Traffic Safety on Bus Corridors

Guidelines for integrating pedestrian and traffic safety into the planning, design, and operation of BRT, Busways and bus lanes

Pilot Version - Road Test

Nicolae Duduta, Claudia Adriazola, Carsten Wass, Dario Hidalgo, Luis Antonio Lindau

Report by:

NICOLAE DUDUTA
Transport Planner
EMBARQ, the WRI Center for Sustainable Transport
nduduta@wri.org

CLAUDIA ADRIAZOLA
Director, Health and Road Safety Program, EMBARQ
cadriazola@wri.org

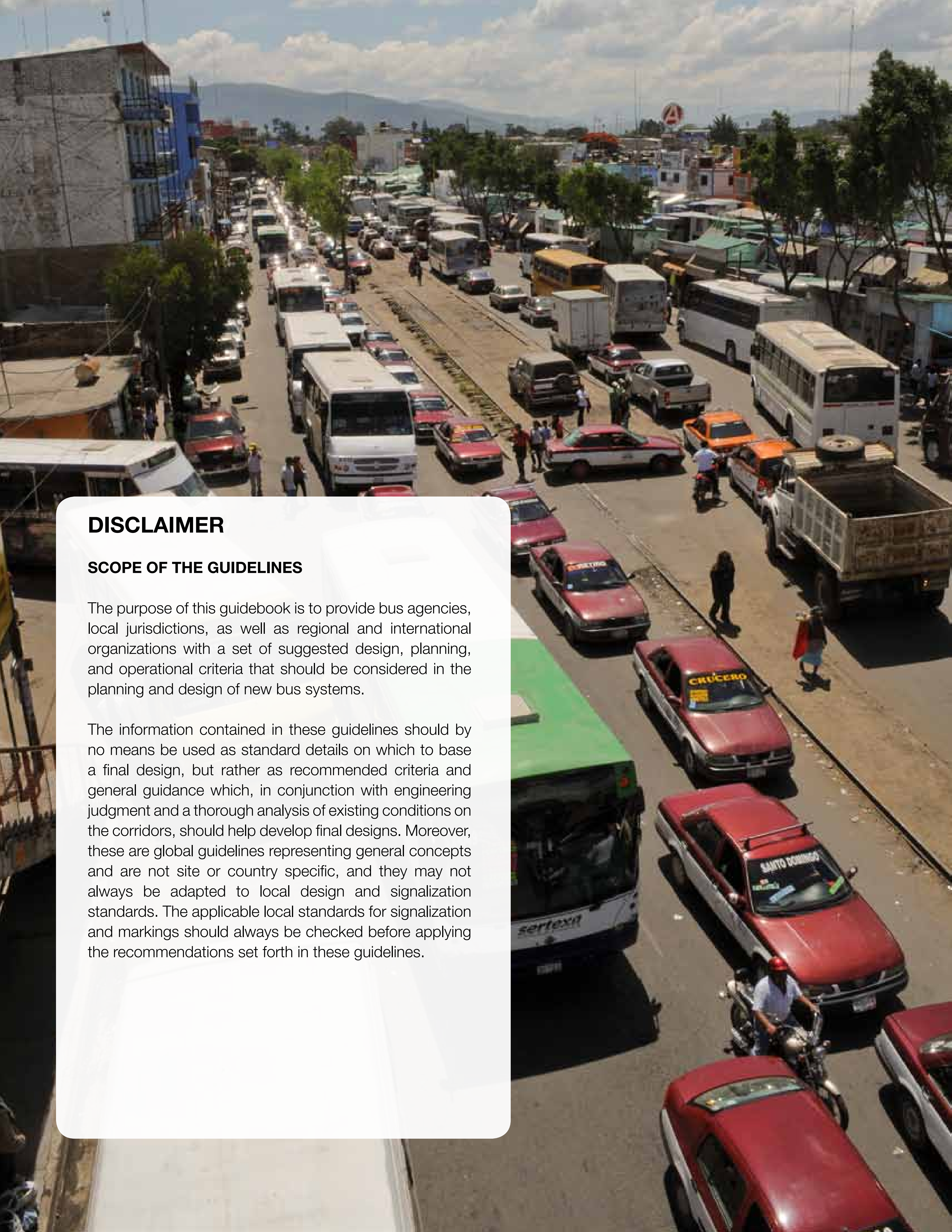
CARSTEN WASS
Technical Director, Consia Consultants
wass@consia.com

DARIO HIDALGO
Director of Research and Practice, EMBARQ
dhidalgo@wri.org

LUIS ANTONIO LINDAU
President, EMBARQ Brasil
tlindau@embarqbrasil.org

CONTENTS

Bloomberg Philanthropies



DISCLAIMER

SCOPE OF THE GUIDELINES

The purpose of this guidebook is to provide bus agencies, local jurisdictions, as well as regional and international organizations with a set of suggested design, planning, and operational criteria that should be considered in the planning and design of new bus systems.

The information contained in these guidelines should by no means be used as standard details on which to base a final design, but rather as recommended criteria and general guidance which, in conjunction with engineering judgment and a thorough analysis of existing conditions on the corridors, should help develop final designs. Moreover, these are global guidelines representing general concepts and are not site or country specific, and they may not always be adapted to local design and signalization standards. The applicable local standards for signalization and markings should always be checked before applying the recommendations set forth in these guidelines.

EXECUTIVE SUMMARY

Traffic safety is an aspect that has consistently been missing from publications and planning guides for Bus Rapid Transit (BRT) and Busway corridors.

This was an important gap. Traffic fatalities are projected to become the fifth leading cause of premature death worldwide by 2030, ahead of HIV/AIDS, violence, tuberculosis, or any type of cancer, and most of this growth is expected to occur in developing world cities, according to the World Health Organization.

The impact of bus systems on road safety is particularly important because they tend to be situated along major urban arterials. A study in New York City has found that arterials account for about 15% of the road network in the city, but over 65% of severe pedestrian crashes (Viola et al. 2010). A study in Mexico City indicates that all crash types are heavily concentrated on the main arterials, where major bus routes are usually located (Chias Becerril et al. 2008).

The implementation of a high capacity transit system on any urban arterial will attract large volumes of pedestrians to streets where risks are already high. In New York, streets with bus routes had consistently shown higher pedestrian crash rates than any other streets (Viola et al. 2010). In Porto Alegre, Brazil the presence of Busway corridors and bus stations was correlated with higher mid-block pedestrian crash rates (Diogenes and Lindau 2009). On the other hand, the implementation of some BRT systems, such as Macrobus in Guadalajara and TransMilenio in Bogota, resulted in a significant reduction in crashes and fatalities on the respective corridors. There appears to be a wide range of potential safety impacts from the implementation of bus systems.

EMBARQ has been conducting research on the traffic safety aspects of bus system planning, design, and operations, collecting and analyzing data from over 30 bus corridors from developing world cities, conducting road safety inspections and audits on BRT and Busways, and interviewing road safety experts and bus agency staff to learn from their experience with crashes on bus corridors.

We were thus able to identify the main risks and common crash types on bus corridors, and also the safety impact of different BRT and Busway design features. We found that some key design elements of bus systems can significantly improve safety (e.g. closed stations with high platforms, center-lane systems with left turn interdictions) while others can increase the risk of crashes (e.g. counterflow lanes). We also found that the overall geometry of the road and especially the size and complexity of intersections are important predictors of crash rates on bus corridors. Based on these findings, we were able to formulate a set of design recommendations for improving road safety on bus corridors.

This guidebook is designed as a practical guide for transportation planners, engineers, and urban designers involved in the planning and design of bus systems. It covers a broad spectrum of system and corridor types, ranging from curbside bus priority lanes all the way to high capacity, multi-lane BRTs.

While the main purpose of the guidelines is to illustrate how safety can be improved in bus system design, we also considered how each of our design concepts impact bus operations (in terms of passenger capacity of the bus system, fleet size requirements, and pedestrian capacity of areas around stations) as well as accessibility.

The designs illustrated in this guidebook represent best practices that balance the safety of all road users with the need to provide high passenger capacity and also provide accessible, liveable urban spaces.

ROAD TEST

This is a preliminary version of the guidelines and should be regarded as a work in progress. It is being released by EMBARQ as a pilot version to be tested by our centers as well as external partners in 2012. The lessons learned from this road test will be incorporated into a final version to be released in 2013, and all the road testers will be acknowledged in the final publication.

The road test and review process is open to everyone. Any local or national government agency, development bank, NGO, consultancy, or anyone else interested in testing our guidelines on new or existing bus systems is invited to contact EMBARQ at embarq@wri.org. We can make available copies of this document, as well as questionnaires for providing feedback.

CITIES AND BUS SYSTEMS INCLUDED IN THE PROJECT

ROAD SAFETY INSPECTIONS

- Rede Integrada de Transporte, Curitiba
- TransMilenio, Bogota
- BRTS, Delhi
- Janmarg, Ahmedabad

CITYWIDE CRASH FREQUENCY MODELS

- Mexico City
- Guadalajara
- Porto Alegre
- Bogota

ADDITIONAL DATA COLLECTION AND ANALYSIS

- Metrobus Line 2, Mexico City
- Macrobus, Guadalajara
- TransMilenio, Bogota
- Megabus, Pereira,
- BRT, Santiago de Cali
- SIT, Arequipa
- Busways, Belo Horizonte
- Boqueirao and South Line, Curitiba
- Southeast Busway, Brisbane
- Route 99 and Burrard Street, Vancouver
- BRTS, Delhi
- Busways, Sao Paulo

ROAD SAFETY AUDITS ON BUS CORRIDORS

- Metrobus Lines 3, 4, and 5, Mexico City
- SIT, Arequipa, Peru
- C. Machado and Dom Pedro II Busways, Belo Horizonte
- Antonio Carlos Busway, Belo Horizonte
- Transcarioca BRT, Rio de Janeiro
- Transoeste BRT, Rio de Janeiro
- BRT, Izmit, Turkey
- BRT, Indore, India

DATA SOURCES

- Ministerio de Transporte, Colombia, 2011
- TRANSMILENIO S.A. 2011
- Gobierno de la Ciudad de México 2011
- Secretaría de Vialidad y Transporte de Jalisco, 2011
- Estudios, Proyectos y Señalización Vial S.A. de C.V. 2011
- Empresa Pública de Transporte e Circulação (EPTC), Porto Alegre, 2011
- Matricial Engenharia Consultiva Ltda., 2011
- Empresa de Transporte e Trânsito de Belo Horizonte S.A. (BHTrans), 2011
- Urbanização de Curitiba S.A. (URBS), 2011
- Companhia de Engenharia de Tráfego de São Paulo, 2011
- Delhi Police, 2010
- Road Safety and Systems Management Division, Brisbane, Queensland, Australia, 2009
- Insurance Corporation of British Colombia (ICBC), 2011
- Instituto Metropolitano Protransporte de Lima, 2012

METHODOLOGY

In order to evaluate the safety performance of bus systems around the world, we used a combination of crash data analysis, road safety inspections, and discussions with bus agency safety experts.

DATA COLLECTION

There were no publicly available datasets on crashes on bus corridors in any of the cities we used for our study. For this reason, we worked closely with EMBARQ Centers in Mexico, Brazil, the Andean Region, Turkey, and India, to collect the information needed for our study. We compiled crash datasets using the different data sources available locally (see opposite page). Most of the data were provided by municipal, regional, or national agencies in charge of maintaining road safety databases. For the TransMilenio system in Bogota, we received additional information from the BRT operating agency.

CRASH FREQUENCY MODELS

In the case of four cities in our dataset (Mexico City, Guadalajara, Porto Alegre, and Bogota), the quality and quantity of the data collected were sufficient for developing statistical models. We developed separate crash frequency models for vehicle collisions and pedestrian crashes, using negative binomial or Poisson regressions, depending on the characteristics of the data (Ladron de Guevara et al. 2004).

These models allowed us to explain differences in crash rates at different locations using factors such as road and intersection geometry, bus system design, and land use. We created four variables for bus system configuration: center-lane BRT, center-lane Busway, curbside bus lane, and counterflow bus lane, corresponding to the types of bus corridors present in the cities where we developed the models.

The crash frequency models helped identify key predictors of crash rates on bus corridors - such as the size and complexity of intersections, or the presence of counterflow lanes - and we used these findings to inform our recommendations. The methodology and main findings from the models are described in detail in Appendix A.

ADDITIONAL DATA ANALYSIS

For several bus corridors in our dataset (Macrobus, Guadalajara; Avenida Caracas, TransMilenio, Bogota; and BRTS, Delhi) we had crash data from both before and after the impementation of the bus systems. We were therefore able to evaluate the overall safety impact of implementing each bus system.

For most other corridors in our dataset, we did not have sufficient information to carry out a robust statistical analysis. Nevertheless, we were able to obtain useful information by analyzing frequent crash types and their contributing factors, or by comparing crash rates on different corridors or sections of corridors.

ROAD SAFETY INSPECTIONS

EMBARQ partnered with external certified road safety auditors to carry out inspections of several existing bus systems, including RIT in Curitiba, TransMilenio in Bogota, Janmarg in Ahmedabad, and the BRTS corridor in Delhi. The inspections were useful in identifying safety problems on these corridors that did not always appear in the crash data (e.g. the maintenance of pavement markings and traffic signs, dangerous road user behavior, etc.).

DISCUSSIONS WITH BUS AGENCY STAFF

As part of road safety audits and inspections, we met with staff from each bus agency to learn from their experience dealing with safety on their bus systems. We learned about other safety concerns that did not appear in the police data (such as minor crashes resulting from buses docking improperly to the stations), but also about various safety initiatives implemented on each bus corridor. In some cases, this also helped identify safety issues not captured in the data - such as the growing concern among Metrobus staff in Mexico City about the risk of crashes between BRT vehicles and cyclists using the bus lanes.

ROAD SAFETY AUDITS

While the main role of audits was to provide immediate input to bus agencies on how to improve safety on bus corridors currently under design, the audits also provided valuable input to our road safety guidelines for public transport. In particular, they allowed us to observe common safety problems in the designs of bus corridors, and tailor our recommendations accordingly.

FINDINGS

SAFETY IMPACTS OF A BRT

The overall safety impact of implementing a bus system on a corridor varies depending on the characteristics of the system and the existing conditions on the street. In developing world cities, implementing BRT systems has generally proven to have a positive impact on safety. Other types of corridors, such as Busways or bus priority lanes, have not always had the same positive impact.

A BRT usually involves eliminating several mixed traffic lanes on a street, separating bus traffic from other modes, and adding or expanding a median (in the case of center-lane BRTs) which reduces the length of pedestrian crossings. Bus operations are better organized, commonly replacing a variety of services with a single operating agency with common standards for driver training, vehicle maintenance, etc.

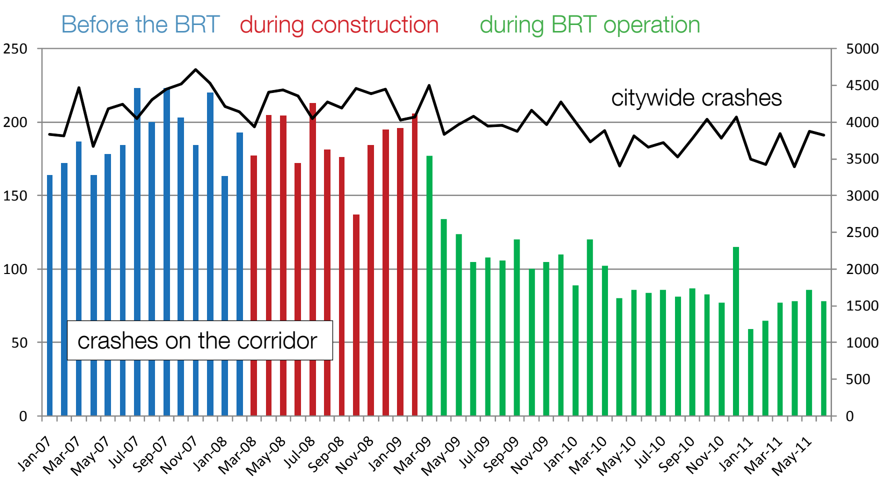
Macrobus in Guadalajara (which replaced an existing bus priority lane on a street with heavy traffic) and TransMilenio in Bogota (which replaced an existing central Busway) both contributed to significant reductions in crashes and fatalities on their respective corridors. Crashes went down by 46% on Calz. Independencia in Guadalajara after Macrobus started operations, while fatalities decreased by 60% on Av. Caracas in Bogota after the implementation of the first TransMilenio corridor.

Not all bus systems had the same positive impact on safety. The Cristiano Machado Busway, in Belo Horizonte (Brazil) remains the street with the highest crash frequencies citywide, despite the presence of a central Busway. In Delhi, after the implementation of the BRTS system, traffic fatalities initially increased on the corridor, and crashes between buses and pedestrians became a particular concern.

While some systems may have a more positive impact than others, there is always room for improving safety performance, through the design of stations, intersections, and road segments.

MACROBUS, GUADALAJARA

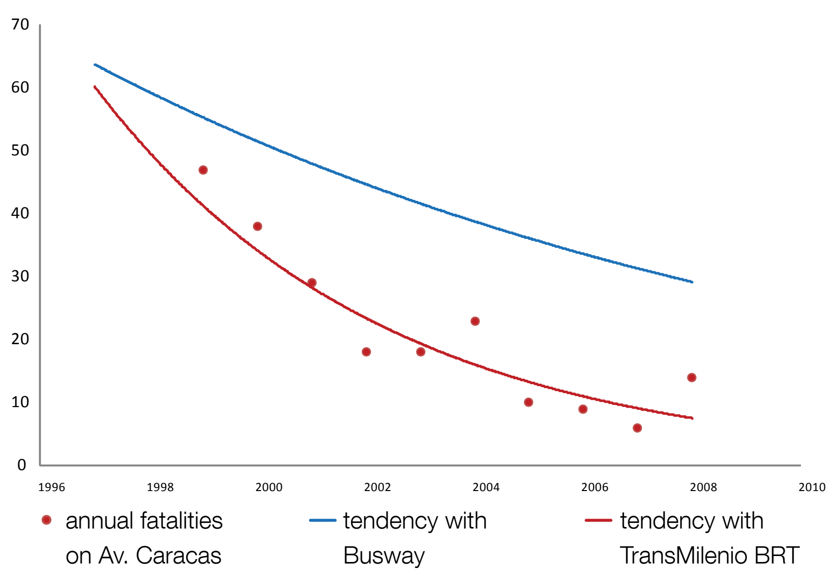
Crashes before and after the implementation of the Macrobus BRT



Source: computed from statistics provided by Secretaria de Vialidad y Transporte de Jalisco, 2011.

AV. CARACAS, TRANSMILENIO, BOGOTA

Fatal crashes before and after the implementation of the TransMilenio BRT



Source: computed from statistics provided by TRANSMILENIO S.A. 2011, Ministerio de Transporte de Colombia 2011, and WHO 2009.

SAFETY IMPACTS BEYOND THE CORRIDOR

After learning that crashes had been reduced, on average, by 46% on the Macrobus BRT corridor in Guadalajara, we checked whether the safety improvement on the corridor may have been offset by an increase in crashes in the area around the corridor. This was based on the hypothesis that the decrease in crashes simply reflects a reduction in traffic volumes and that the traffic had simply been rerouted and had shifted the risk from the BRT corridor to other streets.

