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Traffic safety in surface public transport systems: a synthesis of research

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Abstract While there is a growing body of literature on transit safety, most studies on this topic tend to focus on a single type of transit system or on a single city. There is a need for a better understanding of safety issues across different transit modes and in different geographies in order to help inform city or transit agencies choosing between different transit system design options on the safety implications of their choices. We address this gap by reviewing the existing literature on transit safety for different bus and rail surface transit systems. We found that the main safety issues and common crash types depend more on the geometry of intersections and the corridor layout than on the type of technology used for transit vehicles (i.e. bus or rail) and that these issues are similar across different regions of the world. Furthermore, we found that there is a good understanding of the problems faced by transit systems, and a wide range of suggested countermeasures, but little evidence on the effectiveness of the different countermeasures in reducing target crashes. By taking an approach that cuts across different transit modes, we are also able to suggest solutions from one type of system that could be applicable to another. For example, we point out that Bus Rapid Transit agencies could learn from light rail operations about best practices in managing conflict points between transit vehicles.

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1 Introduction

The topic of traffic safety on different surface public transport systems has received considerable attention in the literature. However, the vast majority of studies on this topic focus on a single type of transit system [e.g. light rail transit (LRT)] and, more commonly, on a single agency or city. Some studies, particularly publications in the Transit Research Cooperative Program (TCRP) series have attempted to create a synthesis of safety research and practice by pooling together data from several LRT systems in the United States (Korve et al. 2001; Klaver Pecheux and Saporta 2009, Cleghorn et al. 2009). However, what is still missing from the literature is a synthesis of safety research across different transit technologies (i.e. bus and rail) and different geographies. Such a review would help inform a city or transit agency choosing between different transit system design options on the safety implications of their choices.

In this paper, we provide an overview of the main safety issues across a range of transit system designs and layouts in different regions of the world, based on a review of the existing literature and available crash data from transit agencies. The first thing to note in this context is that "surface public transport" is a broad category, in theory including everything from minibuses to regional rail systems, with very different safety issues at the opposite ends of the spectrum. To narrow the scope of this study, our paper will cover different types of bus priority measures, from bus priority lanes to Busways (i.e. fully segregated bus lanes and stations, typically situated in the median of an urban arterial and occasionally situated curbside) and Bus Rapid Transit (i.e. a Busway that also features centralized operations control, off-board fare collection, level boarding, or other features aimed at increasing operating speeds and service reliability).[1] The paper will also include rail systems that operate on or adjacent to urban streets, including tramways and LRT.

2 Methodology

Since the majority of studies in the transit safety field have focused on a specific technology or city, the authors have tailored their methodology to the available data and, as a result, there are considerable differences in the methodology, the type data used, and the way findings are reported across the different studies. Nevertheless, we were able to identify three main themes across the literature, corresponding to

[1] While we use these definitions when referring to Busway or BRT in this paper, we acknowledge that delineation between these two categories is not always clear and some studies use the terms interchangeably.

three main questions that authors have sought to answer about the safety of different transit systems. These main themes are listed below:

- What is the overall safety impact of different transit systems and what is the best way to measure it?
- What are the most common crash types on different types of transit systems, and what countermeasures can reduce the frequency of those crashes?
- How do different design features on transit corridors compare in terms of their safety performance (e.g. is a median alignment safer than a curbside alignment)?

These questions have often proven difficult to answer and each can raise numerous methodological concerns, which the authors have addressed in different ways. Given the differences in how each theme has been approached in the literature, we will first structure the paper along these three main topics or questions. For each topic, we will first analyze the different methodologies employed in the literature, and we will then present the findings from the different studies and look at common patterns and insights across different studies and transit system designs.

3 The safety impact of a new transit system

Understanding the potential safety impacts of a new transit system such as a BRT or LRT can be valuable for policy makers as it would allow any safety benefits to be factored into a cost-benefit analysis as part of the decision making process for funding a new transit line. However, answering the question of the safety benefits of a new transit system poses a number of challenges.

First of all, the overall safety impacts will depend not only on the design and configuration of the new system, but also on what that transit system replaces. In many Latin American cities, for example, privately operated minibuses are the predominant mode of transport, accounting for as much as 45 % of the total transport mode share in Mexico City (Mexico City Household Travel Survey, 2007). This typically results in an over-supply of transit vehicles, as private operators compete for the same passengers, and it leads to generally unsafe conditions along a transit route (Small and Verhoef 2007). When BRT systems are implemented in Latin American cities, they typically replace the existing minibus operations. The elimination of the multitude of competing minibuses and their replacement with higher capacity articulated buses, with an operating agency that oversees routes, schedules, and driver training, can be expected to result in significant safety improvements. In other cases, such as the United States or Australia, a new BRT route will typically replace a lower frequency conventional bus system, and so the overall change along the corridor is likely to be less pronounced than in Latin American cases (Goh et al. 2013). A similar BRT layout can therefore be expected to have a more pronounced safety impact in a Latin American context than in the US.

