THE RELATIONSHIP BETWEEN SAFETY, CAPACITY, AND OPERATING SPEED ON BUS RAPID TRANSIT

CASE STUDY: TRANSOESTE BRT, RIO DE JANEIRO

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ABSTRACT

There is a growing body of research on the traffic safety aspects of Bus Rapid Transit (BRT) corridors in Latin American cities. The findings suggest that some BRT design features – such as center lane configurations, left turn prohibitions, and signalized mid-block pedestrian crossings with refuge islands – can significantly improve safety on the corridors where BRTs operate. However, there is still a gap in knowledge about how the different safety features might impact the operational performance of the BRT. In this paper, we study this relationship for the case of the TransOeste BRT corridor in Rio de Janeiro. We start by carrying out a road safety inspection of the corridor, in which we identify main safety concerns and recommend countermeasures for addressing them. We then test the impact of each recommendation – as well as scenarios combining several countermeasures – on BRT operating speeds by using a microsimulation model. We also test the countermeasures' impact on BRT passenger capacity by using formulas for high-capacity BRT operations developed for the TransMilenio system in Bogota, and calibrated for TransOeste through field observations. We found that the safety countermeasures do not have an impact on passenger capacity, but that they tended to slightly decrease operating speeds and increase travel times. We conclude by discussing the best tradeoffs between safety and operational performance.

Keywords: traffic safety, Bus Rapid Transit, Busway, capacity, operations

INTRODUCTION: BRT AND TRAFFIC SAFETY

The topic of traffic safety is a recent addition to the literature on Bus Rapid Transit (BRT), which until now has been focused predominantly on operational performance and project implementation (Hidalgo and Carrigan 2010, Levinson et al. 2003, CERTU 2009). BRT safety studies have focused on estimating the overall safety impacts from implementing different types of bus systems. Bocarejo et al. (2012) found that the implementation of several TransMilenio BRT corridors in Bogota had contributed to a significant reduction in crashes on their respective roads. Goh et al. (2013) also found a significant safety improvement after the implementation of a BRT in Melbourne, Australia.

Some studies have gone a step further and analysed how different BRT design features can impact safety. For example, Diogenes and Lindau (2010) studied pedestrian safety at mid-block locations in Porto Alegre, Brazil, comparing streets with and without median Busway corridors. The authors found that mid-block locations that featured Busway stations were correlated with a 65% increase in pedestrian crashes. Duduta et al. (2012, 2013) developed crash frequency models for several BRT and Busway corridors across Latin America and found that features such as counterflow lanes and large city blocks were correlated with a higher incidence of crashes, while locations with pedestrian refuge islands and left turn prohibitions tended to have a better safety performance.

One of the main takeaways from this literature is that traffic safety on bus corridors is primarily an issue of pedestrian safety, as pedestrians usually account for the majority of traffic fatalities on these corridors (Duduta et al. 2012). The most frequent type of conflict involves pedestrians attempting to cross the street in mid-block and being run over by vehicles. The degree to which this is a problem on various corridors depends on the urban context, the width of the corridor, and vehicle speeds. The problem tends to be more serious on systems such as the TransOeste BRT in Rio de Janeiro, which operates in the middle of a 90-meter wide street with 80kmh speed limits in the central lanes and an average distance of 680 meters between pedestrian crossings. It is also evident in TransMilenio NQS Corridor in Bogotá, an urban expressway with a 60kmh speed limit and high activities on the sides (Bocarejo et al. 2012).

It is not difficult to identify potential countermeasures to improve pedestrian safety on BRT corridors based on the problems identified in the literature. Solutions such as mid-block signalized crossings or traffic calming are well known to road safety professionals and their positive safety impact is well documented (Elvik and Vaa 2004). However, the potential impact of these safety countermeasures on BRT operating performance is less well understood.

In this paper, we use the TransOeste BRT in Rio de Janeiro as a case study to explore the impact of safety countermeasures such as speed reductions and mid-block crossings on several key indicators of BRT operational performance, including passenger capacity, mean operating speed, and operating speed variance. We notably found that these safety countermeasures have no impact on passenger capacity. We also found that they result in slightly lower operating speeds, but that in some cases they might also reduce speed variance, thus making the service more reliable. We also estimate the magnitude of impacts of the countermeasures on both safety and operations, in order to provide bus agencies with all the information to make the right decisions about BRT system design.

METHODOLOGY OVERVIEW

Our approach to this project was to focus first on identifying the key safety issues on the TransOeste BRT. We did this by carrying out a road safety inspection of the 38-kilometer BRT corridor, systematically identifying safety problems and documenting possible countermeasures. We relied both on site observations and existing literature on BRT safety to identify the problems. Once the safety issues were identified, we selected the best countermeasures for addressing them – in this case, reductions in speed limits and the introduction of signalized mid-block pedestrian crossings. We used the existing literature to estimate the impact of the countermeasures on safety.

The next step was to test the impact of the safety countermeasures on BRT operating speed and travel times. This was done using a microscopic simulation model in which we developed scenarios corresponding to the different possible combinations of countermeasures, and evaluated system performance. The third step was to test the countermeasures' impact on passenger capacity, which we did via a spreadsheet tool with capacity formulas developed initially for the TransMilenio BRT in Bogota, Colombia, and calibrated with data from field studies on TransOeste. The following sections describe in more detail the methodology used for each component of this analysis.