The crash data from Guadalajara suggest this was not the case. We selected a 3-kilometer buffer zone on both sides of the corridor. We chose this width in order to include several major arterials than run parallel to the BRT corridor, including Calz. del Ejercito, Av. Alcalde, and Av. 16 de Septiembre. Crashes in the buffer zone (excluding the BRT corridor) decreased by 8% over the same period of time - a trend consistent with that of the rest of the city.

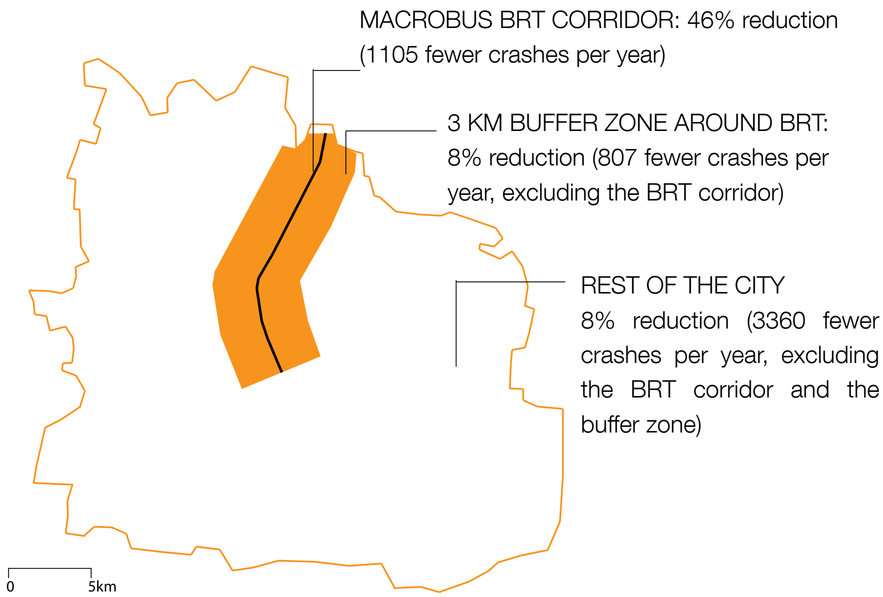
At a smaller scale, however, there were several instances where the implementation of the BRT shifted the risk of crashes to nearby streets. Left turns were prohibited at most intersections - a common feature on center-lane BRT systems. The left turns were replaced with loops, redirecting traffic through the neighborhood.

Some of the better designed loops did not have any impact on crashes in the neighborhood around the BRT corridor. But in at least one case (at the intersection between Calz. Independencia and Circunvalacion) the creation of the loop resulted in an increase in crashes at the intersections along it. This particular loop startes before the intersection, and involves one right turn and two left turns for vehicles trying to reach Av. Circunvalacion.

Annual crashes at the intersection on the BRT corridor with the left turn interdiction went from 93 before the BRT to 43 after. But on Circunvalacion and Siete Colinas (where vehicles may now turn left onto Circunvalacion) crashes increased from 17 to 42. When considering the two intersections together, there was a decrease in accident, from 110 to 85. But the improvements on the BRT corridor were partly offset by an increased risk on the nearby streets.

MACROBUS, GUADALAJARA

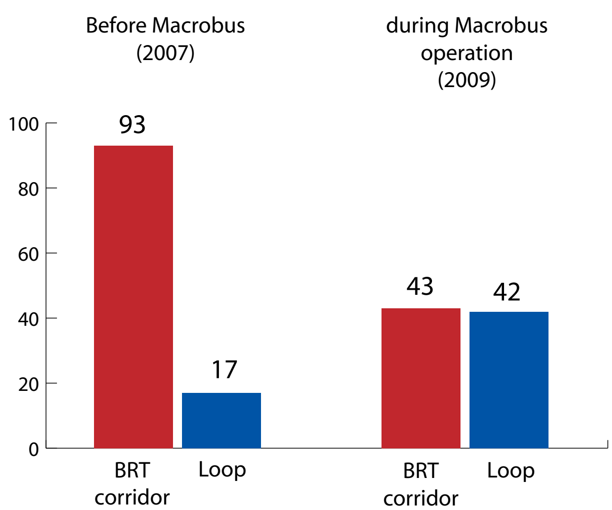
Annual crashes before and after the implementation of the BRT: citywide



Source: computed from statistics provided by Secretaria de Vialidad y Transporte de Jalisco, 2011.

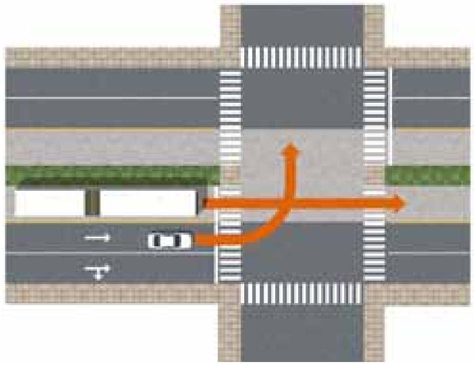
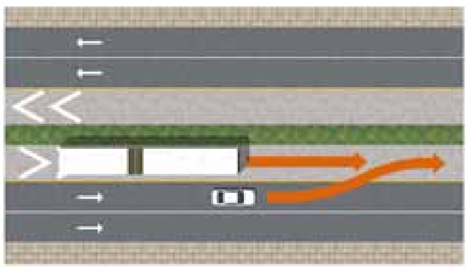
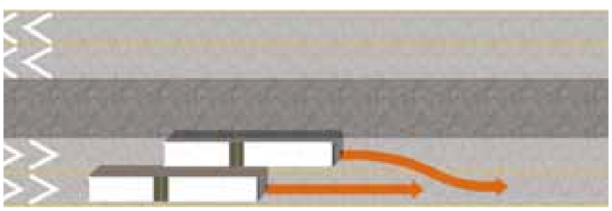
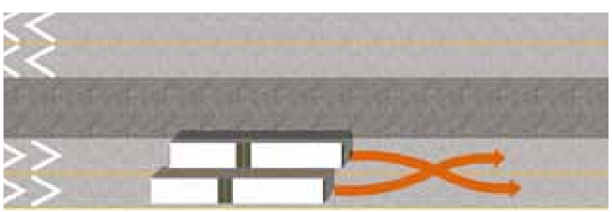
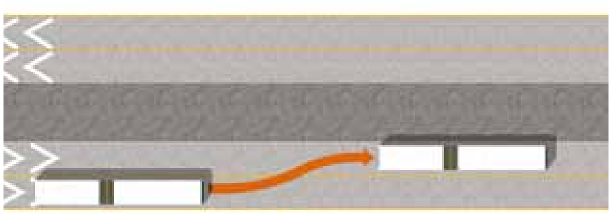
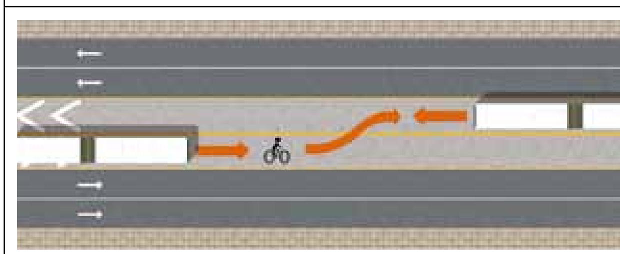
MACROBUS, GUADALAJARA

Annual crashes before and after the implementation of the BRT at two intersections, one on the corridor (red) and one on the loop where left turning traffic from the corridor was redirected



Source: computed from statistics provided by Secretaria de Vialidad y Transporte de Jalisco, 2011.

COMMON CRASH TYPES

Crash diagram	Description
	LEFT TURNS ACROSS BUS LANES This is the most common type of collision between buses and general traffic on center-lane bus corridors.
	UNAUTHORIZED VEHICLES IN BUS LANES A common crash situation on all corridors with dedicated bus lanes where there is no strong physical separation between the bus lanes and other lanes. Unauthorized vehicles enter the bus lanes and collide with buses.
	CRASHES BETWEEN LOCAL AND EXPRESS BUSES A potentially severe type of crash on multi-lane BRT systems with express lanes. Local buses leaving the station and merging onto the express lanes collide with express buses traveling through the station at high speed.
	SIDE SWIPE BETWEEN BUSES AT A STATION A less severe type of crash that can occur when a bus is attempting to leave a station and another bus is trying to access the station from the express lane.
	REAR-END CRASH AT A STATION PLATFORM This occurs when a bus is lining up behind another one to dock at the station platform, but comes in too fast and collides with it.
	CRASHES BETWEEN BRT AND CYCLISTS Cyclists using the bus lanes often attempt evasive maneuvers when buses approach, and can be hit by another bus, or lose control and hit the lane separators, sometimes resulting in serious injuries.
All the diagrams above represent confirmed crash types from one or several of the following bus systems: Mexico City Metrobus, Guadalajara Macrobus, TransMilenio, Metropolitano in Lima.	

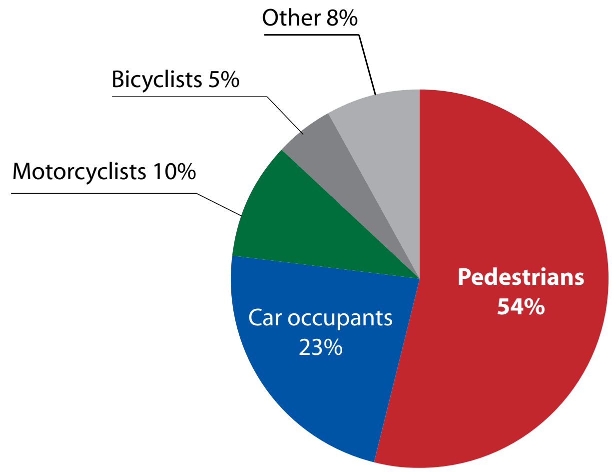
FATAL CRASHES

While accounting for only 7% of reported crashes on bus corridors, pedestrians represent over half of fatalities across all the bus systems included in our database.

Improving safety on bus corridors is therefore primarily an issue of preventing pedestrian crashes. In general, pedestrians are at risk when they cross the corridor in mid-block, often away from designated crossings. The risk is particularly high near transit stations, as passengers will often attempt to cut across the bus lanes going in or out of the station, in order to avoid paying the fare, or simply in order to take a shortcut.

This suggests that station access design can play a key role in improving safety on bus corridors, along with better provisions for pedestrian mid-block crossings.

FATALITIES ON BUS CORRIDORS BY TYPE OF ROAD USER

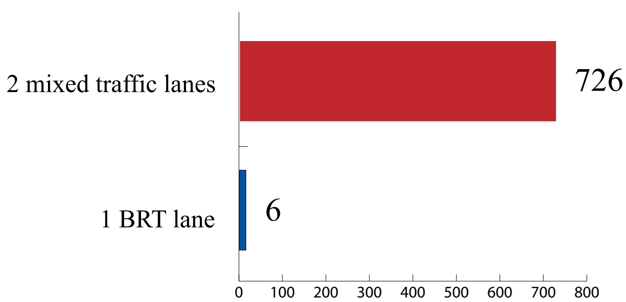


Includes data from Metrobus (Mexico City), TransMilenio, Macrobus (Guadalajara), BRTS (Delhi), Janmarg (Ahmedabad), RIT (Curitiba), as well as Busways in Porto Alegre and Belo Horizonte.

LOCATION OF CRASHES

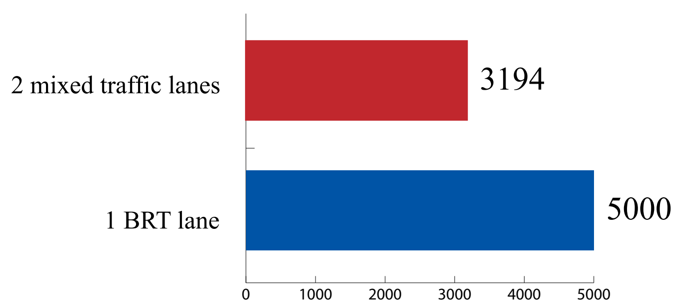
CRASHES

Average monthly crashes between 2009 and 2011 on the Macrobus BRT corridor in Guadalajara, by type of lane



PASSENGER THROUGHPUT

Peak hour passenger throughput on the Macrobus BRT corridor in Guadalajara, by type of lane (2009 data)



Source: computed from crash data provided by Secretaria de Vialidad y Transporte de Jalisco, 2011, traffic counts provided by Estudios, Proyectos y Señalización Vial S.A. de C.V. 2011; BRT passenger data from Hidalgo and Carrigan, 2010.

Dedicated bus lanes can significantly reduce the incidence of crashes involving buses. As a result, segregated high capacity bus corridors can carry more passengers considerably more safely than the mixed traffic lanes. We illustrate this with data from the Macrobus BRT in Guadalajara, which features one BRT lane and two mixed traffic lanes per direction. The BRT lane carried over 30% more passengers, while having over 90% fewer crashes than the mixed traffic lanes.

There are two important takeaways from the statistics presented on this page. The first is that while being on a bus is the safest place on a bus corridor, walking to and from the station is when bus passengers are at the highest risk (see chart above on fatalities by road user type). Ensuring safe station access is therefore the key to improving safety to bus passengers. The second is that on a bus corridor, over 90% of crashes will usually occur outside of the bus facilities (i.e. lanes and stations) and will not involve buses. This was confirmed by similar findings from TransMilenio, and it implies that the safety of a bus corridor will depend more on the layout of the mixed traffic lanes than on the configuration of the bus system itself.

STREET AND INTERSECTION DESIGN

Our crash frequency model results indicate that road width as well as the size and complexity of intersections are the most important predictors of crash frequencies on bus corridors. This makes sense, since on most of the bus corridors in our sample, only about 9% of all crashes occur in the bus lanes, while the vast majority occur in the general traffic lanes and do not involve buses.

The number of approaches per intersection is one of the key issues, along with the number of lanes per approach, and the maximum pedestrian crossing distance. Intersections where traffic on the cross streets is allowed to cross the bus corridor are more dangerous than intersections where only right turns are allowed. The crash frequency models as well as their results are discussed in more detail in Appendix A.

A narrow four-leg intersection along Metrobus Line 1 in Mexico City. Google Earth image.

A wide, complex intersection along Metrobus Line 1 in Mexico City. This type of design has more safety issues than the simple, narrow intersection in the image above. Google Earth image.

LOCATION OF THE BUS LANES

Counterflow bus lanes in Mexico City and Porto Alegre were found to be significantly correlated with higher crash rates for both vehicles and pedestrians. The consistency of the results across the different models suggests that counterflow lanes are the most dangerous configuration for bus systems, of all those included in our study (see the detailed discussion on counterflow on the opposite page).

We also found that curbside bus lanes in Guadalajara increased both vehicle and pedestrian crash rates, whereas in Mexico City they did not have a statistically significant impact on crash frequencies. While the results are not always significant, they generally tend to indicate that curbside lanes may be problematic, though not as much as counterflow lanes.

Assessing the safety impact of center-lane systems is slightly more complex, since the changes introduced by a center-lane BRT on a street are measured by several variables. Unlike curbside bus corridors, which usually only replace one traffic (or parking) lane with a bus lane, center-lane systems imply a more significant reconfiguration of the street. Typically, this involves introducing a central median to replace a traffic lane, shortening the pedestrian crossing distance by creating a pedestrian refuge in the center of the street, and creating more T intersections and fewer 4-way intersections along the corridor. While the variable accounting for the presence of the center-lane BRT in Mexico City was not significant, the variables accounting for number of lanes, central median, crossing distance, and number of legs, were all correlated with lower crash rates and were significant across the different models. Please refer to Appendix A for more detailed information on crash data analysis.

COUNTERFLOW

Counterflow lanes are the most dangerous configuration for any bus system, and should generally be avoided.

1. BI-DIRECTIONAL BUS SYSTEM ON A ONE-WAY STREET

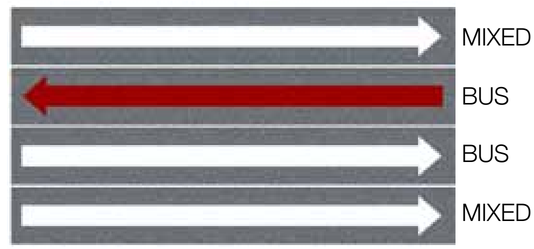
This type of street configuration is present on Metrobus Line 2 in Mexico City, and in a slightly different form on some sections of Metrobus Line 3. It creates an unusual situation for pedestrians crossing the street, as traffic on the mixed traffic lane at the top of the image comes from an unexpected direction.

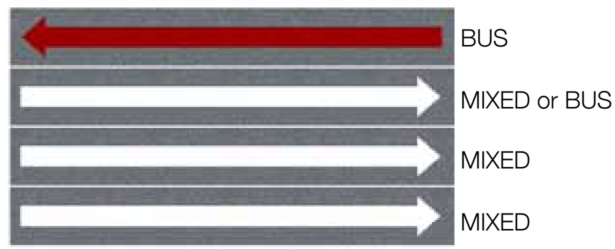
2. CURBSIDE COUNTERFLOW LANE

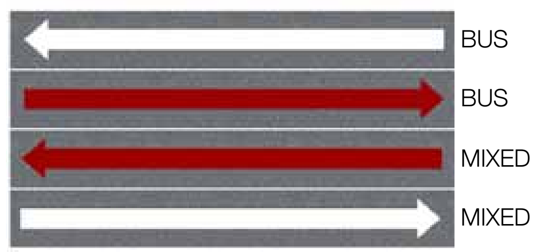
This is the type of counterflow lane included in our crash frequency models. In Mexico City, the presence of this type of counterflow lane was correlated with a 55% increase in vehicle collisions and a 39% increase in pedestrian crashes ($p<0.001$). In Porto Alegre, it was correlated with a 74% increase in vehicle collisions ($p<0.05$) and there was insufficient data to develop a pedestrian model. This variable was highly significant across all models, and was one of the strongest predictors of crash frequencies in both cities. A portion of the South Line in the BRT system in Curitiba features a similar configuration, and it has four times as many crashes per lane kilometer than the rest of the South Line, which has a standard center-lane configuration. The caveat is that the counterflow is in the downtown, which may account for some of the difference in crash rates.

3. SIDE RUNNING ALIGNMENT

A section of the Southeast Busway in Brisbane, Australia features a side running alignment. The most frequent pedestrian crash type on this section - and the only fatal crash included in the data we received - involved collisions between buses operating in the counterflow lane and pedestrians crossing the street.







Diagrams illustrating different counterflow configurations we encountered in our data analysis and road safety inspections. Counterflow lanes are indicated in red.

A curbside counterflow lane on Eje 2 Oriente in Mexico City (the street has a southbound bus lane and five northbound lanes, though only two can be seen in this image). The small truck had been driving southbound illegally on the bus lane, and then attempted to overtake the bus as it stopped at the station. Northbound cars are trying to get out of the way. Also note the pedestrian carrying merchandise in the bus lane. Photo by Carsten Wass.

While safety considerations can be included at any stage during the planning, design, and operation of a bus system, it is always more cost effective to include them early in the planning stages.

ROAD SAFETY AUDITS

A road safety audit is a systematic examination of a proposed roadway or transportation project, with the goal of identifying main safety risks and proposing solutions for eliminating them. Audits can be conducted at any stage during the planning and design process.

An audit should be carried out by a certified road safety auditor, who should be independent from the design team, to ensure objectivity and prevent conflicts of interest. Audits always involve an evaluation of the design drawings and should be accompanied by a site visit, to gain a better understanding of conditions on the ground.

The auditor delivers a report to the design team or the project owner, who are then in charge of implementing the auditor's recommendations.