Moreover, BRT corridors have typically been implemented on a wide range of street types, ranging from narrow cobblestone streets in the historical downtown in Mexico City with speed limits under 20 km h to the 90-m wide Avenida das

Americas in Rio de Janeiro, which has as many as 13 lanes in some locations and speed limits of 80 km h. One can expect that the wider, higher speed street will have a much poorer safety record than the narrow street in the historic center, and this will also impact the overall safety performance and safety impact of the BRTs implemented on these streets.

Another problem arising when trying to estimate the safety impact of a new transit system is that it is difficult to separate the impact of the transit system itself from that of other confounding factors. The implementation of a new BRT or LRT system typically involves major changes to the street infrastructure, the most important of which is usually a significant reduction in capacity for mixed traffic as a result of the placement of the dedicated transit infrastructure (i.e. bus lanes or tracks, and stations). This can result in major changes in traffic patterns not only on the street where the transit system is built, but in the surrounding areas as well. Moreover, as with any public works project, the construction of new transit infrastructure is also an opportunity for cities to improve markings, crosswalks, and traffic signals, all of which can improve safety and are not necessarily attributable to the transit system.

Finally, any before and after comparison of crash data needs to account for the problem of regression to the mean (RTM). RTM happens when, in repeated observations of the same variable (e.g. traffic fatalities at an intersection) unusually large or small observations tend to be followed by measurements that are closer to the mean (Barnett et al. 2004). Before and after comparisons which do not account for this can lead to overestimation or underestimation of the safety impact of any intervention.

Several studies have sought to answer this question of the overall safety impact for new BRT systems, while the issue is not raised in the literature on light rail (Bocarejo et al. 2012; Duduta et al. 2012, 2013; Goh et al. 2013). We discuss their findings below, as well as their different approaches to addressing the problems outlined above. The results of the different studies and summarized in Table 1.

Bocarejo et al. (2012) analyze the overall safety impact of two TransMilenio BRT corridors in Bogota, Colombia—the Av. Caracas and NQS corridors. The estimation of impact is based on a before and after comparison, looking at crash statistics for 1998 (before BRT implementation) and 2008 (after implementation) and observing the percent reduction in personal injury accidents on each corridor, compared to citywide trends. The authors note that injury accidents dropped by 60 and 48 % on Av. Caracas and NQS, respectively, while citywide injury accidents dropped by 39 % over the same period. As the focus of the study is not to estimate the magnitude of the safety benefits, the authors do not attempt to control for confounding factors, RTM, or citywide trends in providing the estimates.

Duduta et al. (2012), seek to estimate the magnitude of fatality reductions attributable to the TransMilenio BRT on the Av. Caracas corridor. The authors begin by noting that fatalities had been declining citywide in Bogota, at an average annual rate of 8 %, since the mid-1990s, as a result of various safety initiatives and policies implemented during that time. Therefore, fatalities on Av. Caracas would have been expected to decrease even in the absence of any intervention. A simple before and after comparison might, therefore, overestimate the safety impact of the

Table 1 Safety impacts of BRT systems

Transit system	"Before" conditions	"After" conditions	Change in accidents			Method	Controls for citywide trends	Source
			Fatal crashes	Injury crashes	All crashes			
Macrobus, Guadalajara (Mexico)	Curbside bus priority lane, private bus operators	Median BRT with overtaking lanes at stations, and some private operators in mixed traffic lanes	N/S	−69 %	−38 %	EB	Yes	Duduta et al. (2013)
TransMilenio NQS, Bogota	Mixed traffic	Median BRT with 2 bus lanes/direction	N/S	−28 %	N/S	B/A	Yes	Calculated from data provided by Bocarejo et al. (2012)
TransMilenio, Av. Caracas, Bogota	Central Busway, private bus operators	Median BRT with 2 bus lanes/direction	−48 %	−21 %	N/S	B/A	Yes	Calculated from data provided by Bocarejo et al. (2012) and Duduta et al. (2012)
Janmarg, Ahmedabad (India)	Mixed traffic	Median, single lane/direction BRT	−55 %	−28 %	−32 %	B/A	No	Calculated from data reported by CEPT, Ahmedabad
Melbourne BRT (Australia)	Conventional bus service in mixed traffic	Curbside BRT	N/S	N/S	−18 %	EB	No	Goh et al. (2013)

EB empirical Bayes, *B/A* before and after comparison, N/S not specified

BRT. To control for this, the authors build a baseline scenario of fatalities on Av. Caracas for a “no BRT” case, using the reported data from before the start of BRT construction and applying the 8 % annual reduction observed for the rest of the city. When comparing the projected baseline fatalities with reported fatalities for the years of BRT operation (2001–2008) the authors find that the street witnessed a reduction in fatalities of 48 % above what could have been expected from the existing trends. By applying a similar methodology to the Macrobús BRT in Guadalajara, Mexico, Duduta et al. (2013) find that after BRT implementation, crashes decreased across the board on the street by 38 %, while injury crashes decreased by 69 %.