SAFETY: MAIN FINDINGS AND RECOMMENDATIONS FROM THE ROAD SAFETY INSPECTION

Overview of the BRT corridor

As part of the infrastructure investments for the 2016 Olympic Games, Rio de Janeiro is currently planning and building four BRT corridors totalling over 150 kilometres and expected to carry 2.1 million trips per day in 2016. The BRTs will connect all the major Olympic sites with other key destinations in the city, including Barra da Tjiuca, the downtown, and the international airport, and should also connect to Rio's Metro system. TransOeste was the first corridor to be inaugurated, starting operations in June 2012, with Transcarioca expected to follow in 2013, and Transbrasil and Transolimpica in 2015 and 2016. TransOeste connects Barra da Tijuca – a high income neighbourhood that will also be the site of the Olympic Village in 2016 – to Santa Cruz – a low income neighbourhood at the western edge of Rio. According to the BRT agency, the system is currently used almost exclusively by Santa Cruz residents traveling to and from jobs in Barra da Tijuca. The demand is heavily concentrated during the peak hour, with some stations remaining completely empty outside of the morning and afternoon peak.

The main safety issue we observed on Avenida das Americas is the high number of pedestrians crossing in mid-block. This is a very common problem on major urban roads in developing world cities and on BRT corridors as well (Diogenes and Lindau 2010, Duduta et al. 2012). However, the problem is more significant on Avenida das Americas than on most other BRT corridors due to the excessive street width (up to 115 meters in places, including service roads), the long distances between pedestrian crossings, and the high speed limit of 80 kilometers per hour (kmh) in the central lanes.

Figure 1 illustrates the differences between the street in which TransOeste operates and other BRT corridors in Latin America with at-grade intersections in terms of distance between crossings and average street width. While there are BRT corridors on comparably wide streets (TransMilenio Autopista Norte in Bogota or Metrobus in Istanbul) those corridors function as expressways, with few or no traffic lights and no at-grade pedestrian crossings.

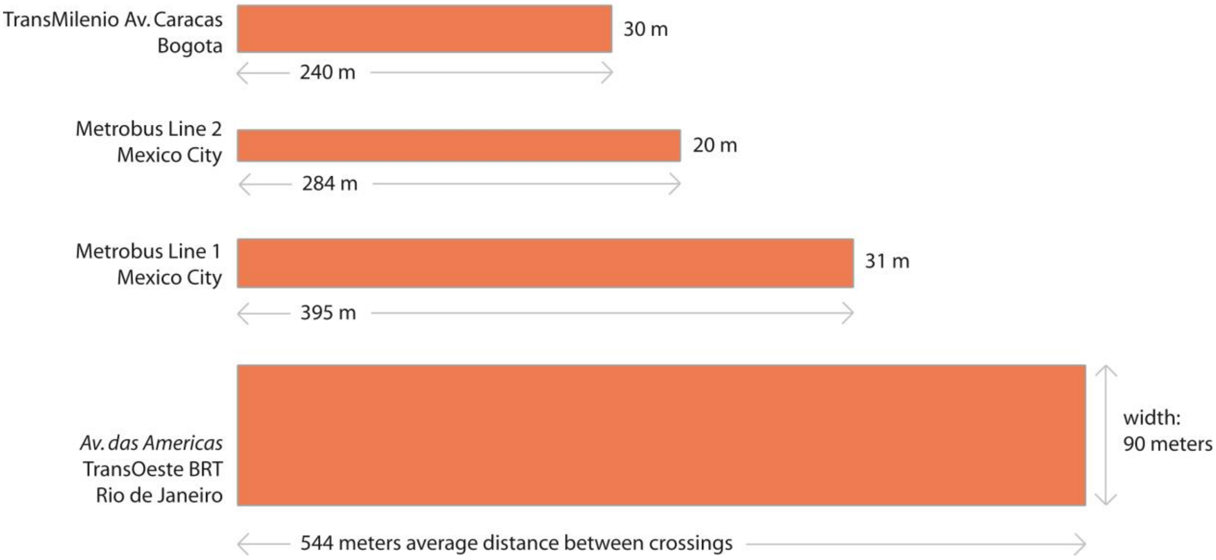

Figure 1: Comparison of average street width and distance between pedestrian crossings on select Latin American BRT corridors

Main safety issues

The current speed limit on Av. das Americas is 80kmh in the central lanes and 70kmh in the side lanes. The design of the road – straight sections with long distances between signals and signal priority for through traffic – is conducive to even higher speeds, which is a documented risk factor for severe pedestrian crashes (Viola et al. 2010). The high travel speeds, the street width and the relatively long distance between signalized crossings pose a significant safety issue for pedestrians on Av. das Americas. As a result, it is not surprising that historically, 78% of accidents on the 38 kilometer stretch that is now TransOeste have occurred on the 12 kilometers of Av. das Americas and that the vast majority of fatal crashes are also focused on this stretch.

Similarly to most urban streets, the majority of fatalities on the TransOeste BRT involve pedestrians. In addition to the general risk related to crossing in mid-block, the presence of the central BRT lanes pose specific safety issues. Several crashes between BRT vehicles and pedestrians have been reported on Av. das Americas. The most common scenario involves people crossing in mid-block between cars stopped at a red light or caught in congestion, then being hit by a BRT traveling at high speed. This is a difficult crash type to avoid, especially for the bus driver, since it involves a situation of low visibility, with the pedestrian emerging suddenly from behind stopped cars (Figure 2).