ROAD SAFETY INSPECTIONS

An inspection is a systematic evaluation of an existing roadway or transportation project. The objective is similar to that of an audit, identifying safety risks and proposing solutions.

Audits tend to be a more cost effective tool for improving safety than inspections. It is always easier to change a drawing than to modify an existing piece of infrastructure.

An inspection, on the other hand, can identify more safety issues, since the auditor can observe the roadway in operation and also study crash data, in addition to evaluating the design of the roadway. Inspections can also deal with issues such as the maintenance of signs and pavement markings.

Inspections are more effective if carried out before major maintenance work other design improvements are scheduled on a corridor. This way, the recommendations from the inspection can be incorporated into the planned work.

DESIGN GUIDELINES

Traffic safety design guidelines are not meant to replace audits or inspections. Rather, they should be seen as a complementary tool. They should be consulted before the start of the planning process of a new bus corridor, and used as a reference throughout the design process.
They can be a very effective in improving safety, since they would help planners, engineers, and designers integrate safety considerations throughout the planning and design of a corridor.

Unlike audits and inspections, however, guidelines cannot be site specific, so the recommendations contained in them are not directly applicable to a specific corridor or intersection. It is up to those in charge of the design of the corridor to adapt the general recommendations from the guidelines to the specific site conditions, while considering the applicable design and signalization standards.

DESIGN GUIDELINES

The design guidelines are organized along the following chapters:

- STREET DESIGN
- INTERSECTIONS
- STATIONS AND STATION ACCESS
- TRANSFERS AND TERMINALS

Each chapter begins with an overview of the main safety issues to consider when designing that specific piece of infrastructure. It then goes on to illustrate design concepts for common street, intersection, or station configurations.

TYPES OF BUS SYSTEMS INCLUDED

While focusing on center-lane BRT systems, this guidebook includes the following types of bus corridors:

- center-lane BRT (single lane or multi-lane) with high-floor buses and closed median stations
- center-lane Busways with low-floor, right-door buses and open stations
- curbside BRT or Busway corridors
- curbside bus priority lanes
- conventional bus service in mixed traffic

DESIGN CONCEPTS

Each concept is illustrated through a 3D design illustration that includes considerations on geometry, signalization and markings, street furniture, lighting, and types of pavement. We used annotations to discuss specific aspects of each design, suggest design alternatives, or recommend specific dimensions where appropriate.

In addition to illustrating best design practices, we provide analysis on the impacts of each design choice in terms of traffic safety and bus operations.

SAFETY ANALYSIS

The safety analysis focuses on common risks and crash types for that specific design. We use excerpts from our data analysis, or observations from road safety inspections to illustrate the safety issues.

BUS OPERATIONS

For each design concept, we also provide a brief discussion on how the recommended safety features may impact bus operations. We focus in particular on two aspects of operations that are key indicators of system performance: operating speeds and passenger capacity.

The passenger capacity of a bus system is usually constrained by station configuration rather than intersections or mid-block sections (Hidalgo, Lleras, and Hernandez 2011, Lindau et al. 2011). None of our recommendations have any impact on the station design elements that impact capacity, such as the number of stopping bays per station, the presence of overtaking lanes and express services, etc. Some of our recommendations (such as installing signalized mid-block pedestrian crossings) may reduce capacity in mid-block sections of the corridors. However, even this reduced capacity will generally be much higher than station capacity. As an example, a single-lane per direction BRT system with a 50 second green phase out of a 90 second signal cycle at a mid-block crossing will have a capacity of just over 55,000 passengers per hour per direction (pphpd) at that location (computed from Hidalgo, Lleras, and Hernandez, 2011). This is over three times higher than the maximum station capacity for this type of system, which is 15,000 pphpd (Lindau et al. 2011).

On the other hand, some of our recommendations will have a definite impact on bus speeds. In some cases, we directly recommend reductions in bus speeds at specific locations (e.g. express buses on the approach to stations) in order to address a specific crash type. In other cases, our recommendations for placing additional mid-block crossings or lengthening the signal phase for pedestrians crossing the corridor may also contribute to lowering bus speeds. When that is the case, we point it out in the text associated with the drawing, with the understanding that safety should be the first priority when dealing with potential trade-offs between safety, speed, and capacity.

KEY SAFETY ISSUES

MID-BLOCK CROSSINGS

In any dense urban center, especially in the developing world, one can expect large volumes of pedestrians crossing, waiting, or walking in the bus lanes. Moreover, pedestrians often perceive bus lanes as being safer than the general traffic lanes, due to their lower traffic volume. In Mexico City, pedestrians crossing the BRT in mid-block have been observed to cross the street halfway, and then wait in the BRT lanes for a gap in traffic in the opposite direction, before completing the crossing

This issue becomes particularly problematic at the urban periphery. Often, the main roads at the periphery are former highways that have not been retrofitted to reflect the changes in land use around them as the city has expanded. As a result, buses here often run on high speed roads with few crossing opportunities for pedestrians, and blocks are considerably longer than in the downtown - sometimes upwards of 1 kilometer.

Commercial speed is a key performance indicator for BRT and Busways, but raising the speed limit for buses may contribute to increasing the severity of crashes for pedestrians. Limiting opportunities for pedestrian crossings by placing barriers and guardrails will mitigate both risks, but would reduce accessibility for pedestrians and transform the bus corridor into a major urban barrier. The risk of this type of intervention is that pedestrians will simply jump over guardrails, or remove or damage the guardrails, and continue to cross in mid-block.

In order to address this problem, we recommend carrying out an accessibility study for the new bus corridor, in order to identify locations with a high demand for mid-block pedestrian crossings. Our observations from road safety inspections suggest that areas around major markets will often have high pedestrian volumes and an especially high incidence of mid-block crossings. Other land uses to consider are educational facilities (especially large campuses), religious buildings, and event venues. It is important to make sure that these locations have adequate crossing facilities for pedestrians, and that when crossings are not provided, there are guardrails or other barriers to prevent jaywalking.

Pedestrians crossing the Delhi BRTS corridor in mid block. EMBARQ photo.

Pedestrian crossing a TransMilenio corridor in mid-block. EMBARQ photo.

On the following pages, we present several design concepts for street segments that address the key safety issues discussed on the previous page.

The types of streets chosen, their width, and the types of bus systems featured are based on common street configurations found in on the bus corridors included in our dataset.

We start by featuring a center-lane BRT corridor, and illustrate different ways in which mid-block crossings can be managed, depending on the type of street: urban arterial, narrower street, and expressway.

All the design principles and safety features we present for center lane BRT corridors are applicable to all other types of bus systems as well. These include traffic calming measures for the mixed traffic lanes, configuration of mid-block crossings, pedestrian bridges, cycle infrastructure, guardrails, and the appropriate placement of vegetation along the corridor.

There are also some key issues that are specific to curbside bus corridors, particularly the recommended location of guardrails. For this reason, we also include a separate design concept for curbside lanes, illustrating the importance of placing guardrails or planted medians along the sidewalk, to prevent pedestrian traffic from spilling over into the bus lanes.

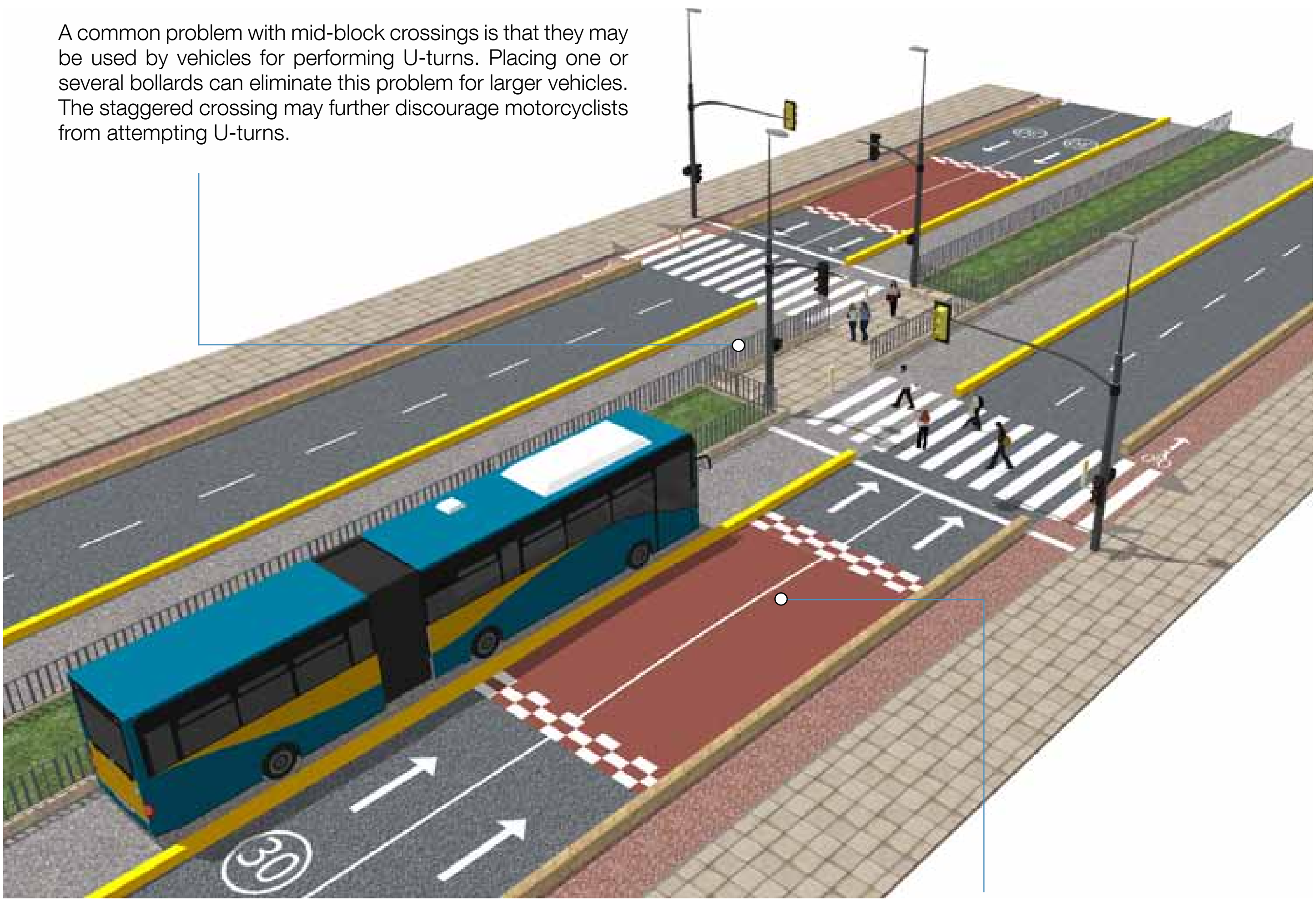
LIST OF ILLUSTRATIONS

MID-BLOCK CROSSING ON AN URBAN ARTERIAL

All pedestrian crossings on bus systems situated on urban arterials should be signalized.

We recommend using staggered mid-block crossings. If configured as in this image, pedestrians in the median will always be facing the direction of traffic for the portion of street they are about to cross. A staggered crossing also increases the area available for pedestrians to wait if they cannot cross the street in one phase.

A common problem with mid-block crossings is that they may be used by vehicles for performing U-turns. Placing one or several bollards can eliminate this problem for larger vehicles. The staggered crossing may further discourage motorcyclists from attempting U-turns.



Vehicles may not always stop at a red light for a mid-block pedestrian crossing. We recommend mitigating this risk by placing speed humps or other traffic calming devices in advance of the crossing, to at least ensure that vehicles arrive at the crossing at a lower speed. For the bus lanes, this could be addressed through driver training and enforcement.

SAFETY

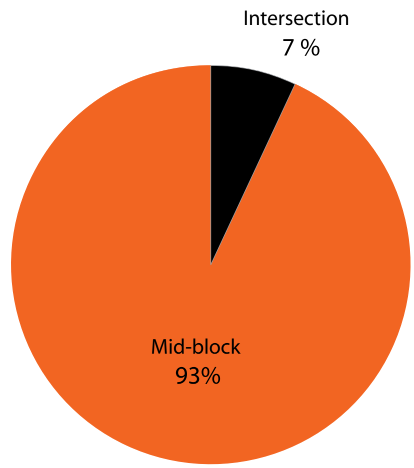
Mid-block crosswalks on urban arterials should always be signalized. This is the most important safety feature for pedestrians, since these crossings are usually located on sections of the corridor with longer blocks, where traffic speeds may be higher.

Ideally, the length of the pedestrian green phase should provide sufficient time for pedestrians to cross the entire street in one phase. We recommend considering a walking speed of 1.2 meters / second (m/s) in most cases and 1 m/s in areas where more than 20% of pedestrians are elderly for determining the length of the pedestrian green phase (HCM 2010).

We also recommend using a central median and providing a pedestrian refuge island in the center of the crossing. Our research has shown that refuge islands can considerably improve pedestrian safety.

Pedestrians jaywalking across the bus lanes on the TransMilenio BRT in Bogota. EMBARQ Photo.

LOCATION OF PEDESTRIAN CRASHES IN PORTO ALEGRE, BRAZIL



Calculated from a crash database provided by Empresa Pública de Transporte e Circulação (EPTC), Porto Alegre, 2011.

OPERATIONS

The maximum capacity for a single-lane BRT corridor with no overtaking at stations is usually between 9,000 and 10,000 pphpd (Hidalgo and Carrigan 2010, Wright and Hook 2007). For a corridor that uses two lanes per direction, along with a combination of local and express service and multiple platforms at stations, the capacity can be as high as 43,000 pphpd (Hidalgo, and Carrigan 2011).

The passenger capacity of the bus corridor at this mid-block crossing ranges from 40,000 to 52,000 pphpd per lane, depending on the length and configuration of the signal cycle. This is considerably higher than the actual capacity of the system. Providing mid-block crossings at locations where high volumes of pedestrians are expected to cross should therefore not have a negative impact on passenger capacity.

Placing mid-block crossings along stretches of the corridor that do not have intersections may reduce average operating speeds for the bus system. While speed is a key performance indicator for bus systems and especially for BRT, pedestrian safety should always take priority.

MID-BLOCK CROSSING ON A NARROW STREET

Narrower streets in the downtown area typically have higher pedestrian volumes. In these cases, it is important to reduce bus speeds in order to give drivers more time to react to conflicts with pedestrians, and to ensure that buses can stop in a shorter distance.

This type of solution has been implemented on Eje Ambiental in Bogota - a section of BRT corridor with only bus and pedestrian traffic - where maximum speeds for TransMilenio buses are 20kmh, as opposed to 60kmh on the rest of the system.

The bollards prevent cars from parking illegally on the sidewalk. We recommend also placing at least one bollard in the middle of the pedestrian refuge islands, to prevent cars from attempting U-turns at the mid-block crossing.

Whenever bollards are placed across a crosswalk or refuge island, it is important to ensure that they are spaced correctly to allow strollers and wheelchairs to pass between them.

Recommended minimum distance between bollards: 1.2 meters.

This street configuration features only one mixed traffic lane per direction, and a buffer space between it and the sidewalk. The buffer can be used as a parking lane, planted area, cycle track, or for placing chicanes to slow down traffic near mid-block pedestrian crossings.

This sign should indicate to drivers the presence of the chicane.

SAFETY

Pedestrian delay is a key issue to consider when designing mid-block crossings. The longer pedestrians have to wait for the green light to cross, the greater the chances that they will cross on red.

The Highway Capacity Manual (HCM 2010) recommends keeping pedestrian delay under 30 seconds, and ideally bringing it under 10 seconds if possible.

The key to keeping pedestrian delay low is to avoid having a long red signal phase for pedestrians. The examples below illustrate two signal timing configurations and their implications on pedestrian delay.

Example 1 seeks to minimize delay for pedestrians and this is achieved by shortening the signal cycle and the bus green phase. Delay is under 10 seconds, as recommended by the HCM, and the capacity of the single lane bus corridor, at 36,300 pphpd, is still higher than what a station could typically handle.

Example 2 seeks to maximize passenger capacity for the bus corridor. The signal cycle is longer, at 90 seconds, and the bus green phase is also longer. Under these conditions, pedestrian delay is considerably higher, though still under 30 seconds.

CALCULATING PEDESTRIAN DELAY:

$$d_p = \frac{(C - g_{walk,mi})^2}{2C}$$

Source: Equation 18-71 from HCM 2010, where dp is the pedestrian delay, C is the length of the signal cycle, and gwalk,mi is the effective walk time for pedestrians crossing the bus corridor. All the measurements are in seconds. gwalk,mi can be estimated as being equal to the length of the pedestrian green phase, plus four seconds (equation 18-49, HCM 2010).

EXAMPLES:

	g bus (s)	C(s)	Ca (pphpd)	dp (s)
Example 1	30	70	36,300	9.3
Example 2	50	90	47,000	19.3

Where Ca (pphpd) is the passenger capacity per lane of the bus corridor (in passengers per hour per direction) and all other variables are as previously defined.

OPERATIONS

Since this street is narrower than the previous example, the amount of green time required for pedestrians to cross the street in one phase is lower. As a result, it is possible to achieve a higher passenger capacity at this mid-block crossing, while keeping average pedestrian delays low.

It is important to note that in both cases, the capacity at this crossing would be considerably higher than the actual capacity of the system - which is limited by stations. We would therefore recommend using a shorter cycle and maximizing the pedestrian green phase, to discourage pedestrians from crossing on a red light.

On the opposite page, we suggest considering reducing bus speeds on this type of street if pedestrian volumes are particularly high along the corridor. In terms of operations, this would not impact capacity as much as the size of the bus fleet. With a lower speed limit, the bus agency may need more buses to carry the same number of passengers.

PEDESTRIAN BRIDGES

Pedestrian bridges need to be accompanied by guardrails along the edge of the sidewalk. Pedestrians will often try to jump over the guardrails, or walk around them, even if it involves a detour, to avoid using the bridge. The guardrails should extend along the entire length of the section of the corridor where at-grade pedestrian crossings are not allowed.

Pedestrian bridges require infrastructure adapted to wheelchair users. This is normally a ramp with a slope of no more than 10%, and preferably closer to 5%, also featuring resting areas (see Rickert 2007). Given that the bridge must be high enough to allow large vehicles to pass, the ramps can end up being quite long. Elevators can also be used to provide access for the disabled.

SAFETY

Most pedestrian bridges do little to improve safety for pedestrians. Our statistical analysis in Mexico City found no correlation between pedestrian bridges and pedestrian crashes. Our observations from road safety inspections suggest that pedestrians rarely use them, preferring to jaywalk instead.

As a general rule, we recommend using at-grade signalized pedestrian crossings on BRT corridors and avoiding pedestrian bridges. Bridges should only be used on high-speed roads, such as expressways, in cases where it is not practical to place a signalized crosswalk. The street should have a minimum of three mixed traffic lanes per direction, in addition to the BRT lanes. A good example of the use of pedestrian bridges on a BRT on an expressway is the Autopista Norte corridor on TransMilenio, in Bogota. If the street is narrower, there is a higher chance that pedestrians will climb over guardrails and cross at-grade under the pedestrian bridge.

Pedestrian bridges should always be accompanied by guardrails to prevent pedestrians from jaywalking. The guardrails should be high enough to prevent people from jumping over them. They should also be inspected often, and replaced when they are damaged or destroyed.

Pedestrian jaywalking under a pedestrian bridge in Arequipa, Peru. Photo by Carsten Wass.