One of the key limitations of the before and after analyses presented here is that they do not account for changes in traffic volumes. Since BRTs such as TransMilenio and Macrobús have eliminated mixed traffic lanes and reduced mixed traffic capacity, they may have reduced overall traffic on the streets as well. Furthermore, if that traffic was diverted to another street, then the BRTs may have simply shifted the risk elsewhere. Duduta et al. (2013) analyze the potential spillover effects from BRT by performing the before and after analysis at three scales: the street on which the BRT operates, a buffer zone around the BRT corridor that includes all streets within 3 km on each side of the corridor, and the metropolitan area. In addition to the 38 % reduction in crashes observed on the BRT corridor, the authors find an 8 % reduction in accidents at the metropolitan level, and also an 8 % reduction in the buffer area. This indicates that the implementation of the Macrobús BRT had resulted in a net safety improvement for the BRT corridor and the area around it, with no negative spillover effects.

Goh et al. (2013) propose the Empirical Bayes (EB) method as a very robust technique for estimating the safety impact of a new transit system, and apply EB to the Melbourne BRT. EB can help control for RTM effects, as well as for the general randomness of traffic accident data (particularly important when overall crash or fatality numbers are low). The basic premise of the EB method is that there are more clues to the safety of an entity (e.g. a street with transit service) than the accident records at that entity. Hauer et al. (2001) provide an overview of the method and its application to road safety. Applying the EB method involves averaging the actual crash counts on a street with an estimate of “expected” crash counts on the same street, based on a safety performance function, typically developed using a negative binomial or Poisson model with data from similar and nearby streets. Using EB, Goh et al. (2013) estimate that the implementation of the Melbourne BRT resulted in an 18 % decrease in accidents on those streets where the BRT operates. Duduta et al. (2013) apply EB to the Macrobús BRT in Guadalajara and find a larger safety impact, as shown in Table 1.

The results in Table 1 indicate that the estimates of safety impacts of BRT systems can vary widely depending on the methodology used for the analysis, the type of crashes studied, the local conditions, and the number of confounding factors that the authors were able to control for. Despite these limitations and the variations in the magnitude of impacts, the results of the different studies consistently show safety improvements when replacing various other types of bus systems with a BRT. As expected, the reductions in crashes are considerably higher in cases where the

BRT replaces private bus and minibus operators (e.g. Bogota and Guadalajara) than when the BRT is simply an upgrade of the infrastructure for operating a public bus system (e.g. Melbourne). It should also be noted that the implementation of a new transit system will typically be accompanied by an overall improvement in the infrastructure, with better signalization and markings, all of which might also contribute to the improved safety record.

The difference in the magnitude of impacts can also be attributed to differences in the overall street and intersection geometry across these various systems. In this context, it is important to note that while each study reports overall crash reductions at the corridor level, some of the studies point out the emergence of new black spots at several locations after the implementation of a BRT. Bocarejo et al. (2012) find that some areas in the vicinity of new TransMilenio stations have witnessed an increase in crashes, possibly explained by the higher volumes of pedestrians accessing the stations. Similarly, Duduta et al. (2012) found that while the interdiction of left turns across BRT lanes in Guadalajara has resulted in lower crash frequencies at intersections along the corridor, there has been a slight increase in crashes along the loops that redirect left turning traffic through the neighborhood.

Estimates of the overall safety impact of a transit system can be useful for evaluating a project or for estimating the potential safety benefits of similar projects as part of a cost-benefit analysis. Nevertheless, there are limits to the usefulness of such aggregate data, and there is a need for in-depth evaluation of common crash types on different transit systems and their respective countermeasures, as well as an understanding of how detailed design features impact safety performance.

4 Common crash types involving transit vehicles and their countermeasures

There is considerably more research available on this topic than on the overall safety impact of transit, and most of this research is focused on light rail systems in the United States and Europe, with limited research available on BRTs in Latin America and Asia. There are two common methodologies used in this type of analysis. When data quality allowed it, researchers have used existing crash data reports to extract the information on common crash types (Chalanton and Jadoul 2009). This requires accident records with a high level of detail, including an accident diagram. Since this level of detail is not always available, researchers have also used interviews with transit agency staff through which they classified accidents into common types or diagrams (Klaver Pecheux and Saporta 2009; Duduta et al. 2012). This is often also presented in the literature through case studies detailing the experience of various transit agencies with safety issues over time.

A key finding across the different studies is that the main crash types depend almost exclusively on the geometry of intersections along the transit corridor and the location of the transit infrastructure on the street. There appears to be no difference in terms of common crash types between bus and rail systems (Table 2).

