TRANSMILENIO BRT CAPACITY DETERMINATION USING A MICROSIMULATION MODEL IN VISSIM

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ABSTRACT

The main objective of this research is to include stochasticity and randomness inherent to the operation of a bus transport system as well as the interaction between buses on the capacity calculation process. Congestion on platforms, poor condition of the pavement and interaction between vehicles can affect the operation of buses. Deterministic formulas are not able to include such phenomena on the capacity estimation.

For the development of this research, 3 VISSIM models were built and calibrated in order to calculate the capacity of 3 different locations on a BRT system.

The research outcomes show how the use of formulas and deterministic conditions can yield very different results of the capacity of a transport system compared to micro-simulation model results. This confirms the need of stochastic elements during the capacity estimation of a BRT system.
INTRODUCTION

Currently Bogota’s (Colombia) BRT system “Transmilenio” (TM) has 114 stations, 84 kilometers of segregated roads in operation, 1263 buses and 190,000 people moving around during peak hour (TM, 2010). What many people does not know is that Bogotá’s mass transit system is worldwide known as one of the BRT (Bus Rapid Transit) with greater capacity and one of the best examples of high-level BRT (Cain et al. 2007).

The HCM defines capacity as "the maximum hourly rate at which persons or vehicles can cross a point or uniform section of a road or rail for a defined time under prevailing road conditions, traffic and control conditions" (Agyemang-Duah & Hall, 1992).

It is a very good capacity definition, however we must emphasize on the fact that capacity relates to prevailing road conditions. In this manner if road shows poor pavement quality or most of the time parked vehicles are blocking one lane of the roads, these conditions must be included on the capacity estimation process as it certainly affects speed and volume on the road, making sure that this condition appears to be a usual scenario on this particular road and not only a momentary situation.

According to that, some authors (Shao, 2011) (Ozbay & Ozguven, 2007) claim that the traffic flow and capacity of a road should be based on stochastic concepts. Hwang et al. (2005) states that the capacity of a road stands as the aggregate result of each vehicle’s individual behaviour. This research aims to include the intrinsic randomness of transportation systems, so as the behaviour of individual vehicles in the capacity calculation of a BRT system through a micro simulation model.

LITERATURE REVIEW

As previously mentioned, Hwang et al. (2005) states that the capacity of a road should be seen as the aggregate result of each vehicle’s individual behavior. Microsimulation models represent an accurate alternative for representing individual vehicle’s behavior. Additionally, these models contain random elements that help to successfully represent probabilistic vehicular traffic.

In the literature review carried during this research, three helpful investigations were found (Arasan & Vedagiri, 2010) (Arasan & Vedagiri, 2008) (Chen, Yu Zhu, Guo, & Sun, 2010). These authors use micro simulation models to evaluate transport systems with dedicated lanes. Chen et al. (2010) even use these models to estimate the capacity of these systems. However these methodologies are applied to systems with bus lanes where buses are forced to interact with mixed traffic. This represents conceptual differences compared to a BRT system where bus traffic is completely segregated from the mixed traffic. According to this, the mentioned investigations can be helpful, however they cannot be replicated for a TM system analysis, as TM is totally segregated of mixed traffic and there are even some segments of the dedicated lanes where buses can overtake another buses.

On the other hand Rangarajan (2010) use a micro simulation model to analyze a traffic situation before and after the implementation of a BRT system for the city of Pune in India. This research shows how BRT systems not only carry savings in travel time, but also represents a more efficient system compared to a system without segregated bus lanes.
Although this document is proof of the effectiveness of BRT systems, the only evaluation parameter considered was travel time, however the author does not know the capacity of the system; not even tried to use the micro simulation model to estimate it.

Another publication was found where authors use the concept of capacity together with a BRT system micro simulation model. This study corresponds to a BRT system operation in the city of Ottawa, Canada (Siddique & Khan, 2006). In this study authors wanted to evaluate the capacity of the system 20 years later. Three scenarios were built showing different numbers of buses and operating conditions. This research shows as main result, differences up to 35% between the estimated capacity using the HCM2000 manual compared with simulation results. This outcome confirms how the use of formulas and deterministic conditions can yield very different results from the capacity of a system compared to a micro simulation model and confirms the need of using stochastic elements in the process.

**METHODOLOGY**

Figure 1 shows a simplified diagram explaining the methodology used to develop the research. The main objective was to choose three locations corresponding to an intersection, a station and a section of a TM system trunk to be modeled and analyzed in VISSIM.