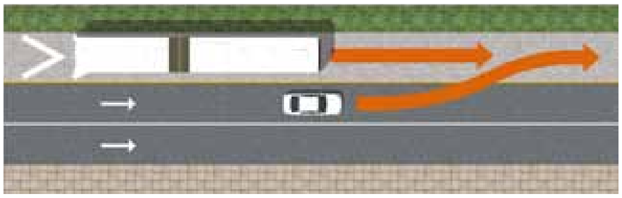
Pedestrians jumping over a guardrail and jaywalking across a Busway in Delhi, next to a pedestrian bridge. EMBARQ photo.

OPERATIONS

Pedestrian overpasses provide complete separation between bus and pedestrian traffic. As a result, the capacity of a bus lane is not affected by the pedestrian crossing, and neither are operating speeds.

However, if the pedestrian bridge is used in an inappropriate context (e.g. narrow urban arterial), it is likely that pedestrians will be crossing the bus lanes on foot, or waiting in the bus lanes for a gap in traffic, all of which poses safety issues for both pedestrians and bus passengers.

GUARDRAILS



Crash diagram: a common crash type on bus corridors with dedicated bus lanes - cars entering the bus lanes and colliding with buses

Physical segregation between the bus lanes and the mixed traffic lanes is essential for eliminating the risk of vehicles entering the bus lanes and colliding with buses. Lane markings and raised pavement markings are not effective measures for eliminating these conflicts. We recommend using a raised curb or a median.

Guardrails may be used along the length of the corridor between pedestrian crossings, to prevent pedestrians from jaywalking. We recommend using resistant guardrails and inspecting them often, as they might get damaged or destroyed.

Guardrails should also be high enough to discourage pedestrians from climbing over them. Using a planted median between the guardrails may also help deter people from attempting to cross.

Guardrail along a Busway in Belo Horizonte, Brazil, damaged in order to allow crossing in mid-block . Photo by Carsten Wass.

Pedestrians climbing over guardrails on a Busway corridor in Delhi. EMBARQ India photo.

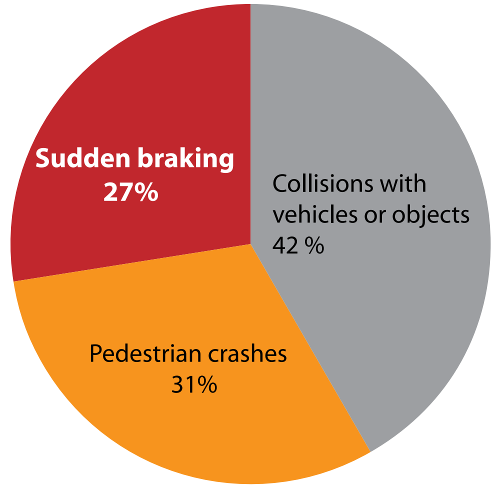
SAFETY

For those sections of the corridor between pedestrian crossings - and especially if bus speeds are high - it is important to prevent jaywalking, and to keep pedestrians out of the bus lanes. This is a key issue for pedestrian safety, but can also help reduce the number of injuries to bus passengers. A common cause of injuries to BRT passengers is when drivers brake suddenly to avoid pedestrians in the bus lanes.

Buses have a relatively high maximum braking rate. While this can help a bus driver brake in time to avoid hitting pedestrians, it poses a safety risk for passengers inside the bus.

Crash data from TransMilenio in Bogota show that the number of injury crashes on the system due to sudden braking is comparable to those due to collisions with other vehicles or pedestrian crashes. From crash descriptions as well as discussions with TransMilenio safety staff, we learned that drivers have been trained to react to pedestrians in the bus lanes by braking suddenly to avoid running them over. As a result of implementing this measure, TransMilenio staff reported that pedestrian crashes on the system have gone down, while injuries to bus passengers have gone up, as people fall inside the bus and get injured when the vehicles brake suddenly. Sudden braking to avoid pedestrian crashes has also led to several rear-end collisions between BRT buses travelling in convoy.

INJURY ACCIDENTS INVOLVING TRANSMILENIO VEHICLES IN BOGOTA, BY TYPE



Calculated from data provided by TransMilenio S.A.. Includes accidents involving BRT vehicles reported by TransMilenio staff between 2005 and 2011.

OPERATIONS

From a pedestrian safety perspective, the precise location of the guardrails is not important, so long as they provide an efficient barrier to prevent jaywalking. Guardrails can be located in the median, along the sidewalk, or between the mixed traffic lanes and the bus lanes.

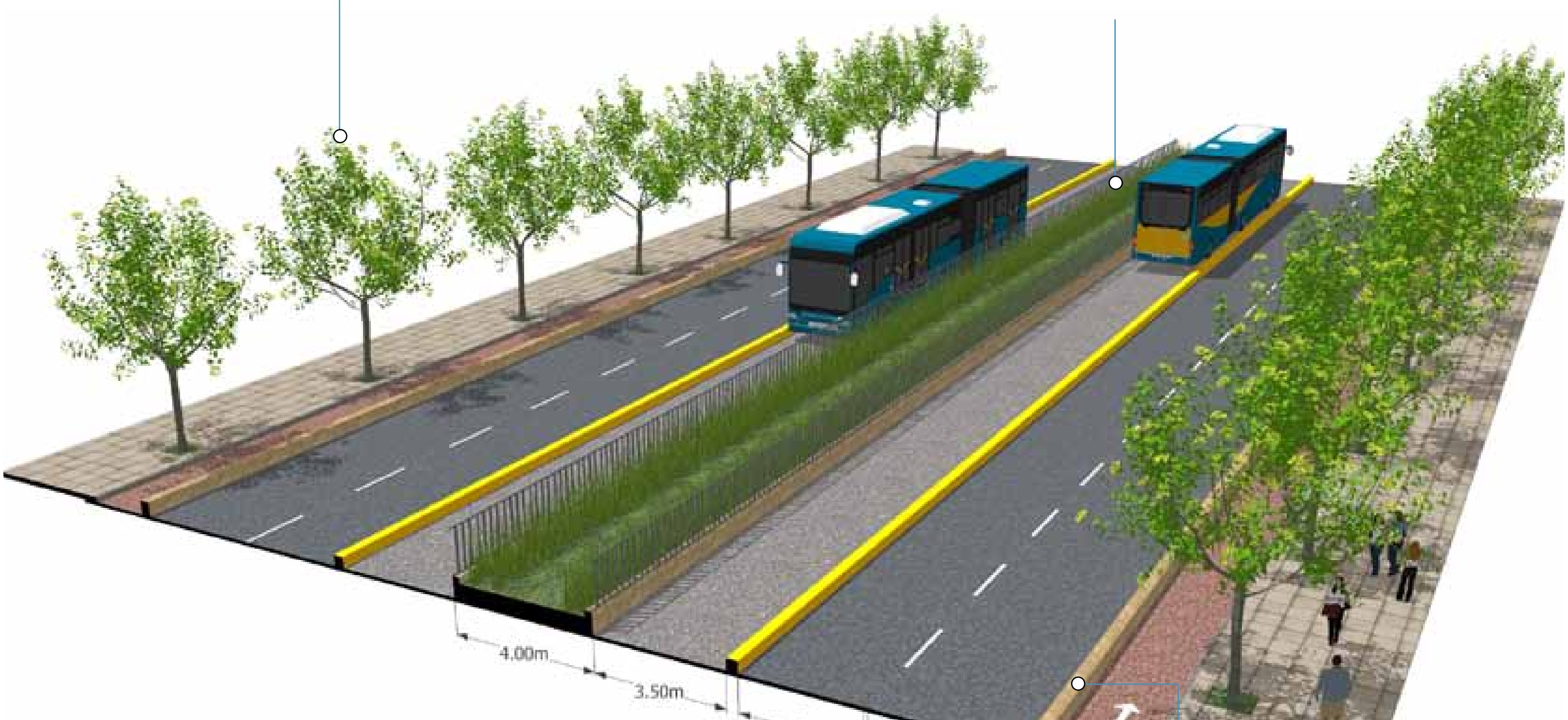
For bus operations, it might be more advantageous to place the guardrails between the bus lanes and the mixed traffic lanes. This would help prevent jaywalking in the bus lanes, and also create a stronger separation from mixed traffic.

Guardrails between the bus lane and the mixed traffic lanes on the Janmarg BRT corridor in Ahmedabad. EMBARQ photo.

CYCLE INFRASTRUCTURE AND VEGETATION

We recommend using street trees along sidewalks and bicycle lanes, provided that they do not obstruct the line of sight on approaches to intersections or mid-block crossings. In hot climates, we would recommend spacing the trees so that they create a continuous canopy, offering shade to pedestrians and cyclists.

We recommend not planting large trees in the central median, as their foliage may grow into the bus lanes, potentially causing dangerous evasive actions from drivers. This could be managed by adequately maintaining and cutting back vegetation, but in most cases, this will not be the responsibility of the bus agency, but rather that of another local government agency. Large trees should also be avoided on the approaches to intersections and mid-block crossings. When choosing which trees to use, we recommend checking the applicable national standards and ensuring that the required sight lines are maintained.



Delivery truck parked on a bike lane in Mexico City. EMBARQ photo.

Cycle track on the Janmarg BRT in Ahmedabad, used as parking for motorcycles. EMBARQ photo.

Physical segregation for the cycle tracks is essential for ensuring that vehicles will not encroach on them. A raised curb is a simple device for creating the segregation. It is also easy to maintain and takes up little space (20 - 30 cm).

It is also important to ensure that the cycle track is not encroached upon by street vendors, or used as motorcycle parking, as in the case of some sections of the Janmarg BRT in Ahmedabad. In part, this could be addressed by providing adequate space for all activities along the street - including provisions for two-wheeler parking. But it also needs to be addressed through enforcement and education.

SAFETY

When there are no bike facilities on the street, cyclists will often choose to bike in the dedicated bus lanes, because they perceive them to be safer than the mixed traffic lanes. But the bus lanes are not designed to accommodate both buses and bicycles, and sharing the lanes can often result in serious, and even fatal crashes.

It is possible for bikes and buses to share the same lane, but this usually involves lowering speeds for buses, and providing additional width to the lane to allow buses to overtake cyclists. This is generally not practical on BRT or Busway corridors, which feature lane widths of 3 to 3.5 meters, and large articulated or bi-articulated buses travelling at high speeds.

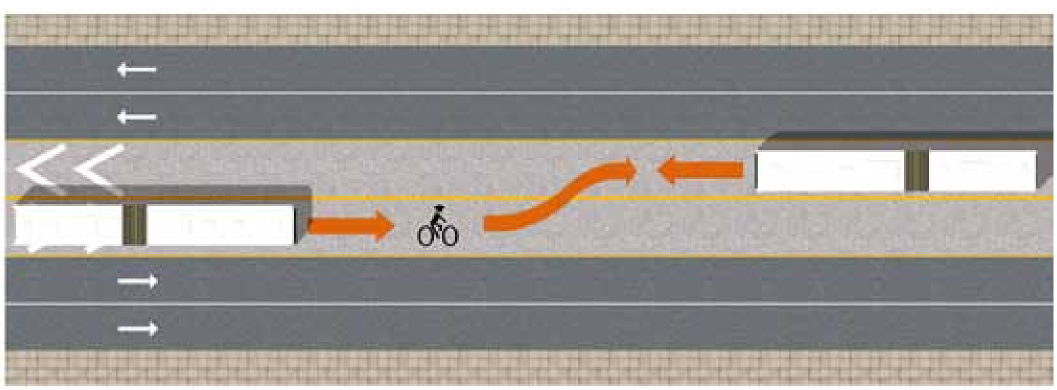
Whenever there is a significant volume of cyclists that can be expected to use the corridor, we recommend using dedicated infrastructure for cyclists. Ideally, on a dense street network with short blocks, cycle infrastructure should be provided on a street parallel to the BRT corridor, to avoid conflicts between bicycles and all the other traffic modes using the bus corridor. If that is not feasible, then cycling infrastructure should be provided on the bus corridor.

We recommend using cycle tracks, which are physically separated from motor traffic, and distinct from the sidewalk (NACTO 2011) as opposed to bike lanes, which do not provide a physical separation.

Physical separation is important in developing world cities, as drivers may not respect signs and markings indicating bike lanes, and will often use the bike lanes for parking. In commercial areas, the designers of the corridor will need to consider deliveries to local stores and whether these could be made from an adjacent street.

Bicyclist using the dedicated bus lanes on Metrobus Line 3 (Puente de Alvarado), in Mexico City. Photo by Carsten Wass.

Bicyclist using the dedicated bus lanes on the BRT system in Curitiba. Bicycles are not allowed in the bus lanes. Photo courtesy of EMBARQ Brasil.

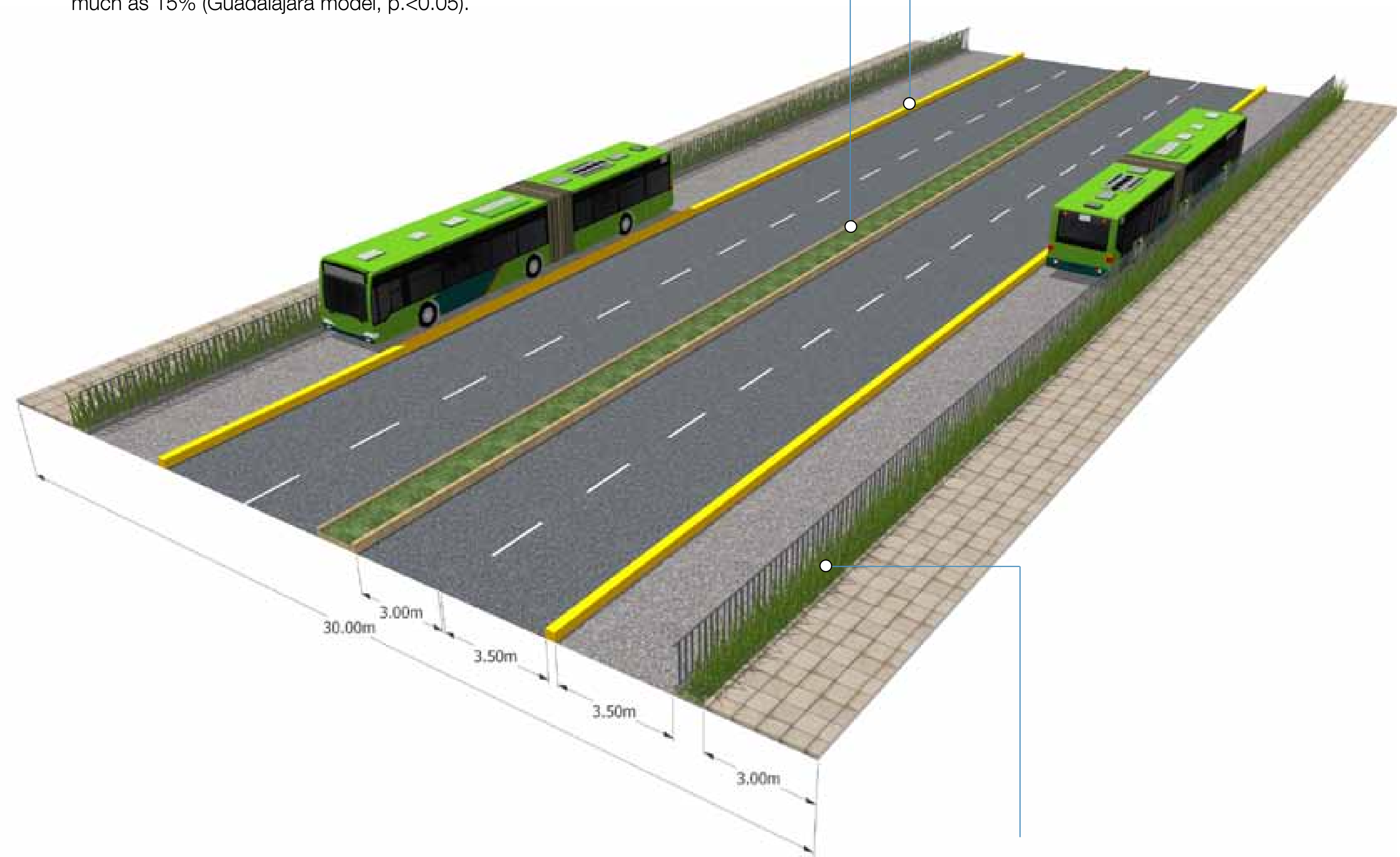


Crash diagram: collision between a bicyclist and a BRT vehicle, as described by staff from Metrobus, Mexico City. A common crash situation involves cyclists attempting to get out of the way of a bus approaching from behind, and either crashing into an incoming bus, or losing control and falling. All these situations usually results in serious injuries.

STREET DESIGN FOR CURBSIDE LANES

Curbside bus lanes are often used on narrower streets, where there isn't enough space for adding bus infrastructure in the center without substantially reducing the amount of street space available to mixed traffic. Regardless of street width, we recommend placing a median between the two traffic directions, as it may reduce vehicle collisions on the street by as much as 15% (Guadalajara model, p.<0.05).

For safety, it would be ideal to provide a physical segregation between curbside bus lanes and mixed traffic lanes. In practice, however, this may only be possible on sections with very long blocks.



Curbside bus lanes cannot operate safely without some form of physical barrier between the bus lanes and the sidewalk. As with all pedestrian guardrails, they may get damaged or destroyed, so they should be inspected often. They can also be integrated into good street design by using vegetation or street furniture around them.

Pedestrians walking in the curbside bus lane on Eje 1 Oriente, Mexico City. Note the narrow sidewalk and the damaged guardrail. Photo by Carsten Wass

A Mariachi band standing in the curbside bus lane on Eje Central (Lazaro Cardenas) in Mexico City, trying to attract customers. A car will eventually stop illegally in the bus lane and pick them up. EMBARQ photo.

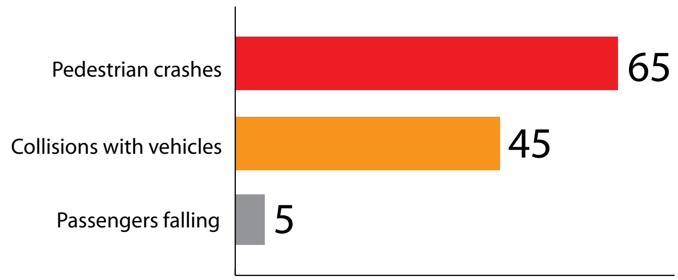
SAFETY

Curbside bus lanes tend to have more safety problems than center lane bus corridors. The main safety issue are crashes between buses and pedestrians. Since the bus lanes are directly adjacent to the sidewalk, pedestrian traffic will frequently spill over into the bus lanes.

In areas with high pedestrian volumes, it is not uncommon to see people walking, waiting, or hauling merchandise in the bus lanes. In some cases, this may be due to crowding on the sidewalks, but not always. During our site inspection, the sidewalks on Eje Central in Mexico City were not crowded, yet we noticed a lot of people using the bus lanes.

To some extent, this is an accessibility issue. People who need to push carts, for example, will often prefer to use the bus lanes rather than go up the ramps to the sidewalk. It is also possibly due to the perception that bus lanes are relatively safe, since they carry fewer vehicles than the general traffic lanes. In order to address this issue, we recommend placing guardrails along the sidewalk to keep pedestrians out of the bus lanes, but also ensuring that sidewalks along the corridor are in good condition, without level changes, steep ramps, or objects blocking access to ramps.

ACCIDENTS INVOLVING BUSES, BY TYPE, ON THE EJE CENTRAL CURBSIDE BUS CORRIDOR, MEXICO CITY (2006 - 2010)



Calculated from data provided by the Mexico City Government, 2011.