Some of the other crash types mentioned in Table 2, such as mid-block pedestrian crashes and right-angle collisions are not necessarily specific to transit systems. Rather, they are typical crash scenarios on any urban road, and simply have

Table 2 Common crash types by type of transit system and geometric characteristics (sources: Klaver Pecheux and Saporta 2009; Chalanton and Jadoul 2009; Duduta et al. 2012)

Type of alignment	Bus systems	Rail systems
Median alignment, strong physical segregation between transit infrastructure and mixed traffic lanes	Vehicles making illegal left turns at intersections and colliding with a bus arriving from behind	Vehicles making illegal left turns at intersections and colliding with an LRV arriving from behind
Median alignment, without strong physical segregation between transit infrastructure and mixed traffic lanes	Vehicles entering the bus lanes and colliding with buses driving in the lanes or buses stopped at stations	Vehicles encroaching on the LRT tracks and colliding with LRVs
All median alignments	Vehicles running a red light and colliding with a bus at a right angle	Vehicles running a red light and colliding with an LRV at a right angle
	Pedestrians crossing in mid-block and being run over by buses	Pedestrians crossing away from designated crosswalks and being hit by LRVs or tramways

slightly different implications due to the geometry of a transit corridor with dedicated bus or light rail infrastructure. For example, one of the main advantages of BRT over mixed traffic—its independence from mixed traffic conditions—can also lead to more complex safety issues, as illustrated in Fig. 1. A common type of conflict observed on the Transoeste BRT in Rio de Janeiro involves pedestrians trying to cross the street in mid-block when traffic is stopped as a result of congestion. Pedestrians make their way between the stopped cars and emerge into the bus lane, where a BRT vehicle might be arriving at high speed. The limited visibility in this scenario makes it very difficult for the BRT driver to notice the pedestrian and brake on time to avoid a crash.

Chalanton and Jadoul (2009) identify comparable safety issues on tramway corridors in Belgium and France, with the difference that most tram—pedestrian accidents occur at stations and intersections, with only a small fraction occurring in mid-block. The higher quality of crash data available in European cities compared to Latin America allows the authors to identify some key contributing factors in terms of pedestrian behavior that contribute to crashes. The most frequently cited factors are "pedestrian running across the tramway tracks" and "pedestrian crossing without checking for traffic." Korve et al. (2001) highlight a similar issue on light rail corridors in the United States, noting that a common crash scenario involves "pedestrians darting across the LRT tracks without looking both ways (especially for a second LRV approaching the crossing from the opposite direction)." The similarity of findings across different types of systems in different regions of the world indicates that the safety issues depend more on the geometry of the transit corridor than on the type of technology used (bus or rail).

The findings also suggest that the key to addressing pedestrian safety on both BRT and LRT corridors is to better control and regulate pedestrian crossings. Korve et al. (2001) provide a list of possible countermeasures, including warning signs

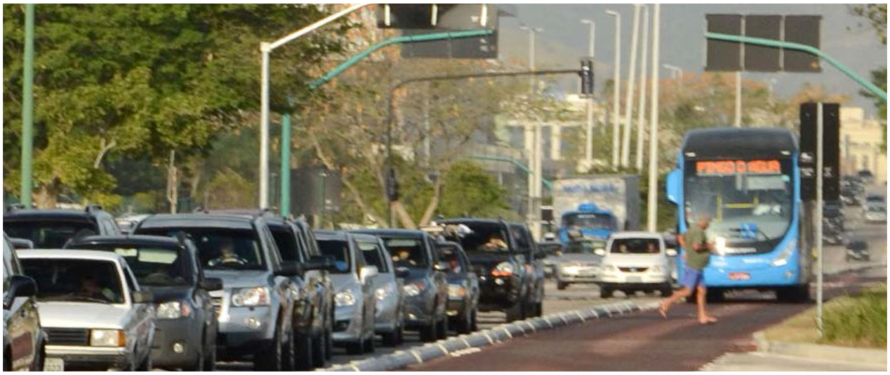

Fig. 1 Pedestrian emerging from between stopped cars in front of a BRT vehicle in Rio de Janeiro (photo by Mariana Gil, EMBARQ Brazil)

activated by the approach of an LRV, pedestrian Z crossings and swing gates, among others. Duduta et al. (2012) discuss the possibility of using guardrails to prevent jaywalking, coupled with signalized mid-block crosswalks to provide safer crossing opportunities. While the different studies offer a wide range of possible countermeasures, there is little evidence of the evaluation of the countermeasures' effectiveness in the literature. The most common type of evaluation available is in the form of reports from transit agencies that various measures have been effective, which are reported by researchers from interviews with transit agencies (Korve et al. 2001).

There are also crash types that are specific to BRT and LRT corridors. Median-running transit systems introduce an unusual configuration in which, contrary to any other street type, vehicles make left turns usually not from the leftmost lane [which is the transit right-of-way (ROW)], but from the second lane from the left. Motorists do not usually need to check for traffic coming from behind them when turning left, but they do need to check for that when turning left on a median running BRT or LRT corridor.

