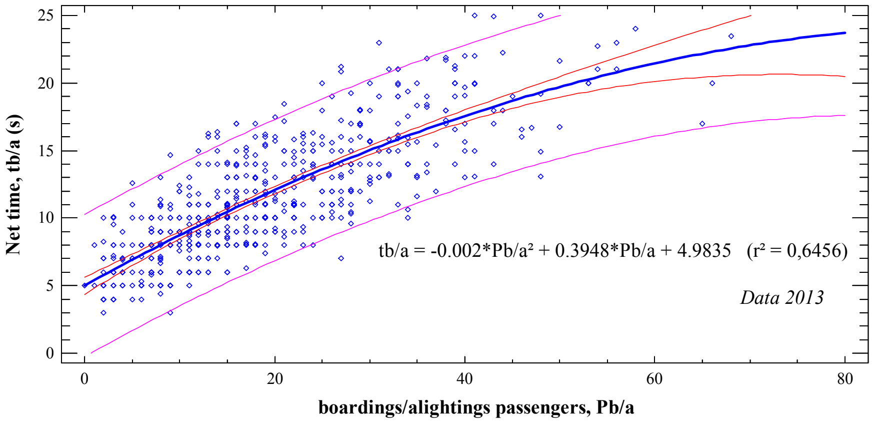

Fig. 3. Net time model by boardings and alightings passengers at bus stop.

Table 2. Analysis of variance for variable adjustment in order.

Source	Sum of squares	Gl	Mean square	Reason-F	Value-p
Pb/a	7150.15	1	7150.15	1010.46	0.0000
Pb/a^2	96.3077	1	96.3077	13.61	0.0002
Model	7246.46	2			

P-value less than 0.05 indicate possible correlation with a confidence level of 95%. This result is similar to that found in systems with analog transfer process at stops (Moreno & Romana, 2012). Analyzing the model found in Transmilenio we can see that there is an approximate delay of 5 s without passengers in the process, and if increase the number of passengers, the delay grows to lower rate than observed to low demand.

7. Dwell-time and main parameters

Once the statistical analysis is realized the result of main parameters is obtained. It should be noted that net time by boarding and alighting at stop is the time when the passengers flow pass through the open door and the more important variable is the total number of passengers, i.e., boardings and alightings. As a result, the dwell-time must include the average spent time in doors.

$$t_d = t_{b/a} + 4 \quad (3)$$

The spent time by doors can influence significantly, this aspect has several causes: bus doors operation, and glass-doors at each stop. Cases with anomaly are not taken into account since they constitute operational failures that define high dispersion.

Data taken in several buses determine 4 s for doors in normal operating; this time should be added to the delay by net flow of passengers if we want average dwell-time.

Table 3. Dwell-time model and main parameters in Transmilenio.

	Main parameters		
Stretch	Dwell-time (prediction model), td (s)	Clearance time, tc (s)	Variability coefficient, Cv
Troncal Norte	$- 0,002\ Pb/a^2 + 0,3948\ Pb/a + 8,9835$	6,4 7,6*	0,21

(*) clearance time in bi-articulated bus

The observed dispersion is due to aspects such as: bi-articulated bus, damaged door that prevents normal flow of passengers, high occupancy in articulated bus –full bus–, obstacle to the bus exit, loading-area occupation and often slower passenger: older persons, disabilities persons and children.

These incidents occur at peak hours, complicating operation at stop. A means analysis for boarding /alighting rate under some factors with 95% decision limits is shown.

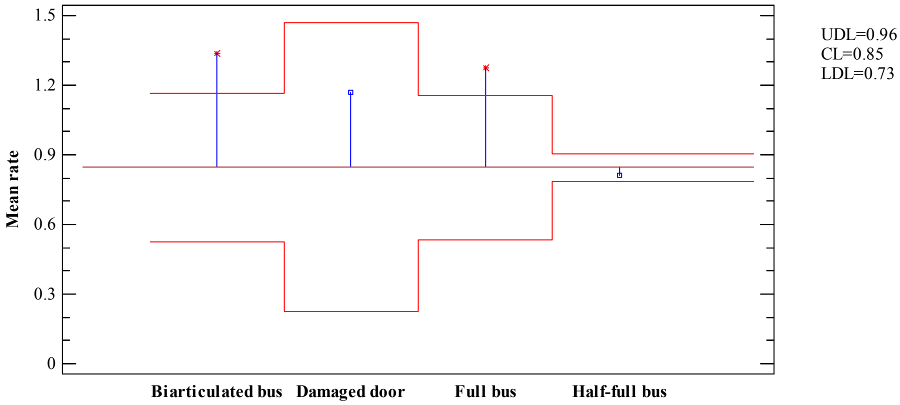

Fig. 4. Analysis of means for boarding / alighting rate.