Figure 2: A common type of conflict on the TransOeste BRT: pedestrians emerging in front of buses from between stopped cars in mid-block

Pedestrian access to median stations and crossing opportunities on Av. das Americas are currently provided via signalized mid-block crosswalks. It is common for these crosswalks to feature button activated pedestrian signals. Our field observations indicate that the average waiting time between the activation of the button and the start of the pedestrian green phase is 90 seconds. Moreover, the pedestrian signal phase never allows pedestrians to cross the entire street. Therefore, the actual time for crossing Av. das Americas varies between 3 and 8 minutes depending on actual signal configurations. We noticed that pedestrians commonly reacted to this by crossing on red without even pressing the button.

Proposed countermeasures

While the road safety inspection revealed a number of other safety issues – such as problems with signage and the layout of bus bays for local bus services – we will focus here only on those issues for which the proposed countermeasures can have an impact on BRT operations: changes to speed limits and changes to pedestrian crossing infrastructure. Based on the problems identified in the previous section, we selected a package of design measures to recommend for improving pedestrian safety on the corridor that include:

- Lowering speed limits for all traffic on Av. das Americas (including the BRT) from the current 80kmh to 60kmh;
- Lowering speed limits for express buses passing through stations to 30kmh, to minimize conflicts with pedestrians who may jaywalk to and from the station, and

also to give drivers more time to react to potential conflicts between local and express buses;

- Placing signalized mid-block crossings at locations where we observed a high volume of pedestrians crossing in mid-block (usually near commercial areas or local bus stations); in most cases, we considered that crossing demand was low enough to warrant the use of button activated signals;
- Configuring signals to minimize pedestrian delay; in particular, we recommended that so long as a minimum of 40 seconds of vehicle green time had elapsed, the pushing of the button by a pedestrian should immediately activate a vehicle yellow phase, followed by a red phase; pedestrians should then be given 40 seconds to cross half of the street, before pressing another button which would immediately activate the green phase for crossing the remainder of the street (Figure 3);

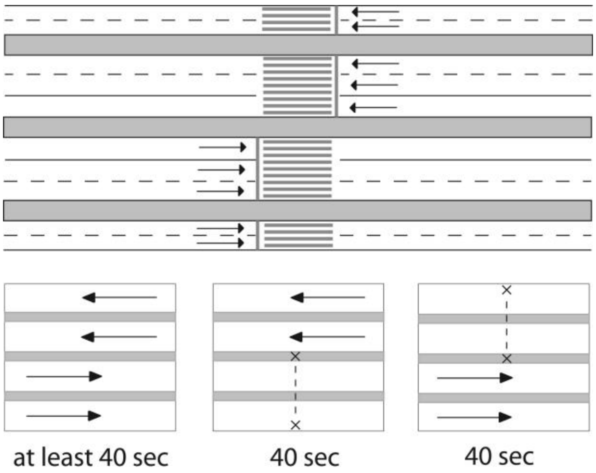

Figure 3: Recommended configuration for a button-activated pedestrian mid-block signal on the TransOeste BRT in Rio de Janeiro

We recommend a signal configuration where the pedestrian light turns green immediately after a pedestrian has pushed the button, allowing only a 4 second delay for providing a yellow phase for traffic. The 40 second green phase should allow pedestrians to cross all the way to the central median, where they could push a second button, giving them another 40 second green phase for crossing the second half of the street. The signal should also be programmed to ensure a minimum all green phase for through traffic of 40 seconds between pedestrian green phases.

We propose adding button activated signals at eight locations where we observed some demand for pedestrian crossing in mid-block. They are typically near shopping areas, local bus stations, or main entrances to developments around the corridor. We added a total of eight signals between Terminal Alvorada and Recreio Shopping, excluding the one discussed above, between Novo Leblon and Santa Monica Jardins. The cycle will be structured as follows:

- A minimum green time for traffic on Av. das Americas of 40 seconds. This means that if the light has just turned green for traffic and a pedestrian pushes the button, there will be a delay of 40 seconds before the light turns red for traffic
- If traffic on Av. das Americas has already had at least 36 seconds of green and a pedestrian pushes the button, the pedestrian signal should turn green within 4 seconds (enough time to provide a yellow phase for traffic)
- Once a pedestrian has pushed the button, the pedestrian light should turn green for the half of Av. das Americas where the button was pushed, giving pedestrians as 40 second green phase to cross to the central median. The pedestrian signal will remain red for the opposite side of Av. das Americas during this time
- Once the pedestrian reached the median and pushes the button for crossing the other half of Av. das Americas, the light should also turn green within 4 seconds
- The pedestrian light should then be green for 40 seconds for the second half of Av. das Americas, allowing pedestrians to complete the crossing, while the first half of the avenue (that the pedestrian has already crossed) should now have green for traffic.

IMPACT OF COUNTERMEASURES ON CRASH FREQUENCIES

At the time of this study, there was no evaluation available of the safety impact of our proposed countermeasures on a BRT corridor. Therefore, we had to rely on other sources of information to develop the estimates. The most widely used source for estimating the safety impact of countermeasures is the *Handbook of Road Safety Measures* (Elvik and Vaa 2004). This study is based on a meta-analysis of available research for a wide range of safety policies and interventions that have carried out before and after measurements. For our project, it had the downside of being based almost exclusively on studies from the United States and Europe, with no examples from Latin America.