Person pushing a cart of goods on a curbside bus lane on Eje Central, in Mexico City. EMBARQ photo.

OPERATIONS

In practice, curbside bus lanes rarely achieve capacities higher than 5,000 passengers per hour per direction (Wright and Hook, 2007).

First of all, this is due to the fact that curbside lanes are almost never able to operate as exclusive bus lanes. The most frequent conflict is with right turning vehicles, which often merge into the bus lane before making the right turn. Not only will these vehicles reduce the lane's capacity for buses, they will also slow bus traffic down. In addition, there are numerous conflicts with pedestrians, and cyclists sharing the lanes that can also contribute to slowing down traffic in the bus lanes.

Another conflict to consider is with minibuses, and this is particularly relevant in Latin American cities. Minibuses operate on predetermined routes, but they usually do not have fixed stops. Instead, they may pick up and drop off passengers at different locations on a street. On a curbside bus corridor, minibuses loading or unloading passengers will stop in the bus lane, as in the case of Eje Central in Mexico City. Using a physical barrier between the curbside bus lane and the mixed traffic lanes may solve this problem at some sections of the corridor (especially those with longer blocks). But right turning traffic will often need to merge into the bus lanes on approaches to intersections, and the barriers will need to be discontinued there.

INTERSECTIONS

KEY SAFETY ISSUES

The key to improving safety at intersections is to design simple, tight junctions. The size and complexity of intersections were consistently correlated with higher crash frequencies across all the bus corridors included in our database.

INTERSECTION SIZE

The area of an intersection is influenced by the length of right-turning radii and the width of each approach. Our crash frequency model results suggest that each additional lane entering an intersection can increase crashes by up to 10% (all models, $p<0.001$, Appendix A).

In order to keep intersections as narrow as possible, we recommend tightening right turn radii, providing only the minimum width necessary for making right turns. In addition, we recommend using curb extensions over parking lanes, and keeping the overall number of lanes on the bus corridor low.

LEFT TURNS

We found that each left turn movement allowed at an intersection may increase crashes by over 30% (Mexico City model, $p<0.001$). While left turns are generally considered to be a road safety risk on any type of street configuration, they are particularly dangerous on center-lane bus corridors.

The most common type of accident involving buses on center-lane corridors occur when cars make illegal left turns from the corridor across the bus lanes and collide with a transit vehicle approaching from behind.

On most center-lane bus corridors, left turns are banned and replaced with loops at most intersections. This requires careful design of the loop, to avoid simply shifting the risk from the bus corridor to a nearby street. It is also recommended to use signs indicating both the left turn interdiction and the replacing loop. Alternatively, left turns can be allowed at select locations, with a dedicated left turn phase.

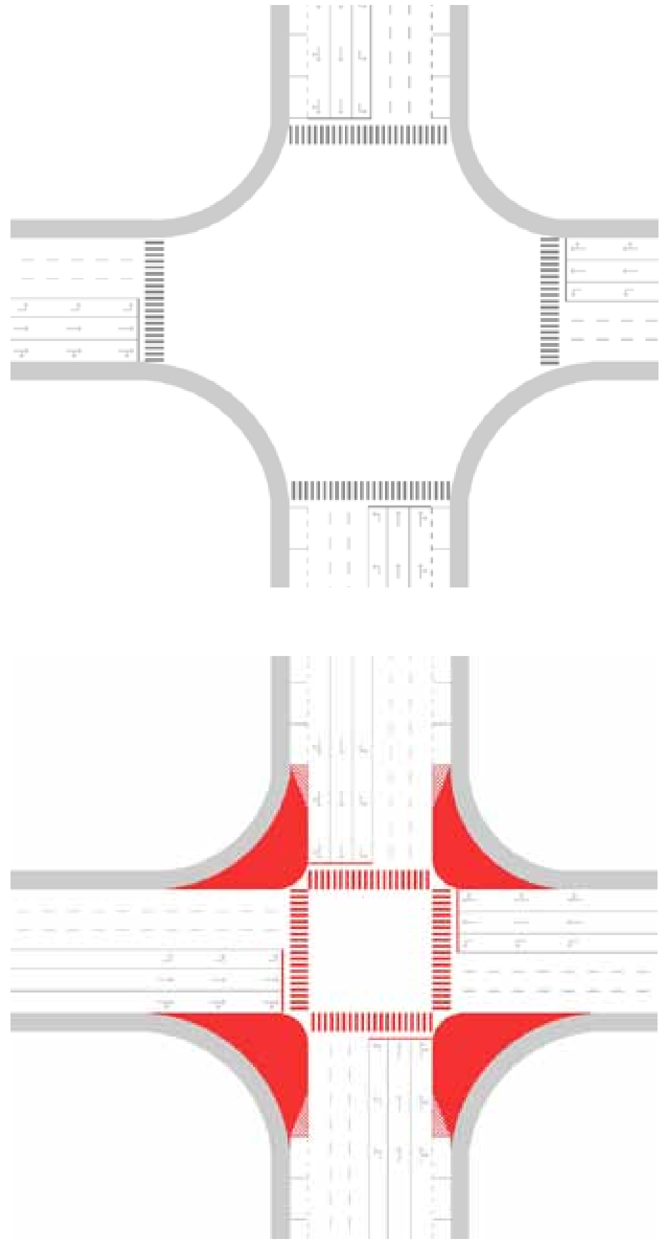
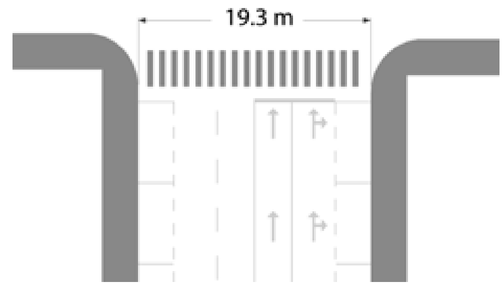


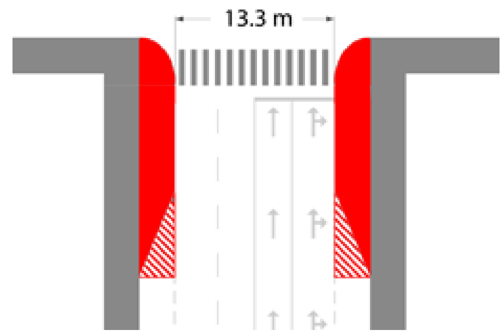
Diagram illustrating how narrower turning radii and curb extensions (in red) can be used to reduce the area of an intersection.

PEDESTRIAN CROSSINGS

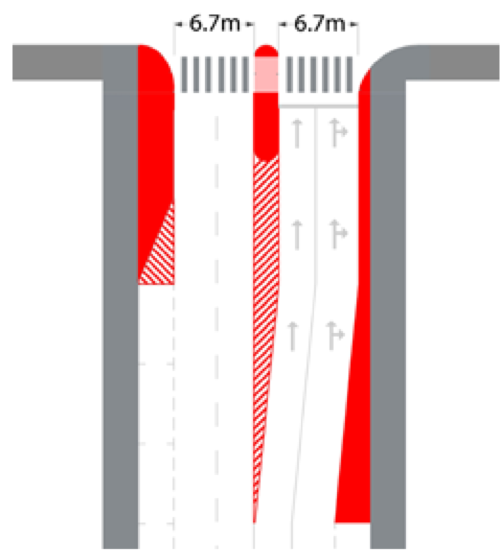
Our model results indicate that each additional meter in a pedestrian crosswalk is correlated with a 3% to 5% increase in the number of pedestrian crashes. We present here two design concepts for reducing the pedestrian crossing distance at an intersection, without taking out traffic lanes. We start with an example of a four-lane street with one parking lane in each direction. The crossing distance here is 19.3 meters.



By using curb extensions (or curb bulb-outs), we can extend the sidewalk over the two parking lanes on the approach to the intersection. This can help reduce the crossing distance by 6 meters, bringing it down to 13.3 m. It also improves visibility for both drivers and pedestrians. If there is a row of parked cars extending all the way to the crosswalk, there is a chance that pedestrians may appear unexpectedly from behind parked cars. This is a common contributing factor to pedestrian crashes. By removing parking spaces in advance of the intersection (also known as “daylighting”) drivers and pedestrians can see each other easier, which can help avoid crashes.



Another solution is to take out the parking lane on the approach to the intersection, shift two of the four lanes nearer the sidewalk, and use the resulting space to create a pedestrian refuge island in the center of the crosswalk. This should improve pedestrian safety even more, as pedestrians would only need to cross two lanes (or 6.7 meters) at a time. Depending on how it is designed, the lane shift on the approach to the intersection can also be used as a speed reduction measure, further improving safety for pedestrians.



PROTECTED PEDESTRIAN SPACE

In 2011, a fatal crash occurred on the Metrobus BRT in Mexico City when a bus apparently missed a turn, climbed on a pedestrian waiting area, and ran over a group of people, killing three and injuring several others.

Wherever there is a pedestrian waiting area - such as a refuge island - situated in the middle of a street, it is important to provide some protection to pedestrians. This can be done by placing bollards or raised curbs. This should help ensure that if a driver loses control of the vehicle or misses a turn, the vehicle would hit a bollard or a curb instead of running over pedestrians.

JUNCTION MARKINGS

For larger intersections, it is recommended to use special pavement markings that help guide movements - and especially turns - through the intersection area. There are two main types of junction markings: extensions of lane markings (usually in the form of dotted lines where one lane crosses an intersection, and in the shape of a cross where two lanes intersect) and ghost islands (areas where no movements occur through the intersection and which can be marked off with hatch markings). The shape and dimension of pavement markings vary from country to country. We recommend checking the applicable standards for finding the correct type of markings for each location. In this guidebook, we illustrate the type of junction markings commonly used in Denmark.

LANE ALIGNMENT

Lanes continuing through an intersection should always be well aligned on both sides of the junction. A slight change in lane alignment can confuse drivers, who may then end up driving in the wrong lane as they exit the intersection, or make sudden movements to stay in the correct lane - both of which could result in crashes.

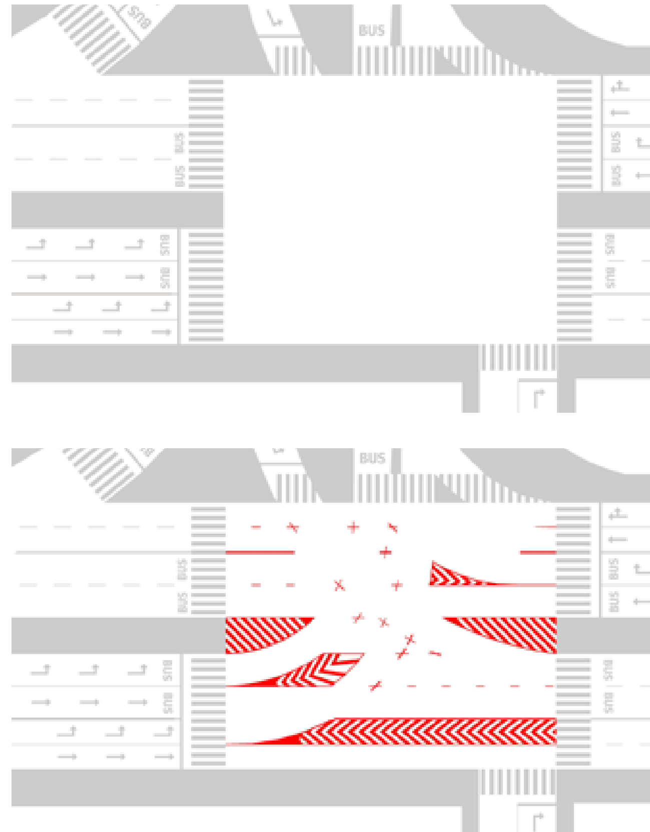
A slight misalignment can be addressed by using junction markings to help drivers stay in lane. A major misalignment - such as one that would send cars into the opposite lanes - should not be allowed. For minor cross streets that have poor lane alignment, consider closing them off and allowing only right turns.

LANE BALANCE

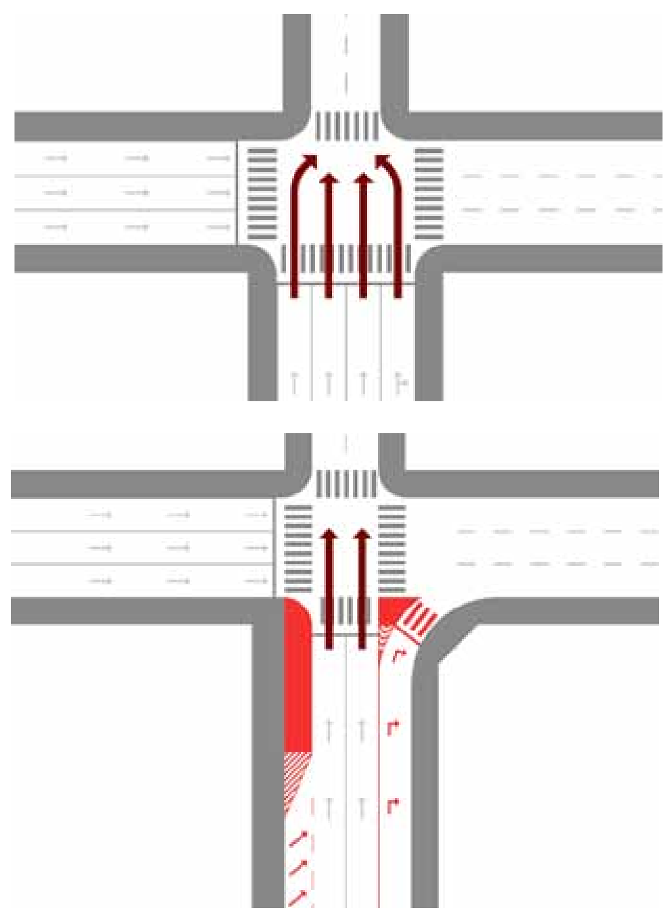
When the number of lanes entering an intersection along any given approach or turning movement is larger than the number of lanes exiting the intersection along that same movement (i.e. continuing straight, turning left, etc.) this is referred to as lane imbalance. This is problematic because vehicles will be converging on fewer lanes and some drivers may react to this by changing lanes suddenly, which could result in crashes.

In some cases, this can be resolved by designating some lanes as turn-only. For example, if a street has four lanes entering an intersection, but only three lanes after the intersection, one of the lanes on the approach could be designated as right-turn or left-turn only. This would effectively leave only three through lanes, which would restore lane balance.

Another option is to take out one lane at the previous intersection, or to take it out in mid-block, with advance warning to drivers



Example of an intersection with and without junction markings.



Example of how lane imbalance can be addressed by taking out lanes on one approach, or creating turn only lanes.

LOOPS

It is common to prohibit left turns on center-lane bus corridors. This can help improve safety, by eliminating one of the most important conflicts on between buses and the general traffic. It also helps improve capacity on the bus corridor, by eliminating a signal phase and allowing a higher green time to signal cycle (g/C) ratio for buses.

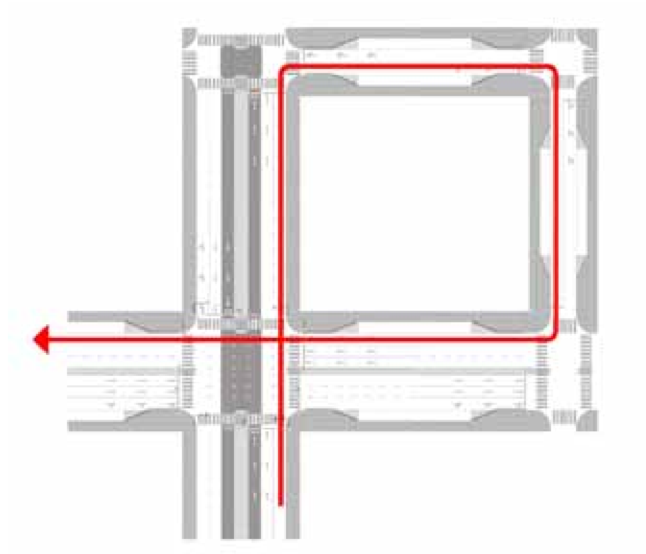
OPTION 1: AFTER THE INTERSECTION

This is the preferred solution from a safety perspective, because it replaces a left turn with three right turns (right turns are generally far less problematic). However, it can only be used when the following conditions are met:

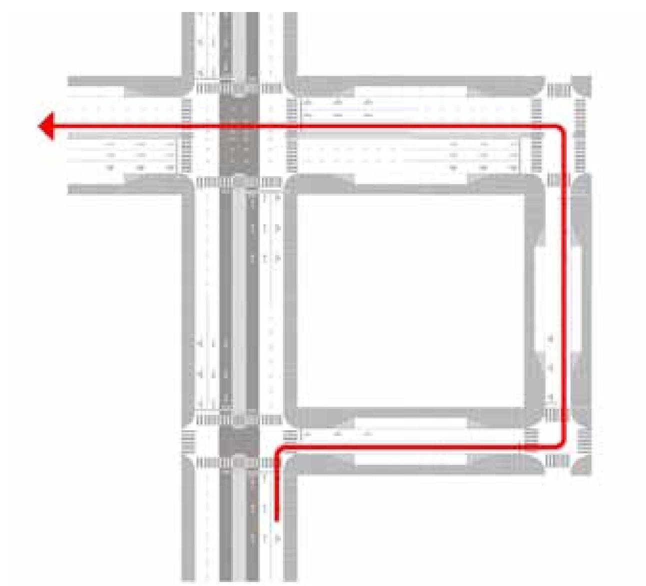
- The streets along the loop are capable of accommodating the additional volume of traffic without creating any safety problems or congestion
- The loop is not exceedingly long. If the blocks adjacent to the intersection are longer than 150 - 200 meters, the detour involved by the loop might be too long and driver may not use it

OPTION 2: BEFORE THE INTERSECTION

This option should only be used when the previous one is not feasible. This type of loop replaced a left turn with one right turn and two left turns on a parallel street, and there is the possibility that it may simply shift the risk from the bus corridor to another street. The same conditions apply as for option 1: the streets must be able to accommodate the extra traffic and the loop should not be exceedingly long.



Loop option 1: starting after the intersection with the left turn prohibition.



Loop option 2: starting before the intersection with the left turn prohibition.

LOOP SIGNS

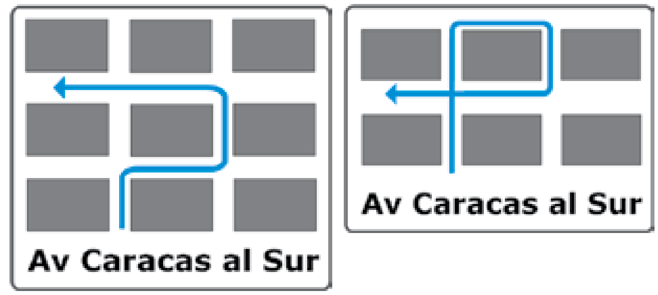
Regardless of whether the loop starts before or after the intersection, the signs announcing it should be placed on the approach to the intersection. The exact design and layout of the signs should follow the specifications from the applicable local or national design standards. We also recommend the following principles for placing and designing loop signs:

PLACEMENT

- The signs announcing the loop should always be placed before the intersection where left turns are prohibited, regardless of whether the loop starts before or after the intersection.
- On wide roads (more than three mixed traffic lanes per direction) consider placing the loop sign above the lanes instead of on the sidewalk, or else placing it both on the sidewalk and in the median, to ensure good visibility.