8. Transmilenio system capacity in Troncal Norte

To calculate capacity must take into account the main parameters found. Thus, the theoretical capacity according to articulated and bi-articulated bus can be obtained. In Equation 4 and 5, a failure rate of 25%, i.e., standard normal variable corresponding to a desired failure rate of 0.674 is used; the results are expressed in bus/hour per loading area.

$$B_l articulated = \frac{3600}{6,4 + \left(0,002 \cdot Pb/a^2 + 0,3948 \cdot Pb/a + 8,9835\right) \cdot \left(1 + 0,674 \cdot 0,21\right)} \quad (4)$$

$$B_l biarticulated = \frac{3600}{7,6 + \left(0,002 \cdot Pb/a^2 + 0,3948 \cdot Pb/a + 8,9835\right) \cdot \left(1 + 0,674 \cdot 0,21\right)} \quad (5)$$

According to capacity analysis, 205 articulated buses and 192 bi-articulated are obtained for very low demand in most heavily loaded stop. For high demand of passenger, 93 and 90 buses are achieved, respectively. See Fig. 5.

Recent study of capacity confirms similar results in something aspect that is worthwhile to mention. Reilly and Aros-Vera (2013) found 105 articulated buses when service time is 30 s, with variability coefficient of 40% and 25% failure rate, this value is very similar to it found here. Not the case, as is compared the person capacity at stop; 20.800 transported people is less than 26.040 (14880 x 1.75) passengers obtained here.

As we can see, given the amount of loading areas available at Calle 100 -two load areas- the capacity value in critical stop is obtained multiplying by effective number of loading area 1.75 if arrival is random, and by 1.85, if arrival is in convoy.

Person capacity taking into accounts different buses and this is obtained multiplying number of buses by bus capacity, which in articulated bus is approximately 160 passengers, and 250 per bi-articulated according to manufacturer values. Bi-articulated bus shows outstanding capacity in these results. See Fig. 6.

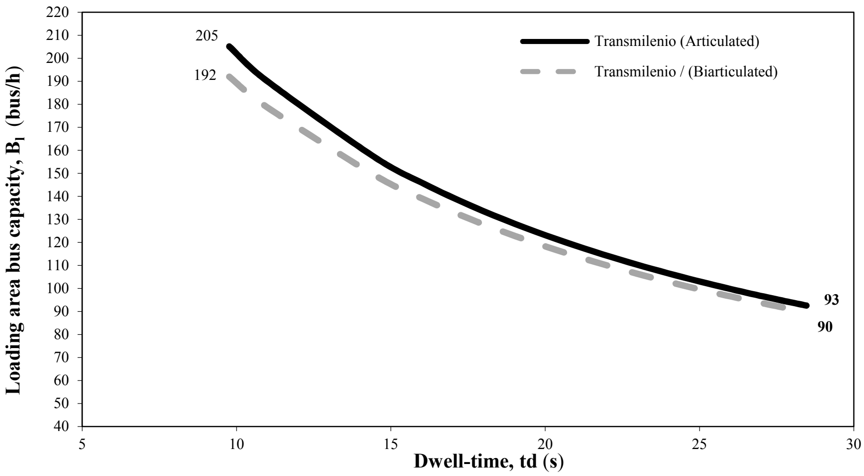

Fig. 5. Loading area bus capacity.

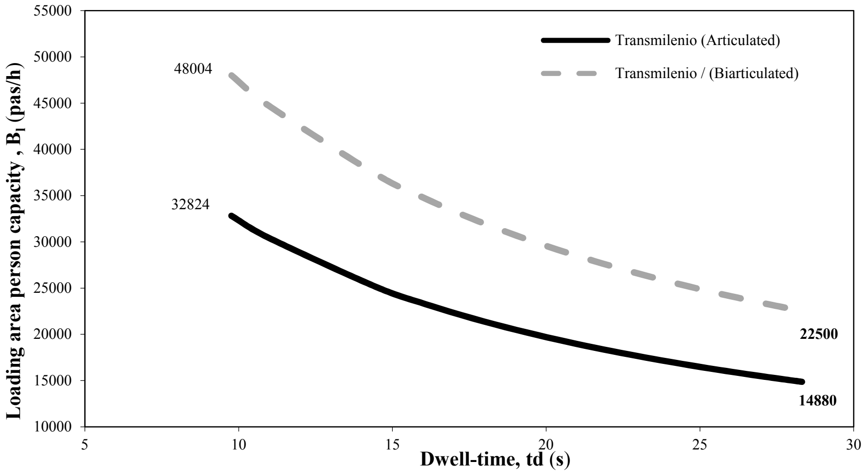

Fig. 6. Loading area person capacity.

Conclusions

- Transmilenio shows capacity comparable to those obtained in systems with higher level of transport infrastructure. However, its capacity is limited by stop capacity.
- The maximum dwell-time depending fundamentally on permissible number of boardings and alightings at stop. However, high bus occupation, passenger concentration at doors, damaged doors and slow passenger, can influence notoriously in the parameter dispersion in peak hour.
- The clearance time between two modes -articulated and bi-articulated- has little effect on the bus capacity when there is high demand.
- Capacity is doubled in cases of express service with bi-articulated bus; this explains their use in peak hours to avoid system saturation.
- Variability coefficient is 20% that represents low dispersion; an average dwell-time close to 30s at bus stop is enough to transport large numbers of travelers; the fast transfer operation and exclusive lanes allow high reliability of this bus system.

- Given the moderate correlation achieved by the quadratic model probably evolve towards a non-linear model with highest percentage of prediction.
- A more representative distribution of passenger arrivals at bus stop could be useful to characterize different stop, and the observation of factors such as bunching can affect the dwell time.

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