Table 1: Expected safety impact of the proposed countermeasures (source: Elvik and Vaa 2004)

Countermeasure	Impact on severe crashes	Impact on all crashes
Reducing BRT speeds from 70kmh to 60kmh	-15%	-9%
Reducing speeds on station approaches to 30kmh	-67%	
Adding a signalized mid-block crosswalk	-12% (pedestrian crashes) - 2% (vehicle crashes)	

There was no baseline data on traffic crashes for Av. das Americas post BRT implementation available at the time of this study, and we are therefore unable to provide an estimate of the magnitude of potential crash reductions beyond the percent changes shown in Table 1.

Nevertheless, these estimates provide a useful point of comparison with the expected impact on operations, which we analyze in the following sections.

IMPACT OF SAFETY COUNTERMEASURES ON BRT OPERATING SPEED

We tested the impact of the proposed safety countermeasures on operational performance of the BRT by looking at three main indicators:

- **Operating speed, by type of service**: this is defined as the average speed of a bus from the moment it leaves the platform at one of the terminals until the moment it docks at the platform of the terminal at the opposite end of the route; this is considered a key performance indicator for BRT systems, and it is common to use a 25 kmh benchmark as the threshold for high quality operations (Wright and Hook 2007)
- **In-vehicle travel time:** this is defined as the total time between the moment a vehicle leaves the platform at one of the terminals until the moment it docks at the platform of the terminal at the opposite end of the route; in our simulation, it is calculated as a function of operating speed by the following formula: $Travel\ time\ [min] = Corridor\ length\ [km]/(Operating\ speed[kmh]/60)$
- **Operating speed variance:** this is an indicator of the reliability of service offered by the BRT, and we would prioritize solutions that minimize this variance. It is calculated from the standard deviation of operating speed by type of service reported by the model. We do not only report variance, but also the coefficient of speed variability, defined as the ratio of standard deviation to the mean, and which is a more effective measure for comparing scenarios (Moreno Gonzalez et al. 2013)

Modeling approach

We developed the model using the EMBARQ BRT Simulator – a miscroscopic simulation tool designed specifically for high capacity bus operations. This software allows for the detailed modeling of BRT routes, including terminal layouts, terminal holding zones, signalized intersections, and complex station configurations with multiple sub-stops and a combination of local and express services.[1]

We started by developing a Baseline scenario, designed to replicate actual conditions on the BRT corridor at the time of the study, and a series of “project” scenarios, representing various combinations of safety countermeasures.

It is important to note that the operating conditions we found on the corridor in 2012 are likely to change considerably by the time the BRT network if fully built out in 2016. In particular, the connections to the future TransOlimpica and TransCarioca corridors are likely

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[1] The description, calibration, and previous applications of the EMBARQ BRT Simulator can be found in Pereira, B. M. ; Lindau, L.A. ; Castilho, R. A. (2010) *A importância de simular sistemas Bus Rapid Transit.* In: Proceedings of XVI CLATPU, Ciudad de México.

to increase demand on TransOeste[2]. Also, through discussions with staff from the BRT operating agency, we learned that they were considering operating some buses on both the TransOeste and TransCarioca corridors to bypass the congested Alvorada terminal, thus effectively increasing overall bus frequency on TransOeste. Previous research has shown that higher passenger demand and higher bus frequencies are usually associated with lower operating speeds.[3] As a result, it seemed necessary to compare the *Baseline* and *Project* scenarios not only in the 2012 operating conditions, but also in 2016, when both passenger demand and bus frequencies are likely to be higher on the corridor. We therefore created 2012 and 2016 versions for all our scenarios. Their specifications are discussed in more detail below.

Model specification and validation

Baseline scenario

Using the BRT Simulator, we built a model for the 38-kilometer TransOeste BRT corridor, including data from field observations and measurements on station and terminal location and design, location of traffic signals, cycle times, dwell times, bus frequency by type of service, passenger demand, and maximum bus speeds by type of service (*parador,* or local buses, and *expresso,* or limited stop services).

We tested the prediction accuracy of the model by running a simulation for the Baseline 2012 scenario and comparing the estimated operating speeds by type of service from the simulation run with the actual operating speeds, as reported by Rio Ônibus – the BRT operating agency in Rio de Janeiro. A major challenge in calibrating the model was the fact that the bus lanes are experiencing pavement deterioration in some sections of the corridor, which significantly reduced bus speeds in those sections. Since the Simulator cannot directly account for this condition, we adjusted for this in our model by measuring actual bus speeds in those sections, and replicating that in the model by specifying the observed speeds as the speed limit for those respective links. As shown in Table 2, predicted speeds fell within 2% and 7% of actual speeds for *parador* and *expresso* services, respectively, indicating that the model was well calibrated, especially considering the length and complexity of the corridor, as well as the pavement issues discussed above.

Table 2: Comparison of actual and estimated operating speeds for the Baseline 2012 scenario

Type of service	Actual operating speed (kmh)	Estimated operating speed (kmh)	% difference
Expresso	35	32.7	7 %
Parador	28	28.6	2 %

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[2] A similar pattern was observed for Line 1 of the Metrobus BRT system in Mexico City, where demand increased progressively from around 150,000 daily passengers in 2005 to over 390,000 daily passengers in 2012, as connections to Lines 2 and 3 were established, respectively in 2008 and 2011. See http://www.metrobus.df.gob.mx/fichas.html

[3] Lindau, L.A., B. Medeiros Pereira, R. A. de Castilho, M. C. Diogenes, J. C. Herrera. *Impact of Design Elements on the Capacity and Speed of Bus Rapid Transit (BRT): the case of a single lane per direction corridor.* presented at Thredbo 12 Conference, Durban.