DESIGN

- The sign should be as simple as possible, including only the minimum amount of information needed to understand the configuration of the loop.
- It should be large enough to be easily noticed and read by a driver passing by at the maximum speed limit
- Do not mark street names on the sign. Only mark the name of the cross street where turns are prohibited, to indicate which street the loop is for.



Recommended design for the two loop options. Note that only the minimum information is included, to keep the sign simple, and that the only street name listed is the one of the cross street where left turns are prohibited.

On the following pages, we present several design concepts for intersections that integrate all the key safety issues discussed in the previous section.

The types of intersections chosen , the street widths, and the types of bus systems featured are based on common street and intersection configurations found in on the bus corridors included in our dataset.

We start with intersections along a center lane BRT, going from large junctions with other urban arterials, to minor intersections and T junctions.

Many of the design principles and safety features we present for center lane BRT corridors are applicable to all other types of bus systems as well. These include minimizing the intersection area, keeping crosswalks short and breaking them up with pedestrian refuge islands where possible, using junction markings, intersection lighting, and guardrails.

There are also some key issues that are specific to curbside bus corridors, particularly how right turns are managed. For this reason, we present two design concepts for curbside lanes that show different ways to deal with right turns across bus lanes.

LIST OF ILLUSTRATIONS

MAJOR 4-WAY INTERSECTION, NO LEFT TURNS

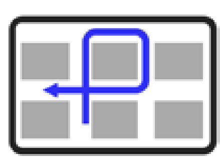
Extending the sidewalk over the parking lane near the intersection can help narrow the junction area and shorten pedestrian crossings. This is relatively easy to implement, does not affect intersection capacity, and can be very effective in improving safety for pedestrians.

It can also help eliminate conflicts between vehicles maneuvering in and out of the parking lane on the cross street and vehicles turning right from the BRT corridor.

Use pedestrian signals in addition to traffic signals on all sides of the intersection, and also use secondary signal on the far side of the intersection, for each approach.

Make sure the central area of the intersection receives sufficient light, so that vehicles and pedestrians crossing it at night have sufficient visibility.

Keep the right turn radius as narrow as possible, to ensure a narrow junction area, but still allow sufficient turning radius for larger vehicles.



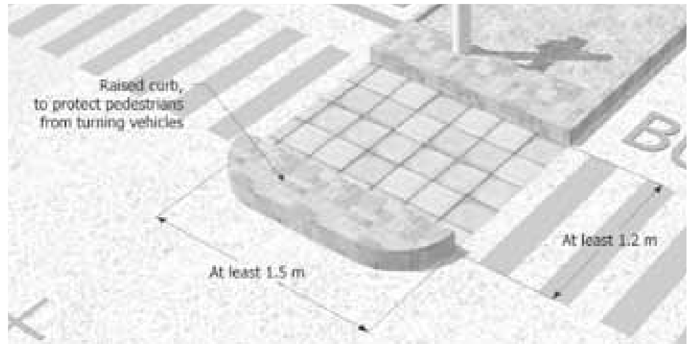
Signs indicating the left turn interdiction and the corresponding loop. Check the applicable local or national standards to find the correct signs. Loop signs should be as simple as possible, to be understood by a driver passing through the intersection.

SAFETY

Intersections with other major urban arterials are among the locations with the highest number of crashes on BRT corridors. These are key locations to target for safety improvements.

The design on the opposite page integrates many of the safety elements discussed in the previous section: tight, simple intersection, restrictions on left turns, short pedestrian crossings with protected refuge islands in the center, guardrails, and signs clearly indicating the loops that replace the prohibited left turns. The annotations provide further details on additional safety features to consider.

Note that this design concept does not include cycle infrastructure on the corridor. Under this scenario, cyclists should be accommodated on a parallel street, to avoid the risk of cyclists using the bus lanes. If a high volume of cyclists can be expected to use the corridors, we recommend including cycle tracks as illustrated on pages 40 - 41.



Detail of the pedestrian refuge island. The island should be at grade with the pavement, and protected from traffic by a raised curb. It should provide sufficient space for the expected volume of pedestrians, and at a minimum should accommodate a person with a stroller.

OPERATIONS

This design concept illustrates the fact that in most cases, the features that improve safety on a bus corridor are compatible with high passenger capacity.

In this case, we prohibit left turns from both the BRT corridor and the cross street and replace them with loops. The number of crashes at this intersection can be expected to be lower than in a configuration that would allow left turns. In addition, eliminating the left turns reduces the number of signal phases needed at the intersection, which helps maximize the amount of green time available for buses.

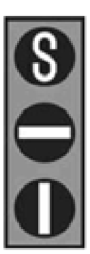
As in the case of mid-block crossings, it would be preferable to allow sufficient green time for pedestrians to cross the street in one signal phase. Here, this would mean a minimum pedestrian green phase of 26 seconds for crossing the BRT corridor and 15 seconds for the cross street.

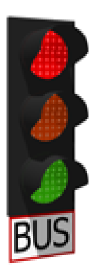
This can easily be achieved with a short signal cycle that also allows high capacity for the bus corridor.

MAJOR 4-WAY INTERSECTION, WITH LEFT TURNS

On streets with a central Busway, left turns originate further from the axis of the roadway than on most other street types. As a result, it might be difficult to accommodate both left turns without them overlapping. A common solution in the TransMilenio system in Bogota is to allow only one of the two left turns (usually the one with the higher traffic volume) and replace the other one with a loop.

We recommend using special traffic signals for buses for the entire length of BRT or Busway corridors. They should be clearly distinguishable from regular signals. We present here several options for designing bus signals (left: bus signal according to Danish requirements, middle: Metrobus signal from Mexico City; right: standard signal with a “BUS” sign).





Left turns should be made from the lane adjacent to the bus lane. Vehicles should have a protected left turn phase, during which all other movements should have a red light.

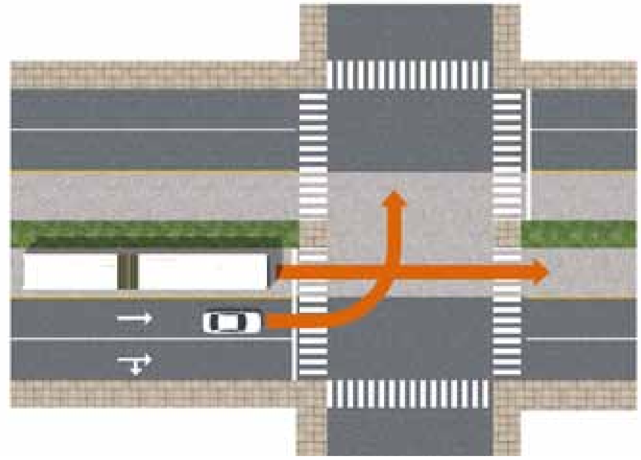
SAFETY

Each added left turn movement at the intersection may increase pedestrian crashes by 30% and vehicle collisions by up to 40% (Mexico City and Porto Alegre models, $p<0.001$).

We recommend allowing left turns from the BRT or Busway corridor only at locations that meet one of the following criteria:

- a large volume of left turning traffic will be expected, and this traffic could not be accommodated on adjacent or nearby streets, making a loop not feasible
- areas where blocks are exceedingly long, meaning that the shortest available loop would mean a significant detour. This could be the case in industrial areas, near major campuses, or in cities with a sparse street network.

If left turns are allowed, they should have a protected signal phase and a dedicated turn lane. We do not recommend allowing traffic to merge into the bus lane and having a shared bus / left turn lane. Data from Bogota, Mexico City, and Guadalajara suggest that whenever vehicles from the mixed traffic lanes enter the bus lanes this often results in collisions with buses.



Crash diagram: the most common type of crash involving buses on center-lane BRT or Busway corridors: cars making illegal left turns in front of buses.

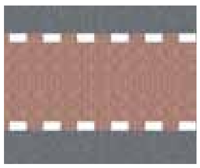
OPERATIONS

Allowing left turns from the bus corridor will reduce the total amount of green time available to buses, since buses must have red during any left turn phase. The exact impact on capacity would depend on the actual traffic signal timing and the number of left turns allowed.

If left turns are allowed only from one of the streets, then capacity at this intersection is still considerably higher than the actual capacity of the system, which will be limited by station layout. However, if left turns are allowed from both the main street and the cross street with protected phases, there is a risk that this intersection will become a bottleneck for the entire corridor.

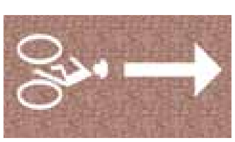
Left turns are one of the issues where the same recommendations improve both safety and operations. Prohibiting left turns eliminates a dangerous movement, while minimizing the number of required signal phases, thus maximizing the capacity of the bus corridor.

MAJOR 4-WAY INTERSECTION, WITH CYCLE TRACKS



The markings for the cycle track should continue through the intersection. Here, we used a thick dotted line to indicate to cyclists locations where vehicles may cross the cycle track. Check the applicable standards to find the correct markings.

Recommended markings for cycle tracks.



We recommend staggering the stop lines for mixed traffic and cyclists, placing the cycle track stop lane slightly ahead. This can help ensure that cyclists are visible to right turning drivers.

Here, we show a 1 meter offset between the two stop lines. The offset could be even larger, up to 5 meters.

SAFETY

The importance of providing cycling infrastructure on BRT and Busway corridors was discussed on pages 26 - 27. Here, we illustrate design concepts for intersections along bus corridors with cycle tracks.

The most important conflict to consider is between cyclists continuing through the intersection and vehicles turning right. The key to improving safety is to make sure the cycle track is clearly visible to drivers on the approach to the intersection. We recommend eliminating the physical barrier along the cycle track several meters in advance of the intersection, to ensure better visibility.

The cycle track should also be clearly marked as it crosses the intersection, and the markings should make it clear to cyclists that other vehicles may cross the cycle track there.

Example of bike lane signs and markings. Photo courtesy of Carsten Wass.

OPERATIONS

The only impact of cycle tracks on bus operations would be to keep bicyclists out of the bus lanes and therefore eliminate possible delays to buses if they are caught behind a cyclist. The capacity or the operating speed of the bus system should not otherwise be affected by the presence of a cycle track.

MINOR 4-WAY INTERSECTION, THROUGH CROSS STREET

SAFETY

Most of the safety problems related to this type of intersection have already been covered on previous pages. The key design issues are: keeping the intersection area as narrow as possible, keeping pedestrian crossings short, and keeping unauthorized vehicles out of the bus lanes.

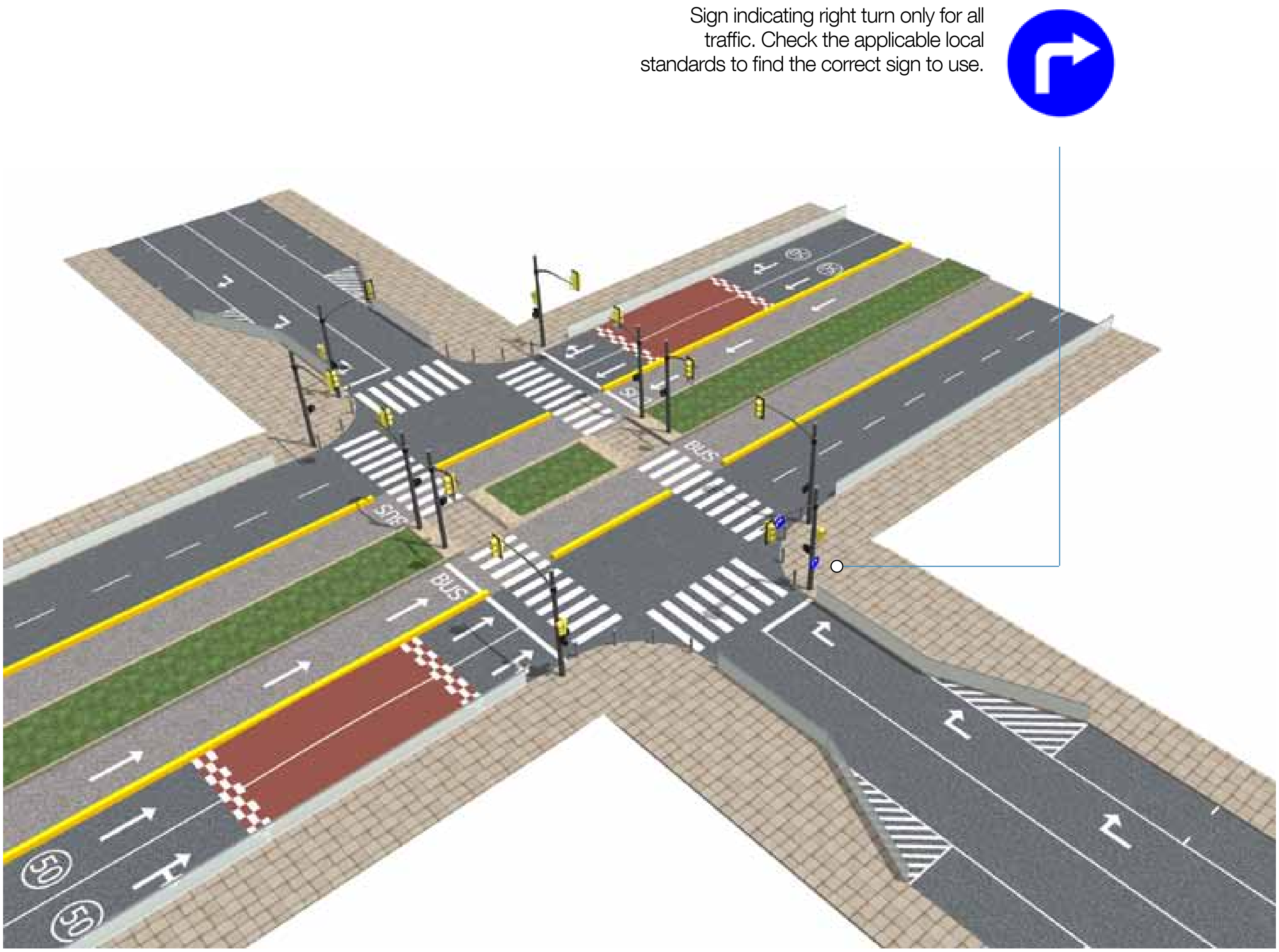
It is also important to ensure that the green signal phase for the cross street allows pedestrians sufficient time to cross the entire bus corridor in one phase.

This design also illustrates how guardrails for pedestrians could be placed along the edge of the sidewalk - instead of in the median. This could also help protect the sidewalk from being used for illegal parking.

OPERATIONS

The green time for the cross street should be at least 28 seconds, to allow pedestrians to cross the main street in one phase, considering that the BRT corridor has a width of 28 meters from curb to curb. This is likely more than would be justified by the traffic volumes on the cross street, but is important for pedestrian safety.

MINOR 4-WAY INTERSECTION, BLOCKED CROSS STREET / T JUNCTION



SAFETY

Blocking off through traffic on the cross street can reduce vehicle collisions at this intersection by up to 36% (Guadalajara model, $p<0.001$).

However, this may not present any benefits for pedestrians. In fact, when the median is extended on the bus corridor across an intersection, it is common on existing BRT systems to eliminate the traffic signals and the pedestrian crossings. But as we observed during road safety inspections, pedestrians will continue to cross at these locations, and will be exposed to the risk of crashes. We therefore recommend maintaining the crossings and the signals. Moreover, some vehicles may not stop at a red light if the only conflict is with pedestrian traffic. We recommend mitigating this potential risk by placing speed humps before the intersection.

OPERATIONS

The capacity of the bus lanes at this intersection is still constrained by the length of the pedestrian green signal phase on the cross street, so if all other things are equal, blocking off the cross street should not have an impact on capacity.

However, this will reduce average operating speeds, compared to the standard practice on BRT corridors to eliminate crosswalks and signals at these locations. This implies a tradeoff between operating speeds and pedestrian safety. At a minimum, we recommend having one signalized pedestrian crossing every 300 meters.

MINOR 4-WAY INTERSECTION, BIKE TURNS

The secondary signals are particularly important here. Cyclists waiting in the queue boxes to complete a left turn will not see the primary signal and rely exclusively on the secondary one.

The safest location for the cycle track is between the sidewalk and the parking lane. This can help eliminate conflicts between cyclists and cars that are either parked or maneuvering in and out of parking spaces.

On-street parking

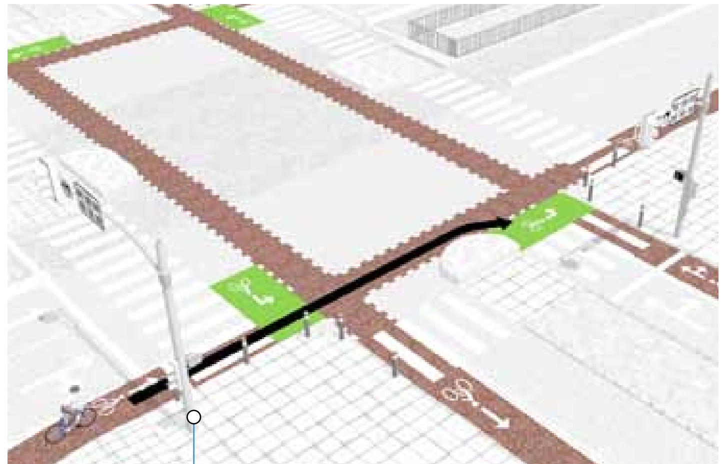
Buffer zone between parking lane and cycle track. This can help protect cyclists from parked car doors opening unexpectedly - a common safety concern for cyclists.

SAFETY

The main safety concern for an intersection where both streets have bicycle infrastructure is how best to accommodate left turns by cyclists. There are several options for designers, including bike boxes and two-stage turn queue boxes (NACTO 2011). We recommend using two-stage turn queue boxes and we illustrate this concept in the image on the opposite page. It should be noted that two-stage turn queue boxes function differently from left turn boxes. Cyclists wishing to turn left will first cross the intersection, then wait in the designated queue box for the green signal on the cross street. When the cross street light turns green, cyclists can then cross the BRT corridor with the rest of the traffic.

This is the typical international best practice (NACTO 2011), and it is also the option that minimizes conflicts between cyclists and other road users. Depending on the local context and previous experience with this type of solution, it may also be a new and relatively unusual configuration. The advantages of using this configuration should be weighed carefully against the need for education and enforcement to ensure cyclists use the turn boxes correctly.

If cyclists are not well informed about how to use this infrastructure, there may not be any safety benefits from introducing it. For other options for accommodating left turns for cyclists, refer to NACTO 2011.



First stage of the left turn. Cyclists should continue straight along the BRT corridor on the green light, stop in the queue box to their right, and wait there for the light to change.

Second stage of the left turn. When the light turns green for the cross street, cyclists can cross the BRT corridor along with the rest of the traffic. Note the importance of the secondary traffic signal here. Cyclists will not be able to see the primary signal and will rely exclusively on the secondary one, situated on the far side of the intersection.