![Figure 1 Methodology Diagram, Source: Own Elaboration](image-url)
LOCATIONS

Many trips throughout the system were made to identify possible flaws in the corridors as poor pavement quality, obstructed intersections, etc. and to finally choose the locations for the study. The preliminary runs showed that the corridor with worst pavement quality is “Avenida Caracas”. According to this first analysis, various points on this road were evaluated, where visible impact on the system operation due to the pavement condition was identified. On these points buses were forced to perform maneuvers to avoid gaps resulting on significant reductions on their speed.

LOCATION #1

Figure 2 shows the characteristics of the first chosen location, which correspond to one of the most important stations on the system, “Calle 100” Station. This station has 5 stop points on each direction and more than 20 routes stop on this location on the morning peak hour. Station’s Diagram shows the route’s number of the buses that stop on each of the stop points during the morning peak hour. The main reason for choosing this location is the high number of passengers that travel through this station every day.

![Figure 2. Location #1 Diagram, Source: Own Elaboration](image)

LOCATION #2

Location #2 corresponds to the intersection of “Avenida Caracas” and “Calle 63”. This location was chosen because of its high vehicular volume and heavy congestion, poor geometric design of the intersection affecting both private vehicles and TM’s exclusive lanes.

LOCATION #3

Finally, as shown in Steer Davies Gleave’s study (SDG, 2007), road capacity is not the main bottleneck on the TM system; however the aim of this study is to model a section of the system’s main corridor where the impact of poor pavement condition on the buses operation can be measured. According to this the section of “Avenida Caracas” between 57th Street and 59th Street was chosen as Location #3. This segment was chosen basically due to bad condition of road’s pavement forcing vehicles to slow down significantly while passing through this point. The photos below show the pavement’s condition along the chosen stretch.
FIELD DATA COLLECTION

Once the locations were chosen, it was necessary to obtain the input data to be used in VISSIM’s micro simulation model, and the data that would allow us to calibrate these models. According to this a field survey was designed in line with Steer Davies Gleave’s study of TM capacity (SDG, 2007) and the calibration methodology proposed by Yu et al. (2006) where they sought to determine the following variables:

- Number of Vehicles (3 Days, 2 Morning Rush Hours)
- Traffic Lights Cycles
- Arrival Rate of Successive Buses (3 Days, 2 Morning Rush Hours)
- Stop Time at Stations (3 Days, 2 Morning Rush Hours)
- Speed of Buses through GPS (At least 10 Trips in the Morning Peak Hour)

*Location #1*

The survey on this point was performed through an HD video camera that allowed us to record with considerable detail the buses operation at this station. The videos were recorded during the morning peak hour and were carried from 7am to 9am during 3 days for each traffic direction.
Table 1 shows the data obtained with the video recordings. The time interval between buses was considered as the time since a bus clears the stop point until the next bus occupies the same stop point. On the other hand, the stop time was calculated from the time a bus occupies the platform until the same bus clears it.
Figures 4 and 5 show the speed profile obtained with a GPS device for each of the traffic orientation. These graphs show the segment between the two stations adjacent to the Location #1, specifically between the “Virrey” and “Calle 106” stations. The blue curve indicates the average of 8 journeys made between 7am and 9am. All speed values above 60 km/h were considered as errors, as this value corresponds to the speed limit set by TM as one of their safety policies. Exponential Smoothing method was used to soften the curve and have a more defined trend as this graph will be used later on the calibration process for the micro simulation model. The red curve shows the result of applying the following formula.

\[ \hat{x}(t) = \alpha \cdot x(t) + (1 - \alpha) \cdot \hat{x}(t-1) \]

Where:

\( x \) is the actual value
\( \hat{x} \) is the forecasted value
\( \alpha \) is the weighing factor, which ranges from 0 to 1
\( t \) is the current time period.