The objective of the simulation was to test the impact of the safety countermeasures on operational performance for the hour and the direction of peak demand on the corridor, when these effects would be expected to be the most pronounced. According to Rio Ônibus, demand on TransOeste tends to be unidirectional, with the vast majority of passengers traveling eastbound in the morning peak from the Santa Cruz neighbourhood to the Alvorada terminal, and then returning in the westbound direction in the afternoon. The morning peak is more concentrated, while the afternoon peak tends to be more spread out. Based on this information, we decided to restrict our model to the eastbound direction during the morning peak hour, which represents the condition of highest demand on the corridor. As Figure 4 illustrates, TransOeste has a somewhat unusual demand profile along the route, with almost all of the boardings occurring at the Santa Cruz (western) terminal and several stations nearby it, and virtually all trips ending at the Alvorada (eastern) terminal. Demand is near zero at most other stations along the route.

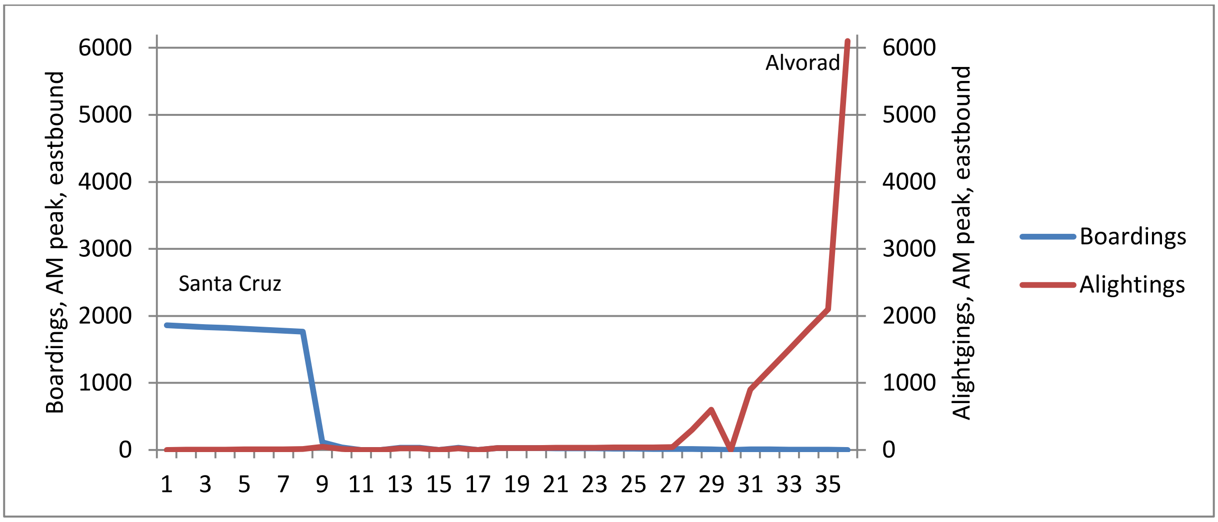

Figure 4: Demand distribution along the corridor in the eastbound direction during the AM peak in 2012

As noted above, the 2012 configuration of TransOeste should really be considered as a temporary condition, since a section of the corridor is still under construction (Alvorada to Jardim Oceânico) as are connections to other BRT corridors. We address this issue in the simulation by testing each scenario under 2016 (i.e. build-out) conditions. The main challenge in this case is forecasting peak loads on the corridor in the future year. We based our estimates of 2016 peak loads on the projected daily demand for 2016 (220,000 trips) and the projected ratio of peak loads to daily trips.

Table 3: Daily trips and peak loads on selected BRT systems[4]

System	City	Daily trips per line	Peak load (pphpd)	Ratio
Metrobus	Quito	186,000	12,000	0.06
Optibus	Leon	73,300	6,000	0.08
Transjakarta	Jakarta	86,600	3,600	0.04
Metrobus	Mexico City	225,000	9,000	0.04
BRT 1	Beijing	120,000	8,000	0.07
Megabus	Pereira	115,000	6,900	0.06
Macrobus	Guadalajara	127,000	5,000	0.04
Janmarg	Ahmedabad	35,000	1,780	0.05
Average of all systems		**120,988**	**6,535**	**0.06**
TransOeste (Sep 2012)	Rio de Janeiro	65,000	15,000	**0.23**

As Table 3 shows, TransOeste has an unusually high ratio of peak loads to daily trips of 23%, closer to what one would expect to see in a commuter rail system than a BRT. This can be explained by TransOeste's urban context. As it connects a major job center, Barra da Tijuca, to a mostly low-income residential area at the city's periphery (Santa Cruz) it is mostly used by Santa Cruz works to access their jobs. Much of the middle portion of TransOeste is currently a greenfield, which explains the lack of demand in that section. If this ratio were to remain constant in 2016, one would expect roughly 50,000 passengers per hour per direction (pphpd) in the morning peak. However, there is reason to expect that this ratio will go down, as the greenfield sections begin to develop and connections are established to other BRTs at different points along the TransOeste route, all of which should result in more complex trip patterns and a more even distribution of demand in both directions during the day.