MAJOR 4-WAY INTERSECTION, BLOCKS OVER 200 METERS

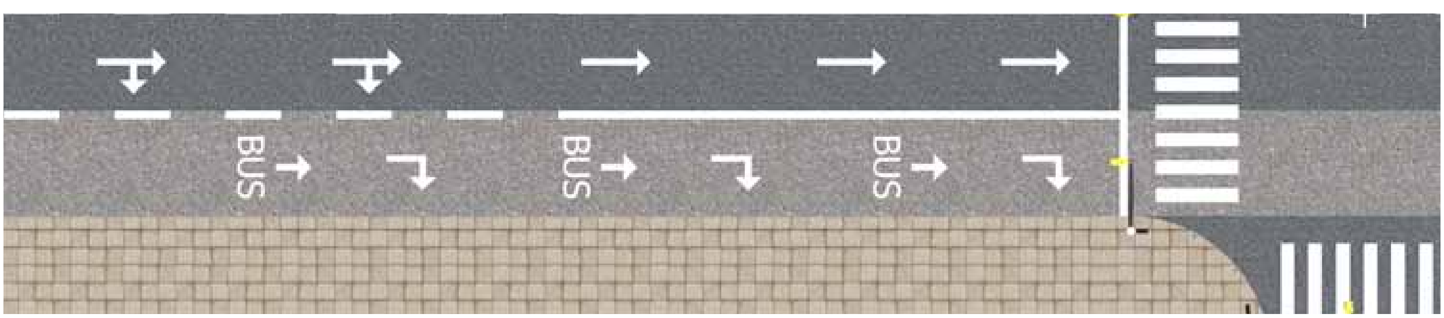
For sections with longer blocks, it may be possible to use barriers between the bus lane and the other lanes, after the intersection. These barriers would have to be taken out eventually, on the approach to the next intersection.

The pavement markings in the curbside lane should clearly indicate that vehicles may only turn right from the lane, but that buses are exempt from this rule. Check the applicable standards to find the correct markings or signs to use in this situation.

The turning radius here is very narrow, to prevent vehicles from accidentally turning right from the cross street into the bus lane. There is, however, sufficient space for turning right safely into one of the mixed traffic lanes.

Do not use this in case there might be a need for some vehicles to turn right into the bus lane (e.g. maintenance vehicles, local bus services sharing the bus lane, ambulances, etc.)

Plan view of one approach to the intersection along the bus corridor. Right turning vehicles can merge into the curbside bus lane in advance of the intersection and then turn right from the bus lane. The space for merging into the bus lane should be at least 50 meters long.



SAFETY

One of the main safety issues at intersections with curbside bus lanes is how to address right turns.

RIGHT TURNING TRAFFIC SHARING THE BUS LANE

This is the recommended option from a safety perspective. The dividers between the bus lane and the mixed traffic lanes should be taken out well in advance of the intersection, and right turning traffic should be allowed to merge into the bus lane. There is a potential conflict when vehicles merge into the bus lane, but this risk can be mitigated by allowing a longer merging area.

RIGHT TURNS DIRECTLY ACROSS CURBSIDE BUS LANE

It is also possible to allow right turns from the lane adjacent to the curbside bus lane. This is currently the case on the Eje Central in Mexico City. While we don't have the data to evaluate how safe this option is, we can point out several potential safety risks. If right turns and through movements share the same green phase as on Eje Central, there is a serious risk of collisions between turning vehicles and buses (the mirror image of the left turn problem on center-lane systems). If right turns have a separate green phase, and if a bus is waiting on red at the stop line, right turning vehicles may have poor visibility of the pedestrian crosswalk to their right. Similarly, pedestrians would not see, and may not expect right turning vehicles appearing from behind the buses, which could lead to crashes.

OPERATIONS

Curbside bus systems rarely achieve capacities over 5,000 pphpd (Wright and Hook, 2007). Even when accounting for vehicles turning right from the bus lane and the delay caused by right turning vehicles yielding to pedestrians, the capacity of this intersection is over 4 times higher than what the corridor would typically be able to carry.

This calculation does not account for interference from minibuses and other unauthorized vehicles using the bus lanes, illegal parking, and pedestrians and cyclists using the bus lanes, all of which would likely further reduce capacity.

MAJOR 4-WAY INTERSECTION, BLOCKS UNDER 200 METERS

SAFETY

When block lengths are below 200 meters (common in dense downtown areas) it is no longer feasible to use any sort of physical barrier between the curbside bus lanes and the mixed traffic lanes. The barriers would not leave enough room to create a safe merging area for right turning vehicles.

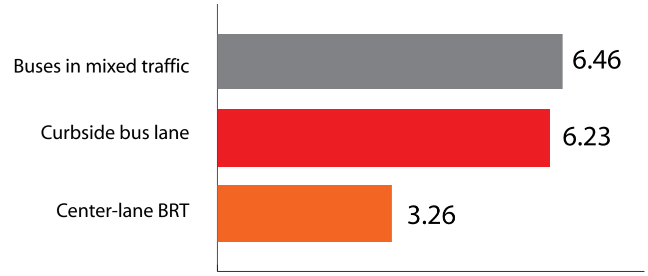
In these cases, a curbside bus corridor will operate more like a conventional bus system in mixed traffic. It will not be possible to keep unauthorized vehicles out of the bus lanes, except through strict enforcement. Due to the high number of possible conflicts with turning vehicles, buses will likely operate at lower speeds. It is also quite possible that the bus lane will be heavily congested, as in the case of the curbside bus lane on Av. Alcalde in downtown Guadalajara, Mexico, or Eje Central as it nears downtown Mexico City.

In the Guadalajara crash frequency model, the presence of the congested curbside lane was correlated with higher crash rates for both vehicles and pedestrians and the results were highly significant ($p.<0.001$). But the vast majority of vehicle collisions were minor and resulted in property damage only.

Crash data also show that buses are the most frequent type of vehicle involved in crashes on Av. Alcalde and 16 de Septiembre, ahead of cars, trucks, and minibuses. The quality of the data is insufficient to allow a more in-depth analysis of crash types and contributing factors on this corridor. However, there is enough in the data to indicate that curbside lanes could pose more safety issues than center-lane systems. It is therefore important, when designing curbside bus lanes, to reduce all the other known risk factors to improve safety: narrowing intersections, shortening pedestrian crossings, ensuring lane balance and alignment, etc.

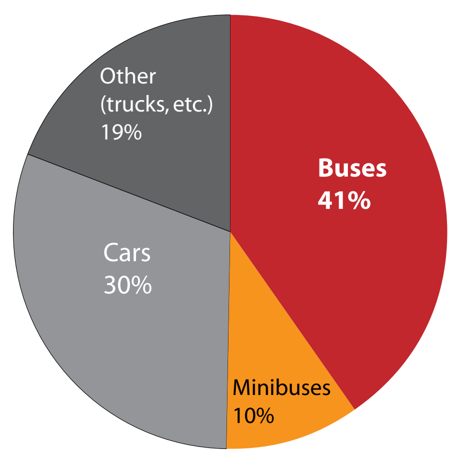
COMPARISON OF ROAD SAFETY RECORD FOR THREE TYPES OF BUS CORRIDORS IN GUADALAJARA, MEXICO

Annual crashes per lane-km per 1,000,000 vehicles



Calculated from data provided by Secretaria de Vialidad y Transporte de Jalisco and by E.P.S., Guadalajara. Curbside bus lanes include portions of Av. Alcalde and 16 de Septiembre. Center-lane BRT includes Calz. Independencia and Av. Gobernador Curiel. Mixed traffic data includes portions of Av. Circunvalacion, Belisario Dominguez, and Calz. del Ejercito.

VEHICLES INVOLVED IN CRASHES ON A CURBSIDE BUS CORRIDOR IN GUADALAJARA (AV. ALCALDE)



OPERATIONS

When there is no physical separation between the bus lanes and the mixed traffic lanes, it becomes a lot more difficult to ensure a high frequency and high capacity bus service. The bus corridor will operate more or less like conventional bus service in mixed traffic. In addition, buses may sometimes need to change lanes to overtake vehicles parked in the bus lanes, which will further slow buses down.

STATIONS

KEY SAFETY ISSUES

PEDESTRIAN ACCESS TO THE STATION

Stations have higher pedestrian volumes than most other locations on a bus corridor, since in addition to the normal pedestrian traffic, there is the traffic to and from the station. The risk of pedestrian crashes here is higher and this is not only due to increased exposure. There is also an issue of dangerous behavior, and particularly attempts to jaywalk to and from the station.

The design and layout of the stations can influence the frequency of dangerous pedestrian movements. Using closed stations with controlled access points that direct pedestrian traffic to signalized crosswalks is the safest configuration. Open stations with low platforms are generally more conducive to jaywalking, while closed stations with high platforms can reduce the incidence of these dangerous movements.

Pedestrians running across the bus lanes to attempt to enter the station without paying the fare, on TransMilenio. EMBARQ photo.

CONFLICTS BETWEEN BUSES

This is an issue to consider on busier corridors, especially those with express lanes and a combination of local and express services, where conflicts between different buses are more likely.

The most common types of conflicts at stations are those between buses moving in and out of the express lanes. The specific crash types are discussed in detail on page 57.

On the following pages, we present several design concepts for bus stations that address the key safety issues discussed in the previous page.

The main issue is the same regardless of the type of station: controlling pedestrian movements and discouraging jaywalking. But the design solutions for achieving this are different depending on the exact type of station and the fare collection method used on the bus system.

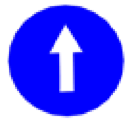
We start with a design concept for a median station for a center-lane BRT corridor. This is separated in two parts, the first dealing with pedestrian access to the station, and the second with detailed station and platform design. For a design concept on bicycle access to a BRT station, refer to the following section (transfers and terminals), on page 77.

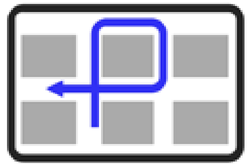
We then show a special case of median stations - those common on high-capacity systems like TransMilenio and which feature multiple sub-stops and express lanes. In this case, in addition to addressing pedestrian access, the designers of the stations also need to pay attention to potential conflicts between different buses.

We then illustrate concepts for bus stations on corridors that do not use off-board fare collection - such as open Busways, curbside bus lanes, or conventional bus service in mixed traffic.

LIST OF ILLUSTRATIONS

STATION ACCESS ON AN URBAN ARTERIAL





We recommend not allowing right turns that conflict with pedestrian access to the station. There should be a sign indicating "no turns" and a loop sign indicating the alternate path for making the left turn. Check the applicable local or national standards to find the correct signs.

A longer green signal phase for the bus corridor will increase passenger capacity for the bus system. But there is a downside to this, especially for stations with a high number of boardings and alightings. A longer green phase for the main corridor means a longer red phase for passengers leaving the station and waiting to cross the street. In some cases, there is a risk that the pedestrian waiting area will be quickly filled to capacity. This can result in people waiting in the bus lanes or crossing on red, both of which are serious safety risks for pedestrians.

Pedestrian area filled to capacity at the exit of the Calle 72 station on TransMilenio. EMBARQ photo.

The downside to prohibiting right turns is that it reroutes traffic through the neighborhood and may simply shift the risk to other streets. Another way to deal with right-turn conflicts is to use a dedicated right turn lane with a dedicated turn phase. This solution has been successfully applied in New York and Washington DC.

SAFETY

In order to improve safety at stations, we recommend tailoring their design to pedestrians' observed behavior. In particular, designers should limit opportunities for jaywalking, by designing closed stations and using guardrails to guide pedestrians to signalized crosswalks.

The most important safety feature that we would recommend is to use closed stations. This is regardless of whether the bus system uses off-board or on-board fare collection. The station should have access points situated only at signalized pedestrian crosswalks or pedestrian bridges.

Another important safety feature is to include a guardrail along the lane divider between the bus lanes and the mixed traffic lanes. This guardrail should help prevent passengers from attempting to run across the bus lanes to and from the station.

We also noted during road safety inspections that pedestrians will often cross along the median when leaving a station situated in the center of the street. This type of behavior is quite prevalent and would be difficult to prevent. It is also not necessarily dangerous, since there are usually no conflicting movements when pedestrians cross during the green phase for buses.

We recommend providing a crosswalk with pedestrian signals to accommodate this movement, following the example of the Macrobus system in Guadalajara. It is also important to make sure that turning movements are prohibited that may conflict with pedestrians crossing here (such as left turns from the bus corridor).

OPERATIONS

The key issue to consider for station access is pedestrian overcrowding on the median and on any refuge islands that may be present.

A typical station on a single-lane BRT system like Metrobus in Mexico City will commonly have anywhere between 2,000 to 12,000 daily passengers exiting the station (EMBARQ Mexico, Metrobus survey, 2007). Findings from a road safety audit on a proposed BRT corridor in Rio de Janeiro indicate that some busier stations may have as many as 100 passengers exiting during one signal cycle in the peak hour.

In these cases, the access path to the station needs to be studied in conjunction with the traffic signal, to ensure that large volumes of pedestrians are not left stranded on narrow medians that cannot accommodate them. A simple solution is to ensure that pedestrians can always cross from the station platform to the sidewalk in one signal phase. Many of the problems we identified through audits were due to the presence of multiple pedestrian signal phases, which often risked leaving large volumes of pedestrians stranded on narrow medians.

STATION DESIGN

A key safety component of station design is to place a barrier or guardrail between the bus lane and the traffic lanes. This should help prevent passengers from attempting to jaywalk across the bus lanes to enter or exit the station.

Platform screen doors at the interface between the buses and the station are a good safety feature for BRT stations. The doors should be aligned with the bus doors, and designed to open only when a bus is docked at the station platform. However, the mechanism for opening the doors needs to be carefully designed, to ensure that it cannot be accidentally activated by a passing express bus, or by a bus docking at another platform nearby.

Pedestrians running across the bus lanes to enter a station on TransMilenio. EMBARQ photo.

A platform screen on a BRT station in Curitiba. The doors are open, even though no bus is present. This is a safety risk in a crowded station, as passengers can accidentally fall in the bus lanes. Photo courtesy of EMBARQ Brasil.

SAFETY

Stations located in the median of a roadway need to be designed as closed spaces - surrounded by screen walls or high guardrails that direct pedestrians to specific access points situated at signalized crosswalks. Stations should follow these design principles regardless of the fare collection system used (on-board or off-board), or the type of vehicles.

USING A HIGH GUARDRAIL BETWEEN THE BUS LANE AND THE MIXED TRAFFIC LANES

This is the most important safety element of station design, as it helps eliminate the most dangerous pedestrian movements - cutting across the bus lanes to enter or exit the station illegally. This guardrail needs to be at least 1.7 meters high, and possibly even higher, to ensure that pedestrians cannot climb over it easily. It should also be resistant, since guardrails are often damaged by people wishing to go across. It should extend for the entire length of the station, without any gaps.

USING PLATFORM SCREENS

Platform screens can be useful in preventing jaywalking, and also in making sure that passengers waiting on the platform stay clear of buses maneuvering in the bus lanes. But the screen doors can pose several problems. Aside from the issues with accidental opening discussed on the opposite page, there is also the problem of people forcing the doors open. Sometimes, this is an attempt to enter or exit the station illegally and running across the bus lanes. But in other cases, passengers have been observed simply preventing the screen doors from closing while waiting for the bus.

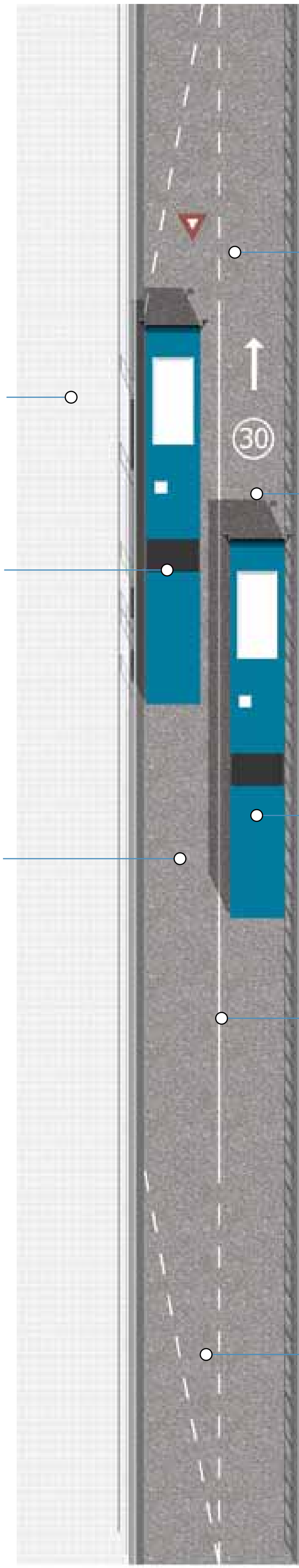
PATHWAYS BETWEEN DIFFERENT SUB-STOPS

TransMilenio 2006: a pathway between two sub-stops at the same station. Note the low guardrails, approximately 1 meter in height. Because they were so low, people could jump over them easily, and this was a major pedestrian safety risk. EMBARQ photo.

TransMilenio 2011: the guardrails along the pathways were raised to make it more difficult to climb over. We recommend using this higher type of guardrail on any pathway connecting different parts of the same station. EMBARQ photo.

Passengers forcing a screen door open on a TransMilenio station platform, while waiting for the bus. Photo by Lucho Molina.

STATION DESIGN: EXPRESS LANES



The place where buses leave the station platform and merge into the express lanes is where the most dangerous crashes between buses can occur. Buses in the express (right) lane should always have priority over buses in the left lane and this should be reinforced through signs, pavement markings, and driver training.

Station platform.

Rear-end crashes between express and local buses tend to be very serious because of the high speed differential between the two vehicles. One possible way to address this is to set a lower speed limit on the express lanes through stations. This would reduce the severity of a crash, and would also give the drivers more time to react and a shorter braking distance. This type of solution has been implemented at tramway stations in Brussels. Tramways are required to approach stations at speeds of no more than 30 kmh, in order to help avoid crashes.

Articulated bus docked at a station platform.

Express bus traveling through the station.

Waiting space for one bus. A bus can pull into this area and wait for the bus in front of it to leave the station, before it docks to the same platform. This type of maneuver can help reduce the interval between two consecutive buses at one platform, which can increase capacity.

The safety concern here is that the second bus may come in too fast and cause a rear-end collision. A possible way to mitigate this risk is to make this area longer, so that the buffer space between the bus at the platform and the waiting bus is increased.

Here: waiting space length is 23m

The continuous line indicates that buses are not allowed to change lanes at this location. Lane changing should only be done across the dotted lines. This should help better organize traffic at the stations.

Merging area for buses leaving the express lane and preparing to dock at the station. The length is usually about the same as that of a bus (18 meters for articulated buses).

SAFETY

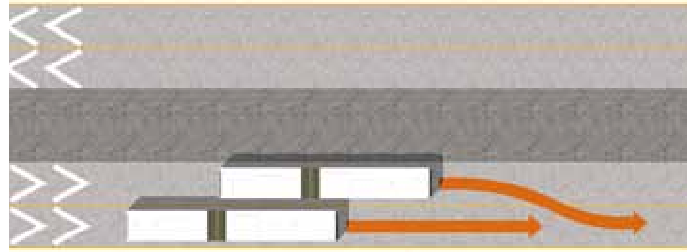
For high capacity stations with express lanes and multiple stopping bays, there are additional safety risks to consider. The most serious one is the chance of collisions between local and express buses, which can be serious and even fatal.

When bus systems need to achieve peak loads of 30,000 or even 40,000 passengers per hour per direction, this is usually done through a combination of multiple lanes, multiple docking bays at stations, and a mix of local and express services. This also results in a much higher density of bus traffic. The busiest section of TransMilenio, for example, has as many as 350 buses per hour per direction, according to TransMilenio. This means that conflicts between buses are a lot more frequent, and the chance of collisions between different buses is higher.