**Location #2 and Location #3**

For the Location #2 successive bus arrival rates were only estimated for the North-South direction, so as the GPS speed profile. Table 2 shows the interval between buses, where lane 1 corresponds to the western lane.
Table 2. Location #2 and #3 Successive Buses Time Interval, Source: Own Elaboration

<table>
<thead>
<tr>
<th></th>
<th>Lane</th>
<th>Time Interval Between Buses (sec)</th>
<th>Standard Deviation (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location #2</td>
<td>1</td>
<td>12</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>16</td>
<td>27</td>
</tr>
<tr>
<td>Location #3</td>
<td>1</td>
<td>13</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>15</td>
<td>24</td>
</tr>
</tbody>
</table>

Figure 6. Location #2 NS GPS Speed Profile, Source: Own Elaboration

The GPS Speed Profile shown in Figure 6, shows the speed at this point obtained between 7am and 9am between “Flores” Station and “Calle 63” Station in the North-South direction only. As in Location #1, Exponential Smoothing method was also used to smooth the curve. Same as in Location #2, at Location #3 only the North-South’s interval between successive buses and GPS speed profile was estimated. Table 2 shows the interval between buses where Lane 1 corresponds to western lane road. One can observe that the range obtained is similar to Location #2 results, so it can be confirmed that the data is consistent.
The GPS speed profile at this point was also obtained only for the North-South direction and between 7am and 9am between adjacent stations “Calle 57” Station and “Calle 63” Station. As in Location #1 and Location #2, Exponential Smoothing method was also used to smooth the data on this location.

CAPACITY DETERMINATION

*Location #1*

As previously mentioned, the first capacity analysis performed was carried on stop points operating individually. The results showed on Figures 8 and 9, ratify the fact that saturation values can be greater than 1. When using traditional deterministic models for capacity determination, saturation values greater than 1 should be discarded. Saturations greater than 1 are not common in reality; even operations near saturation conditions are very rare. Therefore volumes obtained for saturations greater than 1 were calculated just to show the behavior of these models under a hypothetic congested scenario. This is just one of the advantages of micro simulation models over deterministic models, allowing the user to evaluate performance and system capacity under congested conditions.
If we analyze the Figures 8 and 9 showing individual volumes on each stop point of the Location #1 Station on the left axis and queue length on the right axis, it can be seen that the volume is in fact affected by the stop time. Figure 8 shows the capacity curve for stop point A2 which has the lowest average dwell time with 22 seconds. On the other hand Figure 9 shows the stop point with greater stop time (C1) with 43 seconds on average. If we analyze both graphs one can see how effectively stop point A2, with less average stop time, reaches the highest volume of buses with 110 vehicles per hour compared to the 65 on point C1. According to this, differences in stop time of 11 seconds may represent differences in volume up to 45 vehicles per hour.
Figures 8 and 9 also include the queue calculated for each saturation value based on deterministic formulas and simulation results. Deterministic queue length was calculated using the M/D/1 formula shown on Table 3, which represents the queue length in a system having a single server, where arrivals are determined by a Poisson process and job service times are fixed (deterministic). It can be seen that queue length estimated through this deterministic formula differs greatly from those obtained with the simulation. These differences can occur because:

1. Queue length cannot be estimated for saturations greater than 1 due to the limitations of the used formula
2. Formulas are not capable to include the interaction between buses given in a station.
3. Formula contemplates the time of service at the station as a deterministic value which is distant from reality.

Regarding calculated volumes, these were obtained using the following deterministic model developed by Steer Davies Gleave (SDG, 2007):

\[
Ca[\text{personas/hora}] = \sum_{i=1}^{Nsp} X_i \cdot \frac{3600[\text{seg/hora}]}{Tsb[\text{seg/bus}](1-Dir_i) + To_i[\text{seg/bus}]} \cdot Cp[\text{personas/bus}]
\]

Figure 10 Deterministic Capacity Model, Source: (SDG, 2007)

Where:

- \(Ca\) is the estimated capacity
- \(Cp\) is the number of passengers per bus
- \(Tsb\) is the buses approach time
- \(To\) is stop time
- \(Nsp\) is the number of stop points
- \(X\) is the saturation value
- \(Dir\) is the fraction of buses that stop at the stop point

This model only considers stop times and approach times as main variables on the capacity estimation process at a station. It estimates the total capacity of a station as the sum of the individual capacity of each stop point at the station.

According to this, Figures 8 and 9 show the results for Location #1 under 4 scenarios:

- **Determ.** Corresponds to the volume calculated based on deterministic formula shown above.
- **Simult.** corresponds to the volume obtained with the simulation model under a simultaneous operation of every stop point.
- **Sum.** Corresponds to the sum of the individual volumes of every single stop point obtained by the simulation model.
- **Express.** shows the volume results including the express services on the simulation model.