Assuming that only 6% of the additional demand would occur during the peak hour in one direction, the peak hour demand on the corridor would be between 22,000 and 24,000 pphpd. For our simulation, we used the more conservative value of 22,000 pphpd.

Project scenarios

The changes introduced by the project scenarios are identical in 2012 and 2016 and they involve changes in the maximum speed limit for buses on different sections, as well as additional signalized pedestrian crosswalks. The speed reductions were straightforward to model in the Simulator, since they simply involved changing the maximum speed on different links. The difficulty was in modelling the signalized mid-block pedestrian crosswalks with button-activated signals. Since the Simulator does not currently have a feature for this type of signal, we developed a proxy instead. We began by classifying the different locations where we would add mid-block crosswalks as low, medium, or high crossing demand, which corresponded to a pedestrian pushing the signal button every 10, 5, and 2 minutes, respectively. For each crossing location, we assumed that the arrival of pedestrians at the

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[4] Sources: TransOeste data provided by Rio Ônibus. Data for other systems from: Hidalgo, D., A. Carrigan. 2010. *Modernizing Public Transportation. Lessons learned from major bus improvements in Latin America and Asia.* WRI Report, World Resources Institute, Washington DC.

crosswalk would be uniformly distributed over the simulation run time. Based on the specifications for the button-activated signal we estimated that, for each level of crossing demand, there is a corresponding equivalent fixed timing signal configuration. That is, the scenario under which a pedestrian activates the signal every five minutes is equivalent to a pre-timed signal with a 300 second (i.e. 5 minute) cycle composed of a 200 second red pedestrian phase, and two successive 40 second green phases for pedestrians to cross each half of the street. The Simulator also does not model pedestrian signals per se. Instead, the pedestrian phase can be modeled as a red phase for the BRT. The specifications for the signals used for the BRT simulator for the 2, 5, and 10 minute scenarios are shown in Table 4. The timing specifications refer to the traffic signals for eastbound (Santa Cruz to Alvorada) and westbound buses.

Table 4: Signal timing specifications for button activated pedestrian crossings for the BRT Simulator

	1 ped / 2 minutes	**1 ped / 5 minutes**	**1 ped / 10 minutes**
	Westbound signal	Westbound signal	Westbound signal
Green (sec)	80	260	560
Red (sec)	40	40	40
Offset (sec)	0	0	0
	Eastbound signal	Eastbound signal	Eastbound signal
Green (sec)	80	260	560
Red (sec)	40	40	40
Offset (sec)	40	40	40

We tested three different project scenarios. In the “60 kmh” scenario, the only change introduced is the reduction in overall speed limits to 60kmh for all traffic on Av. das Americas. The “60/30” scenario further restricts speeds for all buses approaching stations to 30kmh (including buses not stopping at those stations). Finally, the “complete” scenario also includes the additional signalized mid-block crossings and a slight increase in speed in the greenfield section to 70kmh, to partially offset the impacts of speed reductions on Av. das Americas.

Simulation results

Each simulation run lasted for a total of three hours. The first hour was considered a warm-up period. Statistics were erased at the end of the first hour, and then collected for the remaining two hours of simulation. This was repeated for each baseline and project scenario under 2012 and 2016 conditions. The results of the simulation are shown in Table 5 and Table 6.

Table 5: Simulation results for 2012 scenarios

		Baseline	**60kmh**	**60/30kmh**	**Complete**
Speed (km/h)	expresso	34.35	34	31	33.6

	parador	27.10	27	26	27.8
Travel time (min)	expresso	66	67	73	67
	parador	84	84	87	82
Speed variance	expresso	7.47	6.21	1.75	5.03
	parador	5.84	4.58	4.34	7.5
Speed variability coef.	expresso	0.08	0.07	0.04	0.07
	parador	0.09	0.08	0.08	0.1

Table 6: Simulation results for 2016 scenarios

		Baseline	60kmh	60/30kmh	Complete
Speed (km/h)	expresso	32	31.5	29.6	29.6
	parador	25.6	25.6	25.45	25.43
Travel time (min)	expresso	71	72	77	77
	parador	89	89	89	89
Speed variance	expresso	37	31.3	22.33	15.57
	parador	16	14.94	14.85	15.57
Speed variability coef.	expresso	0.19	0.18	0.16	0.16
	parador	0.16	0.15	0.15	0.16

In the discussion, we focus on the 2016 results, since the 2012 conditions are considered only temporary. As expected, operating speeds in the baseline scenario are lower in 2016 than in 2012, even when using conservative assumptions for future peak loads. The speed variability coefficient is considerably higher in 2016, and within the range of other BRTs in the literature (Moreno Gonzalez et al. 2013), as a result of the increased passenger demand and bus frequency in 2016.

The columns from left to right in Table 6 show the impact of adding each safety countermeasure on the different performance indicators. The reduction in speed limits result in slightly higher commercial speeds for buses and higher travel times for passengers. On the other hand, they reduce speed variability, meaning that the service is more reliable and bus frequency is better maintained throughout the route. The traffic signals have a minimum impact on operating speeds, which is offset by the slightly higher speed limits in the greenfield section (70 kmh).

Overall, the simulation results show that while the safety recommendations have a negative impact on some operational parameters (mean operating speed and mean travel times) these impacts are relatively small, which indicates that TransOeste could maintain high quality operations even when implementing the safety features presented here. It should also be noted that operating speeds are equal or higher than the 25 kmh benchmark across all scenarios..