In a study of LRT safety in the United States, Klaver Pecheux and Saporta (2009) find that left turn collisions (i.e. collisions that occur when a motorist makes an illegal left turn in front of an approaching LRV) are the most common type of crash involving LRVs, accounting for 47 % of total LRV—motor vehicle crashes. Duduta et al. (2012) find a similar crash pattern for BRT systems in Latin America, left turn collisions are also the most common type of crash between BRT and motor vehicles (Table 2). On most Latin American BRTs, left turns are prohibited at most intersections and replaced with loops. When left turning demand warrants it, left turns are allowed with a protected left turn phase. Neither of these two options has managed to completely eliminate this type of crash. In Mexico City and Guadalajara, left turn collisions with BRTs have been recorded at locations with left turn prohibitions and loops, whereas on the Transoeste BRT in Rio de Janeiro, left turn collisions have occurred at intersections with protected left turn phases (Duduta et al. 2012; EMBARQ 2012). On LRT corridors in the United States, the same signage and signal options have been explored for managing left turns, including static no left-turn signs, and protected left turn phases. In addition, some agencies have explored the use of active turn prohibition signs coupled with approaching train warning signs. Klaver Pecheux and Saporta (2009) report that left turn crashes have still been recorded at these locations, including crashes happening when motorists made illegal left turns violating active turn prohibition signs and train-approaching warning signs.

The findings from the literature suggest that left turn collisions can be particularly difficult to eliminate. As in the case of pedestrian crashes, there is no systematic evaluation available of the impact of different countermeasures. There is, however, some evidence presented by Klaver Pecheux and Saporta (2009) citing reports by transit agencies which have implemented specific countermeasures and reported their impact. For example, the Los Angeles County Metropolitan Transportation Authority has implemented photo enforcement to cite drivers for running red left-turn arrows, and the agency reported that accidents caused by motorists making illegal left turns have decreased by 62 % as a result. Also in Los Angeles, the authors report that the use of left turn gates has resulted in a 94 % reduction in the number of risky moves by motorists at the intersections where the gates were installed. The authors also point out that this type of solution may be suited in semi-exclusive ROW operations but would not be practical for street operations.

There appears to be a learning curve for both the transit agency and for all road users after a new transit system is built. It is common to have a higher crash frequency at first, as road users are learning the new street layout and as the transit agency is learning about the issues associated with the new system, and there tends to be a decrease in accidents throughout the first few years of operation. Figure 2 illustrates this with the example of the Macrobús BRT in Guadalajara, using data provided by the State of Jalisco's Secretariat for Roadways and Transport.

The first crash involving a Macrobús BRT vehicle was recorded only a few hours after start of operations, as a truck entered the dedicated bus lanes and collided with a BRT vehicle. Crashes remained high during the first month of operation, but then decreased gradually through the next 2 years, with some occasional spikes. It should be noted here that Fig. 2 includes all crashes occurring on the corridor, not just those involving transit vehicles, and therefore offers a more complete picture of the safety of all road users on the BRT corridor. Another thing to note is that during the construction period from February 2008 through February 2009 crashes remained at comparable levels to before the start of construction. While we do not have traffic counts to verify this, it is very likely that traffic volumes were considerably lower during the construction period than before, since a major portion of the ROW was closed for construction and vehicle capacity was very limited. If that is the case, it indicates that the risk of crashes was higher during construction, which would suggest that there is room for improvement in construction safety practices. It also suggests that the potential negative safety impacts from construction should be factored into any evaluation of a transit system's overall safety impact.

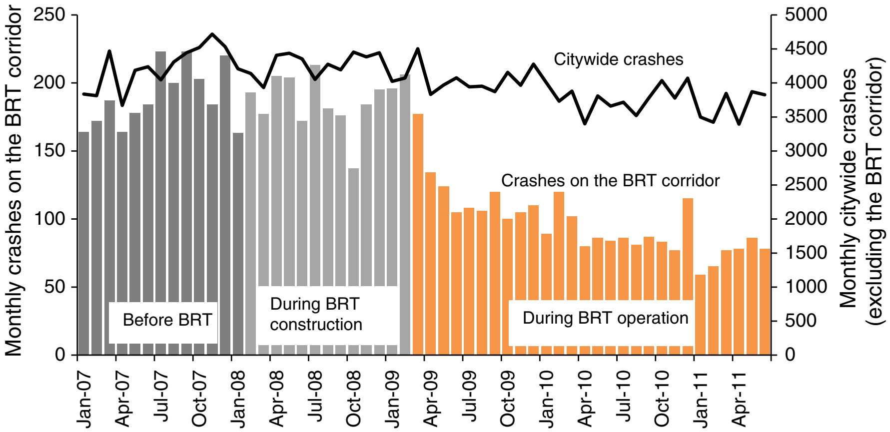

Fig. 2 Corridor level monthly crashes on the Macrobus BRT in Guadalajara through the construction and operation period, compared with citywide crashes

4.1 Bus and rail specific safety issues

While the findings from the literature clearly indicate that the main safety issues depend more on the geometry of the transit corridor than that of the technology used for the transit vehicles, there are two key safety issues are inherent to bus and rail systems: stopping distances and management of conflict points between transit vehicles.