According to Figures 11 and 12, the sum of the individual volumes (sum) differs from the volumes obtained under a simultaneous operation (simult.) of every stop point. This results show the important role of interaction, when many different stop points are operating simultaneously. On the other hand, interaction between vehicles not only changes the capacity curve shape but also may cause differences from up to 200 vehicles on the capacity. It is important to note that in the graphs that shows total capacity per direction, when the graph
shows a volume corresponding to a saturation value of 0.6 this means that each stop point is operating under a saturation value equal to 0.6.

Express services were included in the model so this important characteristic could be analyzed. In the South-North direction a 124 express bus/h flow was introduced. These buses do not stop at any of the stop points of the station, yet are important since they occupy the passing lane. On the North-South direction a 171 express bus/h flow was introduced. These express services volumes correspond to the volumes measured in the field survey and bring the model conditions even closer to reality. Depending on the number of express services that are incorporated to the operation, the capacity curve may or may not change compared to the curve without express services. Consequently it is justified the addition of express services to determine the new total capacity of the station including the buses that do not stop at the stop points.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Saturation</th>
<th>Simult.</th>
<th>Sum</th>
<th>Express.</th>
<th>Determt.</th>
<th>Diff.</th>
<th>Diff. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0,1</td>
<td>59</td>
<td>65</td>
<td>145</td>
<td>186</td>
<td>127</td>
<td>68%</td>
</tr>
<tr>
<td></td>
<td>0,2</td>
<td>113</td>
<td>124</td>
<td>199</td>
<td>247</td>
<td>134</td>
<td>54%</td>
</tr>
<tr>
<td></td>
<td>0,3</td>
<td>165</td>
<td>180</td>
<td>249</td>
<td>309</td>
<td>143</td>
<td>46%</td>
</tr>
<tr>
<td></td>
<td>0,4</td>
<td>210</td>
<td>230</td>
<td>295</td>
<td>370</td>
<td>160</td>
<td>43%</td>
</tr>
<tr>
<td></td>
<td>0,5</td>
<td>244</td>
<td>279</td>
<td>326</td>
<td>432</td>
<td>188</td>
<td>44%</td>
</tr>
<tr>
<td></td>
<td>0,6</td>
<td>232</td>
<td>322</td>
<td>318</td>
<td>494</td>
<td>261</td>
<td>53%</td>
</tr>
<tr>
<td></td>
<td>0,7</td>
<td>210</td>
<td>366</td>
<td>311</td>
<td>555</td>
<td>346</td>
<td>62%</td>
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<tr>
<td></td>
<td>0,8</td>
<td>204</td>
<td>402</td>
<td>307</td>
<td>617</td>
<td>413</td>
<td>47%</td>
</tr>
<tr>
<td></td>
<td>0,9</td>
<td>202</td>
<td>438</td>
<td>305</td>
<td>678</td>
<td>477</td>
<td>50%</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>204</td>
<td>461</td>
<td>306</td>
<td>740</td>
<td>536</td>
<td>72%</td>
</tr>
<tr>
<td></td>
<td>1,1</td>
<td>211</td>
<td>469</td>
<td>307</td>
<td>802</td>
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<tr>
<td></td>
<td>1,2</td>
<td>212</td>
<td>471</td>
<td>306</td>
<td>863</td>
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</tr>
<tr>
<td></td>
<td>1,3</td>
<td>215</td>
<td>471</td>
<td>306</td>
<td>925</td>
<td>710</td>
<td>77%</td>
</tr>
<tr>
<td></td>
<td>1,4</td>
<td>216</td>
<td>471</td>
<td>305</td>
<td>986</td>
<td>771</td>
<td>78%</td>
</tr>
<tr>
<td></td>
<td>1,5</td>
<td>220</td>
<td>471</td>
<td>302</td>
<td>1048</td>
<td>828</td>
<td>79%</td>
</tr>
</tbody>
</table>