IMPACT OF SAFETY COUNTERMEASURES ON BRT PASSENGER CAPACITY

In order to test the impact of our safety recommendations on passenger capacity, we use the formulas developed by Hidalgo et al. (2011) for the TransMilenio BRT in Bogota, calibrated with data from field observations on TransOeste. The capacity of transit system is usually broken down into two components: way capacity and station capacity, which are calculated differently. Vuchic (2005) provides the definitions for these two components: "*way capacity* is the maximum number of passenger spaces that can be transported in vehicles past a point in one direction per hour without stopping. *Station capacity* is the corresponding number of spaces in vehicles stopping at stations." In the case of arterial running BRT such as TransOeste, the critical way capacity is that of signalized intersections. We address the impact of the safety countermeasures on each type of capacity below.

Station capacity

Station capacity for a BRT is a function of the station layout (i.e. the presence of overtaking lanes and/or multiple sub-stops) the dwell time, and the minimum interval between buses (Hidalgo et al. 2011):

$$Ca[pphpd] = \sum_{i=1}^{N_{sp}} x_i \times \frac{3600}{T_{sb} \times (1 - Dir) + T_o} \times Cp[pax/convoy] \times LF \qquad \text{(Eq. 1)}$$

Where: Ca = the passenger capacity of the station, in passengers per hour per direction (pphpd)
N_{sp} = the number of sub-stops per station,
X_i = is the acceptable saturation rate at stations,
3600 = the number of seconds in an hour,
T_{sb} = the boarding and alighting time, in seconds,
Dir = the percentage of buses that do not stop at the station (i.e. express services),
T_0 = the minimum interval between two buses or convoys,
C_p [pax/convoy] = the passenger capacity of a convoy (i.e. buses traveling closely bunched together); if convoying is not used on the corridor, then this simply becomes the capacity of a bus. If more than one vehicle type is used (i.e. articulated and double-articulated buses) this value should be a weighted average of the capacity of the different bus types, based on the percentage of the fleet they each represent.
LF is the load factor for buses (i.e. the percentage of offered capacity that is utilized during the peak hour).

On high capacity BRT systems, stations usually have more than one sub-stop per station. A sub-stop can be defined as an additional platform (or docking bay) situated sufficiently far from the original platform at the station to allow buses to dock simultaneously at sub-stops 1 and 2 without interfering with one another. Commonly, this distance is equal to the length of an articulated bus, which allows a bus sufficient room to dock at sub-stop 2 even if the platform at sub stop 1 is occupied.[5] TransOeste features two main types of stations: local stations with a single sub-stop, and express stations with two sub-stops (one for *parador* and one for *expresso* services, respectively). The saturation rate for a station (X_i) refers to the percentage of time that a given stopping bay is occupied. For all calculations in this paper, we use $X_i = 0.7$.

Our safety recommendations do not affect any of the parameters in equation 1, which indicates that they do not have a significant impact on station capacity. However, it is important to calculate the capacity of each station type to use as a benchmark against the capacity impact of our proposed mid-block crossings. Our station capacity estimates are shown in Table 7. As Vuchic (2005) notes, capacity should not be thought of as a fixed value, but rather a range of values depending on the values we have chosen for our parameters. Therefore, the values in Table 7 should not be interpreted as the *actual* capacity of TransOeste, but rather as one of the values within the range of possible capacity numbers for the system, under the conditions and assumptions listed here. We keep the assumptions constant for intersection capacity calculations and we look at the difference between the two.

Table 7: Passenger capacity at TransOeste stations

Parameter	**Value**	
	Local station	Express station
C_p (passengers per bus)	160	160
LF (load factor)	0.9	0.9
X_i (saturation rate)[6]	0.7	0.7
T_{sb} (dwell time)[7]	16.5	16.5
Dir (percent of express buses)[8]	0.714	0
T_0 (minimum interval between buses)[9]	14.5	14.5
N_{sp} (number of sub stops)	1	2
Station capacity (pphpd)	18,881	23,411

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[5] In some cases, this distance will be equal to twice the length of an articulated bus. This allows a bus to align with the platform at sub-stop 2 while it is still occupied, and not interfere with buses moving in and out of sub-stop 1. This can help reduce the minimum interval between buses and therefore increase capacity.

[6] The saturation level of a station refers to the percentage of time that a vehicle stopping bay is occupied. Wright, L., W. Hook, Eds. 2007. *Bus Rapid Transit Planning Guide.*, 3rd edition. Institute for Transportation and Development Policy (ITDP), New York, vol. 1, p.246

[7] Based on field studies conducted by EMBARQ on TransOeste

[8] Source: Rio BRT operating agency

[9] Source: Hidalgo D., G. Lleras, E. Hernandez. 2011. *Passenger Capacity in Bus Rapid Transit Systems - Formula Development and Application to the TransMilenio System in Bogota, Colombia*, presented at Thredbo 12 Conference, Durban.

Intersection and mid-block crossing capacity

The passenger capacity of an arterial running BRT at a signalized location is essentially a function of the saturation flow rate for a dedicated bus lane, vehicle capacity, and the green to cycle ratio of the bus signal:

$$Ca_{intersection} = C_{vehicle}[pax] \times LF \ \times N \times s \times g/C \qquad \text{(Eq. 2)}$$

Where *Ca* = capacity of the corridor in terms of passengers per hour per direction (pphpd) at a given intersection or mid-block crossing,
$C_{vehicle}$ is the average passenger capacity of vehicles operating in the bus lanes
N is the number of bus lanes per direction,
s is the saturation flow rate for a through bus lane (vehicles per hour of green time),
g/C is the green time to signal cycle time ratio for buses at that particular location.