Buses typically have higher braking rates and, as a result, shorter stopping distances than rail vehicles, though this varies significantly with the type of braking technology used, slope gradient, and weather conditions (Vuchic 2007). The main implication of this is in terms of pedestrian safety. Chalanton and Jadoul (2009) discuss this problem in the case of tramway corridors in Brussels and especially its implication on the rules governing un-signalized crosswalks. As the authors point out, the implicit rule on any un-signalized crosswalk is that the pedestrian has priority over all other traffic modes. However, due to the longer stopping distance required for tramways as compared to most rubber-tired vehicles, a tramway operator may not always have sufficient time to stop for a pedestrian on an un-signalized crosswalk. As a response to this issue, the city of Brussels had created more complex rules for un-signalized crosswalks across tramway tracks. According to these rules, pedestrians have priority for that portion of the crosswalk which intersects with the mixed traffic lanes, and tramways have priority for the portion that covers the rail tracks. The study does not present evidence on the safety performance of such a configuration.

Based on the differences in braking rates, it could be argued that buses represent an overall safer option that tramways with regards to their ability to stop in time to avoid collisions. However, the higher braking rate achievable by buses poses a safety issue for passengers inside the bus. In the case of TransMilenio, for example, sudden braking accounts for nearly as many injuries as collisions, with the difference that the injuries happen to bus occupants as opposed to other road users, and that they tend to be less severe, according to crash data collected by TransMilenio.

But another key difference is the management of conflict points between transit vehicles. This is less a technology issue and more an issue of different historical practices for rail versus bus operating agencies. In the case of rail systems, the general practice has traditionally been to use signals whenever there is a potential conflict, especially in case where tracks merge or intersect at stations or terminals. The majority of BRT systems, on the other hand, tend to leave most conflict points un-signalized and rely on driver training to manage conflicts. Some BRT agencies are employing roundabouts to manage conflict points, such as at the main entrance to the Alvorada Terminal in Rio de Janeiro, where the Transoeste and Transcarioca BRT routes are planned to intersect.

While we can expect traffic signals to be the safer option, there are no studies in the literature comparing the safety performance of these different options. However, the crash data provided by BRT operating agencies in several Latin American cities indicates that some types of conflict points are associated with specific crash types. For example, some BRT systems, such as TransMilenio, Transoeste (Rio de Janeiro) and Metropolitano (Lima) use overtaking lanes at stations to provide increased capacity. This creates a conflict point between express buses that use the overtaking lane to bypass a station, and local buses that are leaving the station and merging into the overtaking lane to avoid other local buses servicing the station. This type of conflict point can be particularly dangerous on corridor sections with few or no intersections, because express buses operate at freeway speeds in those conditions. All three systems mentioned above have recorded crashes between local and express buses at stations. In cases where the speed difference between the buses was high, this has resulted in dozens of injuries per crash. It is important to note here that the risk factor is the way in which the conflict point is designed and not the choice between bus or rail. We consider this to be a BRT specific safety issue simply because it is common practice for BRT agencies to manage conflicts in this manner.

5 The safety performance of different transit corridor design features

This is the third main theme found in the literature, and it involves considerably more methodological challenges than simply looking at common crash types and countermeasures. The main problem is that if one wanted to compare, for example, the safety performance of open median Busway stations with on-board fare collection to that of closed BRT stations with turnstiles and off-board fare collection, it would be quite challenging to assemble a usable dataset. The problem, first of all, is that any statistical study that uses transit stations as the unit of observation risks having a very limited sample size, especially if looking at BRT or LRT systems, for the simple reason that most cities do not have that many BRT and LRT stations (Cervero 2006). On the other hand, those cities that do have more extensive BRT networks (such as Mexico City, which had 118 median BRT stations[2] as of 2013) usually opt for one station configuration and use that throughout the system, with only minor variations. Thus, in Mexico City, one can find 118 closed median BRT stations for lines 1 through 3, and several types of curbside stops for line 4, with only two examples of open median station with on-board fare collection. There is not enough variation in station design for a robust statistical analysis. Other Mexican BRT systems have mostly replicated the configurations found in Metrobus, and as a result, it would be impossible to create a dataset based on Mexico with sufficient variation in station design to be able to test their safety performance. The only solution would be to create an international dataset and include examples from countries such as Brazil, which use predominantly open median stations on Busways. But the problem then becomes that the definition of a crash, injury, or even a traffic fatality is different between Brazil and Mexico[3] (WHO 2009) which makes it nearly impossible to find a reliable dependent variable for the study. As a result, studies that have aimed to use statistical models to test the safety performance of transit design features have had to restrict their datasets to a single city and were only able to observe those variables that changed within a system (Diogenes and Lindau 2009; Duduta et al. 2012).