| NS        | 0          | 0       | 0   | 0        | 0        | 0     | 0      |
|           | 0,1        | 65      | 59  | 170      | 238      | 173   | 73%    |
|           | 0,2        | 124     | 113 | 230      | 305      | 181   | 59%    |
|           | 0,3        | 181     | 164 | 285      | 372      | 191   | 51%    |
|           | 0,4        | 230     | 211 | 323      | 439      | 210   | 48%    |
|           | 0,5        | 249     | 254 | 287      | 506      | 258   | 51%    |
|           | 0,6        | 205     | 294 | 222      | 573      | 368   | 64%    |
|           | 0,7        | 181     | 336 | 183      | 641      | 459   | 72%    |
|           | 0,8        | 172     | 369 | 168      | 708      | 536   | 76%    |
|           | 0,9        | 164     | 403 | 164      | 775      | 610   | 79%    |
|           | 1          | 162     | 427 | 162      | 842      | 680   | 81%    |
|           | 1,1        | 162     | 436 | 160      | 909      | 747   | 82%    |
|           | 1,2        | 160     | 438 | 159      | 976      | 815   | 84%    |
|           | 1,3        | 160     | 438 | 159      | 1043     | 883   | 85%    |
|           | 1,4        | 160     | 438 | 159      | 1110     | 950   | 86%    |
|           | 1,5        | 160     | 438 | 159      | 1177     | 1017  | 86%    |

Table 5 Location #1 Deterministic Volume Results Vs. Simulation Volume Results. Source: Own Elaboration
Table 5 allows us to analyze the difference between total volumes obtained from the sum of the individual volumes (sum) compared to the total volumes obtained under a simultaneous operation (simult.) of every stop point. Additionally the table shows the comparison between the deterministic model results vs. simulation results that include a simultaneous operation and express services on the station. The last column on the right, presenting the percentage difference between deterministic vs. simulation results, shows volume differences up to 80%. This difference confirms the need of including stochasticity and interaction on the capacity calculation process on a station to obtain more reliable and more accurate results.

Location #3

At this location that corresponds to a corridor segment, standard deviation was summed to the arrival rate of the buses, therefore the maximum flow of vehicles at this point stops holds near saturations greater around 0.9. Under these operating conditions the maximum number of buses that could go through this point is close to 1100 vehicles per hour.

If we take into consideration the number of buses that were measured in the field survey, represented in Figure 13 as a red circle, it can be seen that the segregated lane is operating roughly at a saturation value around 0.2. This corridor could then mobilize many more buses per hour if so required confirming that the bottleneck of the system does not correspond to the roads where buses operate. The final analysis performed at this point was a worse scenario which includes a pavement flaw in the road, forcing the buses to decrease their speed from 50 km/h to about 15 km/h. Probably the poor condition of the pavement is uncomfortable for passengers and drivers and many holes along the trunk might have a summed effect on the corridor capacity, but as seen in Figure 12, an isolated gap has no effect on the system capacity, as the curve on this scenario is exactly the same as the one obtained without the pavement flaw.
CONCLUSIONS

The results of this research show that including randomness in the arrival of buses and stop times in a single station, plus the interaction effect of the buses being driven on a segregated bus corridor, may result on significant differences on the capacity of a station and its individual stop points. Additionally micro simulation models provide information about the behavior of the system and the queue length under saturations value greater than 1. As known it is not possible to calculate the queue length for saturations greater than 1 through deterministic models

It is confirmed through micro simulation models, how the capacity is directly affected by the stop time at stations. Stop points with lower stop times have higher capacities compared to the points with high stop times. A difference in stop times of 11 seconds may represent differences on volume of up to 45 vehicles per hour in the case of individual stop points.

It was confirmed that the sum of the individual volumes of each stop point differs from the total volume obtained under a simultaneous operation of the entire station. Although the curve of the sum of individual stop points includes randomness in arrivals of buses and stop times, the obtained differences may be attributed to the interaction that occurs between buses operating simultaneously on different platforms.

By including express services capacity is not affected as thought. Depending on the number of express services the shape of the capacity curve can have different behaviors. It was evident that the increase in capacity which occurs because of the express services is not equal to the number of express buses entered into the model.

There was no procedure performed for calibrating the queues building process at the station. It can be recognized that the model is able to successfully replicate the velocities along the roads on the 3 locations; however there still is uncertainty on the queue length’s accuracy. According to this, queue building analysis is performed only as a theoretical exercise that can provide a first approach to the problem. It is necessary to redefine the calibration methodology and to complement the methodology with a queue calibration process. This process would allow us to be completely sure about the results given at this point, especially on analysis related to station’s storage distances.

Finally it was confirmed that the pavement condition has no effect on the system capacity. It is probably inconvenient for travelers and drivers and may have implications on the level of service, but for capacity purposes these flaws on the pavement don’t have a significant impact.
REFERENCES