All the terms in equation 2 were obtained from field observations on the TransOeste BRT, which the exception of the saturation flow rate (s), for which we did not have a local value and used instead a value of 664 articulated buses / hour, based on field studies from TransMilenio in Bogota (Hidalgo et al. 2011).

Studies have found the saturation flow rate to depend on maximum speed limits. For example, Besten and Meyers (2007) found that a 1kmh change in the speed limit resulted in a change of the saturation flow rate by 8.5 vehicles. The Highway Capacity Manual (HCM), however, does not provide adjustment factors for speed to the base saturation rate, nor does it provide a way to incorporate speed into the calculation of the base saturation rate (TRB 2010). The studies that have looked into the saturation flow rate for BRT lanes also do not provide estimates for how speed limits might affect it (Hidalgo et al. 2011, Wright and Hook 2007). The findings from Besten and Meyers (2007) suggest that our recommendation of reducing bus speed limits from 70kmh to 60kmh might reduce the saturation flow rate for the bus lane from 664 to around 650 buses / hour. However, this is not a reliable estimate, as it is based on a small sample of roads from South Africa with passenger cars as the predominant mode, and it is not clear how this translates to dedicated bus lanes. We will therefore simply note that our recommended speed reductions may result in slightly lower saturation flow rates at existing signalized intersections, but that the impact is likely to be marginal and will not restrict capacity.

Our proposed signalized mid-block crossings will have a more direct impact on capacity at the locations where they are introduced. Table 8 shows a range of values depending on the signal timing, which is a function of the frequency of pedestrian arrivals at the actuated signalized crossings. The values in the rightmost column range from 63,744 pphpd (which represents the highest amount of bus red light per cycle allowable under the signal specifications, and which corresponds to the highest demand for pedestrian crossings) to 95,616 pphpd (which represents a scenario in which the pedestrian signal button is never activated).

Table 8: Estimated passenger capacity at the proposed signalized mid-block crossings

Parameter	**Value** Fixed timing crossing	Actuated signal crossing
S (saturation flow rate)[10]	664	664
N (no. of bus lanes / direction)	1	1
g bus (bus green phase, seconds)	40	Varies
C (signal cycle length, seconds)	80	Varies
g/C bus	0.5	0.67 – 1
Cp (passengers per bus)	160	160
LF (load factor)	0.9	0.9
Ca (BRT capacity, pphpd)	47,808	63,744 – 95,616

The capacity at actuated signalized crossings is always higher than that of the fixed timing signalized crossing, which in turn is higher than the capacity of local stations. This indicates that the safety recommendations proposed for TransOeste would not have an impact on passenger capacity.

CONCLUSION: AN INTEGRATED APPROACH TO TRANSIT CORRIDORS

Designing a safe transit system involves looking not just at the transit facilities, but also the overall road layout and the urban context around it. Transport engineers designing BRT systems often focus only on the transit facilities (bus lanes, stations) and do not fully consider how the transit system interacts with its urban environment. Yet the key to achieving both a safe and high performing system is to understand, for example, how different land uses around the corridor (e.g. shopping centers) might impact the demand for pedestrian crossing on the corridor. Then the question becomes how to best provide safe crossing facilities for pedestrians that take into account pedestrian behavior, while also understanding the impact of these facilities on the performance of the transit system.

We suggest that the best way for designing a safe, high speed and high-capacity transit system is to have an integrated approach that considers the needs of all road users and the impact of each design or operational decision on a wide range of performance

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[10] Based on field studies conducted on TransMilenio corridors in Bogota. Source: Hidalgo et al. 2011, op. cit.

indicators, including safety, travel times, and passenger capacity. This can also help address common concerns that implementing safety measures such as traffic calming or mid-block signalized crosswalks might have an adverse impact on transit system performance.

By implementing an integrated approach to the planning and design of a BRT corridor, as we propose here, it is possible to help decision makers understand which design options to choose and what impact to expect on a range of performance indicators. Table 9 illustrates this with an example from the TransOeste BRT, where we compare the impacts of implementing traffic calming and mid-block signalized pedestrian crossings on safety, capacity, and operational performance. The evidence from TransOeste suggests that if safety countermeasures are designed as part of an integrated approach that also considers bus operations, they can have a significant impact on improving safety and only a limited negative impact on commercial speeds and travel times. Moreover, the speed reductions are most important at key conflict points, such as stations, and they can be offset through speed increases in areas where there is less conflict.

Table 9: Estimated impacts on safety, speed, travel time, and capacity on the TransOeste BRT, resulting from the implementation of a package of safety measures, including traffic calming and mid-block crossings

Performance indicator	Baseline	Project	Change	Source
All crashes	n/a	n/a	**-15% to -67%**	See Table 1 for details
Operating speed (expresso)	32 kmh	29.6 kmh	**-2.4 kmh**	Microsimulation
Travel time	71 min	77 min	**+ 6 min**	Microsimulation
Speed variability	0.19	0.16	**- 0.03**	Microsimulation
Capacity (pphpd)	18,800	18,800	**No impact**	Based on Hidalgo et al. (2011)

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