This proved to be less of a problem for studies looking at LRT safety in the United States, since there is considerably more consistency in crash data definitions and reporting standards across US states, and also sufficient variation in system design between different cities.

The methodologies used for evaluating different system designs range from simple cross-tabulation that shows crash rates per intersection for different types of geometric layouts, to crash frequency models that aim to explain differences in crash rates at different locations by differences in geometric layout, after controlling for exposure.

Cleghorn et al. (2009) provide a comparison of crash rates by type of ROW across different LRT systems and agencies across the US. Though it does not control for detailed intersection geometry, traffic volumes, or for number of track miles by ROW type, this analysis can provide a rough comparison of relative safety performance of different systems and alignments, and allows for inter-system and intra-system comparison in the same table. The authors find that non-exclusive ROW (i.e. mixed traffic operations or LRT and pedestrian mall) concentrate the majority of crashes, followed by semi-exclusive ROW (i.e. separate or shared ROW, protected by barrier curbs) and exclusive ROW (i.e. no at-grade intersections, separate ROW). Duduta et al. (2012) report similar findings for Latin American BRTs. A common type of BRT crash involves vehicles entering the bus

[2] Source: Metrobus, Ciudad de Mexico, Fichas tecnicas, retrieved from http://www.metrobus.df.gob.mx/fichas.html#uno and excluding Metrobus Line 4, which does not have a median alignment.

[3] Brazil uses the standard international definition of a traffic fatality (i.e. a death that occurs within 30 days of a crash and as a result of that crash) while in Mexico, only fatalities at the scene of the crash are reported. While WHO provides adjustment factors for the 30-day definition, these are calibrated at the country level, making their use at the city level subject to high uncertainty. Moreover, the WHO also points out that there is an under-reporting of traffic fatalities in Latin American countries, regardless of the definition used. There are studies that quantify the level of under-reporting, but again these are national level, not city level studies, making their application to city level analysis subject to uncertainty (Jacobs et al. 2000).

lanes and colliding with BRTs (Table 2). This type of crash was relatively common on systems such as Macrobús in Guadalajara or Metrobús in Mexico City, which separate the bus lanes from the mixed traffic lanes through raised pavement markings that serve more as a warning to drivers and not as an actual physical barrier. On the other hand, the TransMilenio BRT in Bogota features curbs or medians separating the bus lanes from other traffic, and the incidence of such crashes is considerably lower.

A more in-depth evaluation of the safety of different design features can be done through crash frequency modeling. Since crash data are count variables, they are usually best represented by a Poisson or negative binomial distribution, depending on the degree of over-dispersion of data (Ladrón de Guevara et al. 2004; Dumbaugh and Rae 2009). We have found several examples of crash frequency models for bus systems in the literature, but none for rail systems.

In a study of pedestrian safety in New York City, Viola et al. (2010) found that streets featuring bus routes (including a combination of mixed traffic operations and bus priority lanes) had higher pedestrian crash rates than any other streets, using crash frequency modeling. The authors attributed this finding to the higher pedestrian volumes on bus routes, compared to other streets. Diogenes and Lindau (2009) use a Poisson model to test the impact of street geometry and signal configuration on the frequency of pedestrian crashes at mid-block crossings in Porto Alegre, Brazil. They find that the presence of open Busway stations in the median and the presence of open Busway systems in general was a significant predictor of pedestrian crash rates, after controlling for pedestrian and traffic volumes. This indicates there is a risk on Busways beyond the higher levels of exposure for pedestrians, especially around stations. This echoes a similar finding from Bocarejo et al. (2012) who found that the implementation of the TransMilenio BRT in Bogota had resulted in the appearance of new pedestrian black spots near stations, though that study did not use crash frequency modeling.

The three studies listed above illustrate the problem discussed at the beginning of this section—it is difficult to make comparisons across systems and most studies focus on one transit system alone. The three cases look at examples from across the spectrum of bus systems, from bus priority lanes to fully segregated BRT with station access via overpasses, yet each study found some reason for concern around pedestrian safety on bus corridors, especially in the vicinity of stations. The limitations in the data discussed previously make it impossible, however, to have an accurate comparison across system types.

Diogenes and Lindau also found that signalized mid-block crosswalks were correlated with reduced pedestrian crash frequencies, though the results were significant only at the 90 % confidence level. The authors conclude that the Busways in Porto Alegre pose some concern for pedestrian safety, as locations around mid-block Busway stations had significantly higher pedestrian crash rates. Nevertheless, the authors also point out the limitations of the methodology discussed above. In addition, the authors point out that it was not possible to separate the safety impact of a crosswalk from that of a traffic signal, since the two features were always present together.

Duduta et al. (2012) propose to deal with these methodological issues by treating each city's bus transit system as a case study, and developing crash frequency models for different case studies using—to the extent possible—the same independent variables. Intra-system comparisons can then be made by interpreting the model results, while inter-system comparisons could then be made between the sign and the significance of each variable across the different case studies. For each city, the authors assemble a dataset of intersections and develop separate crash frequency models for motor vehicle crashes and pedestrian crashes across three cities in Latin America, Mexico City, Guadalajara (Mexico), and Porto Alegre (Brazil). For Mexico City, for example, three types of bus system configurations are included in the model as fixed effect (dummy variables), center-lane BRT, curbside bus lane, and counterflow bus lane (defined, for the purposes of this study, as a street with one-way mixed traffic and a single, curbside bus lane going in the opposite direction), while also controlling for intersection geometry and exposure.

The authors find that the presence of the center-lane BRT and that of the curbside bus lane have no statistically significant impact on crashes, after controlling for intersection geometry. The model results suggest a correlation between the presence of counterflow lanes and a higher incidence of crashes in Latin American cities. While this indicates a potential concern regarding the safety of counterflow lanes, it should also be noted that other factors impacting safety may not be accounted for in the model. First of all, the signalization of counterflow lanes in Mexico City is particularly poor, with some counterflow lanes lacking any sort of vertical or pavement signs indicating their presence to road users. Furthermore, several sections of counterflow lanes pass through areas of Mexico City with heavy pedestrian volumes, which occasionally causes pedestrians to walk in the bus lanes. These risk factors are not accounted for in the model and they might explain at least in part the difference in safety records between counterflow and other types of lanes.

While the models did not pick up a statistically significant difference in safety performance between center-lane and curbside alignments, it is important to consider the other changes to the street infrastructure needed in order to accommodate each type of bus system. A curbside lane is usually introduced by replacing a traffic or parking lane, with no other major changes necessary. Introducing a center-lane BRT (or a median running LRT) is considerably more complex. At a minimum, two lanes of traffic need to be removed (three if the street does not already have a median) in order to accommodate one bus lane or rail track per direction and a median station. The median is usually continued across the rest of the corridor and it is commonly used to break up the pedestrian crossings and provide a median refuge. There are also restrictions on left turns, to eliminate conflicts but also to reduce the number of signal phases at intersections, which can help increase both operating speed and capacity for the transit system. All of these different elements—fewer traffic lanes, central median, shorter pedestrian crossings, left turn restrictions—were significantly correlated with fewer crash frequencies in the models. In the case of left turn restrictions, this shows that while this measure does not eliminate left turn collisions altogether, it reduced crashes overall.

6 Conclusions and further research

This paper has provided an overview of the main topics commonly explored in the transit safety literature, and discussed their methodological issues and main findings. A key takeaway across the different studies is that the main safety issues are likely to depend considerably more on the design of the transit corridor than on the vehicle technology employed. Nevertheless, bus and rail operating agencies also have their own different ways of addressing safety, particularly in the area of managing conflicts between transit vehicles. Rail systems tend to be more heavily signalized, while bus operating agencies rely more on drivers to manage conflicts. This also suggests the opportunity for sharing best practices across different bus and rail systems. While solutions such as left turn gates, which are occasionally employed on North American LRT systems, may not be applicable to bus operations, other solutions, such as signalization of conflict points, is an interesting solution to explore for BRT stations and terminals with overtaking lanes.

Overall, there is a large body of evidence across the different studies on the main crash types that can be expected to occur on different corridor layouts, and some evidence on their expected frequency. While all the studies suggest possible countermeasures for all the problems identified, there is a gap in knowledge about the effectiveness of many countermeasures. When estimates of safety impacts do exist, they tend to be based on anecdotic evidence from one transit agency only and not on a systematic evaluation of a countermeasure across different agencies. This is a key area where more research is needed, as it would allow transit agencies to evaluate the cost-effectiveness of different measures and select the best way to improve safety based on the constraints of their budget.

Another important issue to consider is that some of the factors that can improve safety on a transit system are not the responsibility of the transit agency. For example, the conflict points at BRT stations discussed above could be addressed by redesigning the merging area between local and express bus routes. In the case of a median-running BRT system, this would imply carving out some space out of the central median. However, in cities such as Rio de Janeiro or Bogota, that median is under the jurisdiction of another city agency, and any solution involving changes to the median requires the approval of this other agency. Similarly, several studies have pointed out that the main risk to transit passengers is not while they are riding in a transit vehicle, but rather when they walk to and from the station (Chalanton and Jadoul 2009; Bocarejo et al. 2012; Duduta et al. 2012). Yet transit agencies rarely have any control over station access paths, especially across major intersections. This shows that transit safety is not only an issue of having the right infrastructure design, but also of having the right institutional framework in place that allows for integrated planning across different agencies, in order to reach safety goals.

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