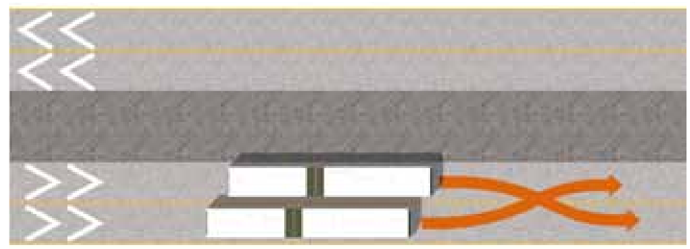
Rear-end collisions represent the most frequent type of accidents recorded between buses on TransMilenio and also on the Metropolitano BRT in Lima, which has a similar layout. The majority of rear-end crashes occur away from stations, but those that happen at stations tend to be more severe, because they usually involve a fast moving express bus colliding with a local bus leaving the station. The three most serious rear-end collisions at TransMilenio stations between 2005 and 2011 together accounted for over 170 injuries.

Another common crash type at stations are side collisions or side swipes between buses maneuvering in and out of the station. These rarely result in injuries and mostly damage the side mirrors on the buses.

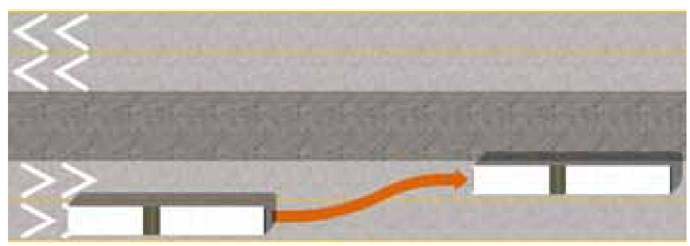
CRASHES BETWEEN BUSES AT STATIONS



Severe crash scenario at a typical TransMilenio station: a local bus is leaving the station platform and merging into the express lane, when it is hit from behind by an express bus travelling through the station. This crash type has resulted in serious injuries and at least one fatality.



Low severity crash scenario at a typical TransMilenio station: a local bus leaving the station platform collides with a bus attempting to dock to another platform. These crashes usually happen at low speed, so they rarely result in injuries.



Crash situation at stations on TransMilenio as well as Metropolitano (Lima) BRTs. A bus docked at the station is hit from behind by another bus lining up behind it to service the station. It is usually a low speed crash and therefore not as serious as rear-end crashes on the express lanes.

STATION ACCESS AND DESIGN

Pedestrians leaving a TransMilenio feeder bus station through an unauthorized exit point.

Placing a guardrail here can help prevent pedestrians from jaywalking across the mixed traffic lanes to the sidewalk. In Porto Alegre, some Busway stations feature this type of guardrail, for a distance of up to 10 meters from the end of the platform, yet pedestrians still cross in mid-block. Guardrails should be long - in excess of 10 meters - to be effective.

We recommend using a continuous wall along the edge of the station, preferably transparent. This would direct pedestrians entering and leaving the station to the signalized crosswalk, and would also allow them to see any vehicles in the mixed traffic lanes.

An important safety feature is the guardrail between the two bus lanes. This will prevent pedestrians from attempting to take shortcuts across the bus lanes from the station platform to the opposite sidewalk, and direct them to the signalized crossing.

SAFETY

Busways often have open, low platform stations and feature on-board fare collection. This often means that pedestrian access to the station is poorly regulated, and there is a high incidence of jaywalking. A study in Porto Alegre, Brazil, found that Busway stations had a higher incidence of pedestrian crashes than other locations, after accounting for differences in street design, traffic, and pedestrian volumes (Diogenes and Lindau 2009). The solution is to design these in a way that better controls pedestrian access.

Controlling pedestrian access can be done by using screen walls and/or guardrails. The key is to consider all possible pedestrian movements to and from the station, and to make sure only those across signalized crossings or pedestrian bridges are allowed.

Pedestrians jaywalking from a station on the BRTS corridor in Delhi. EMBARQ photo.

Pedestrian jaywalking across the bus lanes to reach the station platform on the BRTS corridor in Delhi. EMBARQ photo.

OPERATIONS

The design safety features recommended here (screen walls and guardrails to control pedestrian movement) would not have any impact on operations. Since the design concept illustrated on page 58 involves an open Busway with on-board fare collection, passenger capacity would be quite low. With this station layout, and without multiple stopping bays, it would not exceed 6,000 pphpd (Wright and Hook, 2007).

An important issue to consider is station to intersection interference. If a bus has finished loading passengers and must wait at a red light, it may prevent another bus behind it from accessing the station platform. This can be resolved by providing enough space for a bus to wait at a red light while another bus services the station behind it. It can also be addressed by ensuring that the ratio between the length of the red signal phase and the average stopping time at a station is as low as possible. A shorter signal cycle can help achieve this.

A bus maneuvering around a stopped vehicle at a curbside station on Transantiago, Santiago de Chile. Photo by Dario Hidalgo.

Placing the station on a curbside bus corridor after an intersection instead of before it can help eliminate some of the conflicts between buses and right turning vehicles. In particular, it can lower the likelihood that a vehicle waiting at a red light would block the station for the bus.

There should be sufficient distance between the station and the intersection to accommodate the number of buses that may queue at the station without having them block the intersection.

SAFETY

Pedestrians may attempt to cross in mid-block to access the station - especially if they see a bus approaching in cases where headways are relatively long.

This risk can be mitigated by placing a barrier or guardrail along the station, and extending it at least 10 to 12 meters beyond the end of the station platform. This can help reduce jaywalking and direct pedestrians to the signalized crossing at the intersection.

The risk of pedestrian crashes on bus priority lanes or conventional bus routes is high in the absence of improved safety features. We recommend using a median with guardrails along it to discourage jaywalking, and providing pedestrian refuge islands in the center of the street.

SAFETY

In the case of bus priority lanes or conventional bus service, improving safety has more to do with general street and intersection design that with the station itself.

The goal is the same as in the case of the other stations: preventing jaywalking to and from the station and directing pedestrians towards signalized intersections. This can be done by placing a guardrail in the median and extending it for the entire length of the block where the station is present.

In addition, we recommend addressing all the safety issues identified in the previous sections (street segments and intersections) with a particular focus on jaywalking. Since risks are high for pedestrians on conventional bus corridors, it is important to focus on pedestrian safety improvements along them.

KEY SAFETY ISSUES

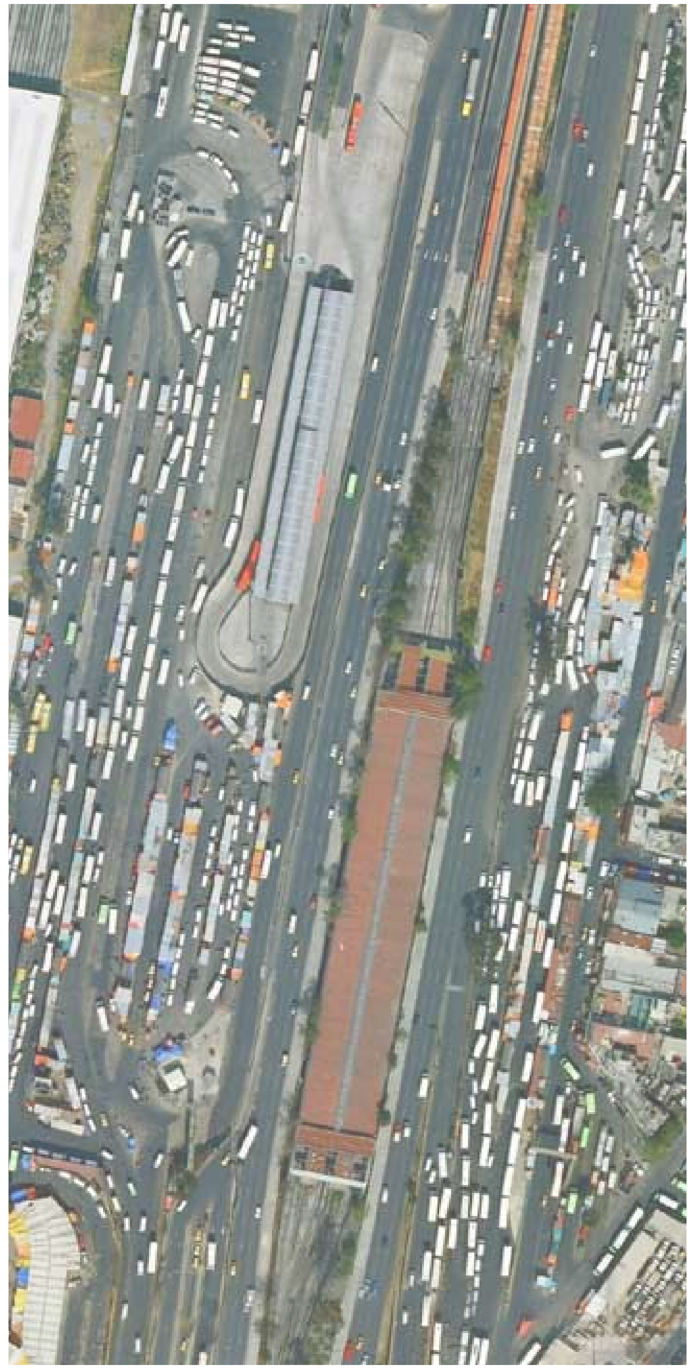
On most public transport systems included in our study, major transfer stations are the locations with the highest number of accidents. Of the top ten locations with the highest number of crashes on Av. Caracas, on TransMilenio, three - including the top one - are either terminals or major transfer stations (Av. Jimenez, Portal de Usme, Santa Lucia). On the South Line, in Curitiba, the top three locations with the highest number of crashes are all terminals (Pinheirinho, Raso, and Portao).

This does not necessarily mean that transfer stations and terminals are more dangerous, but also that they have a lot more vehicle and pedestrian traffic than other locations. As a result, any safety problem at a major transfer station can result in a larger number of crashes and injuries than at any other location.

For any type of transfer, the main safety issue to be considered is pedestrian safety. Our data has shown that people are considerably safer when they are in the bus or on the station platform than when they are walking to and from the station. The safest types of transfers between two main routes are those where the passengers never leave the station platform.

This is not always feasible and it depends on the types of vehicles and stations used by the different public transport routes, and also on the urban context. Large, integrated transfer terminals where all transfers are done cross-platform are the ideal solution, but they tend to take up a lot of space. They can usually be built at the end of a line, close to the edge of the city. One such example is TransMilenio, which features integrated terminals at the end of each major corridor. Trunk and feeder lines meet at these terminals.

In other cases, especially in dense downtown areas, there may not be room to accommodate a large terminal, so the transfers will usually happen at an intersection. In this case, all the safety concepts for intersections apply, with some extra considerations for enhanced pedestrian safety and accommodating bus turns.



Aerial view of Indios Verdes, Mexico City, a transfer point between the Metrobus BRT, the Metro, and minibuses connecting north to Estado de Mexico. Google Earth image.

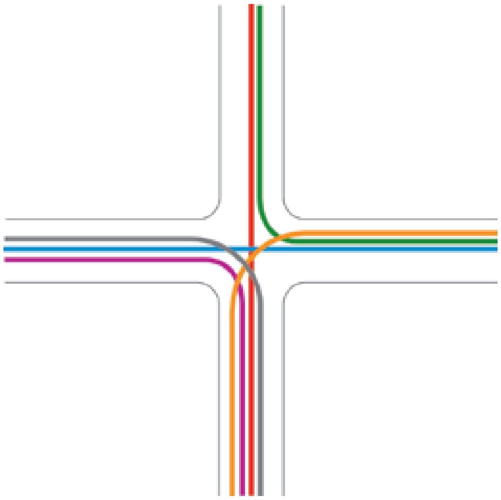
On the following pages, we present several design concepts for transfer stations and terminals that address the key safety issues discussed in the previous page.

We start with transfers between BRT or Busway trunk lines, and then move on to transfers between trunk and feeder lines, as well as transfers between a BRT and local bus services.

In terms of safety, there are two ways to evaluate the relative merits of different transfer configurations. The first is the safety of transfer passengers. From this point of view, the best options are cross platform transfers or direct bus routes making all possible connections.

The second aspect to consider is the overall safety of the location where the transfer occurs - not just for transfer passengers, but for all road users. From this point of view, the issues are the same as for intersections and stations in general: narrow junction areas, turn restrictions, short pedestrian crossings, and good station access design to limit opportunities for jaywalking.

LIST OF ILLUSTRATIONS

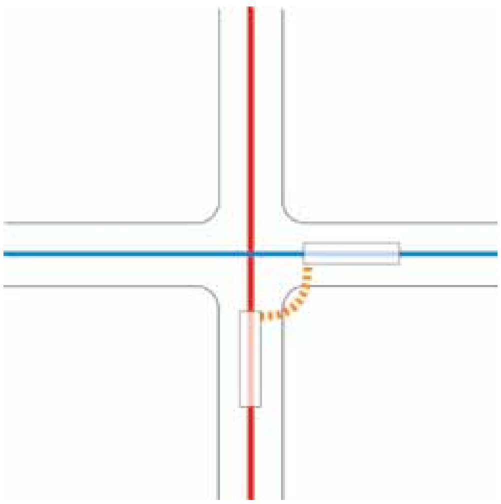


DIRECT ROUTES TO ALL DESTINATIONS

EXAMPLE: TRANSMILENIO

Under this scenario, there are different bus routes on each corridor, and there is one route for every possible destination. Passengers simply need to wait for the bus that will take them in the right direction, so there is no actual transfer involved.

This is the safest option, but also the most operationally complex. The design of the intersection needs to provide separate turn lanes and protected signal phases for the different bus movements, in order to avoid delays, or else use overpasses or underpasses. This is discussed in more detail on pages 66 - 67.

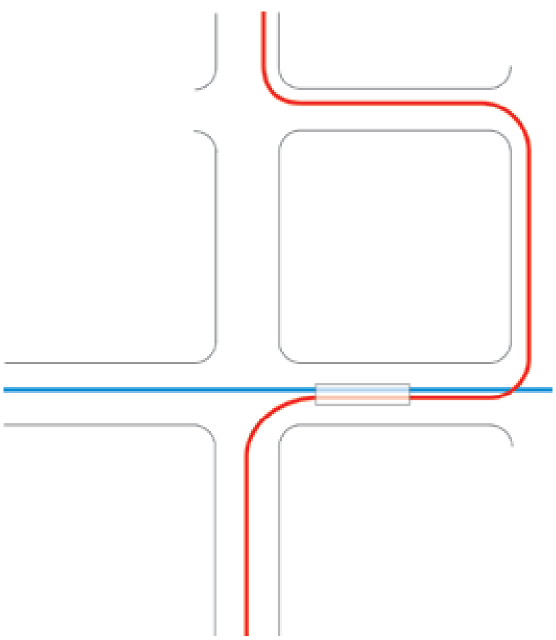


TRANSFER ACROSS AN INTERSECTION

EXAMPLE: MEXICO CITY METROBUS

In this case, there is only one route on each corridor. Transfer passengers must exit at one of the stations, cross the street, and board the other route at the other station.

This is the least safe option, since passengers must cross several traffic lanes to get to the other station. It may also deter passengers from using the system, since it would impose a rather difficult transfer and may require them to pay the fare again to enter the second station. All these problems could be avoided by connecting the two stations via a bridge or overpass. This type of transfer is featured on pages 68 - 69.

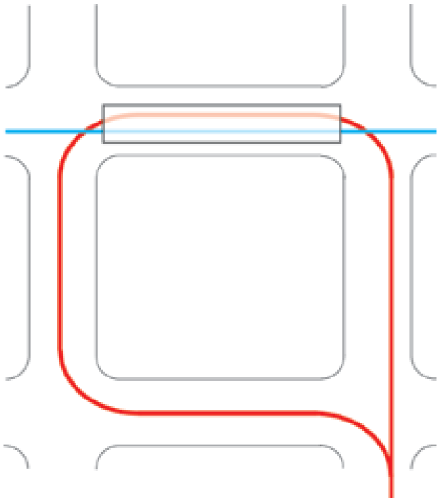


HYBRID OPTION

It would be possible to have cross-platform transfers even with only one bus route per corridor. This would involve a one-block detour on one route, so that buses from both routes could stop at the same station.

For transfer passengers, this would be a safer option and would also save time. But the downside is that this option would increase travel times for those passengers continuing on the red route. Intersection design would also be complicated, because of the different bus turns and the need to maintain lane balance on all sides for safety.

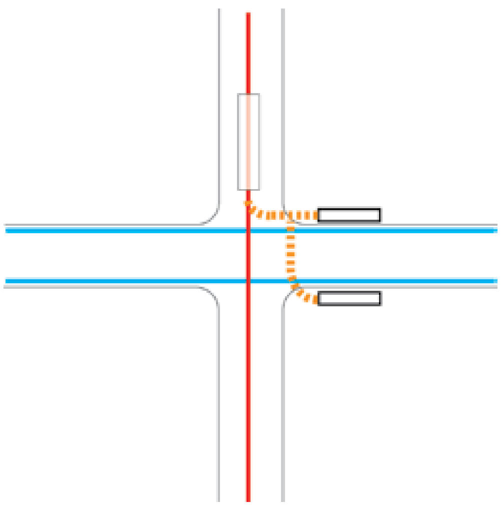
This option might be feasible in cases where the configuration of the street network or the structure of the two bus routes would minimize the detour needed in order to bring all the buses to the same station. We explore this in more detail on pages 70 - 71.



INTEGRATED TERMINAL

EXAMPLES: TRANSMILENIO TERMINALS, SAN JERONIMO TERMINAL ON THE OPTIBUS BRT, LEON

This is a typical transfer terminal for an integrated trunk and feeder service, such as TransMilenio. The terminal has a central platform, and right-door and left-door buses can dock on both sides, so that passengers transfer cross-platform only. It usually involves good integration between the different services, but in theory it can also work with completely independent services. The BRT side of the station can be closed and feature off-board fare collection, while the other side can be open. This is discussed in more detail on pages 72 - 75. The transfer itself is quite safe, but there is a risk of collisions between buses at access points to the terminal.



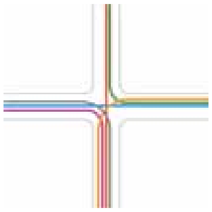
TRANSFER TO LOCAL BUS SERVICES ACROSS AN INTERSECTION

EXAMPLE: MACROBUS, GUADALAJARA

This is a case where a BRT or Busway corridor crosses a street that has local bus service. The different bus services are not integrated (as in the case of a trunk and feeder system) but some passengers may transfer between the different lines. The goals here are to bring the different stations as close together as possible, to make the intersection as safe as possible for pedestrians, and also to arrange the transfer in a way that minimizes crossing distance.

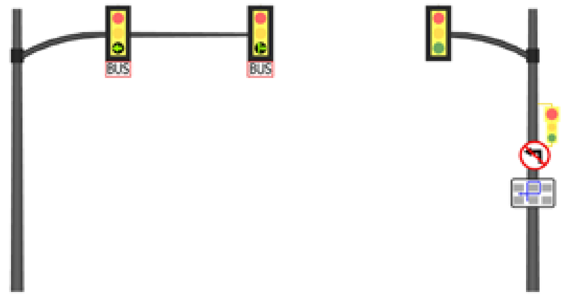
This is not the safest option, since it involves transfers across traffic lanes, but it is the easiest to implement and requires no integration between the different services. This type of transfer is featured on pages 76 - 77.

DIRECT ROUTES TO ALL DESTINATIONS



It is quite difficult in practice to allow buses to make all possible turns at an intersection, since this would result in as many as six signal phases. This can result in a reduced capacity for both streets. In practice, it is common to allow only some bus turns, depending on travel patterns and demand. In the image below, three of the approaches to the intersection can make turns into the fourth one, or continue straight.

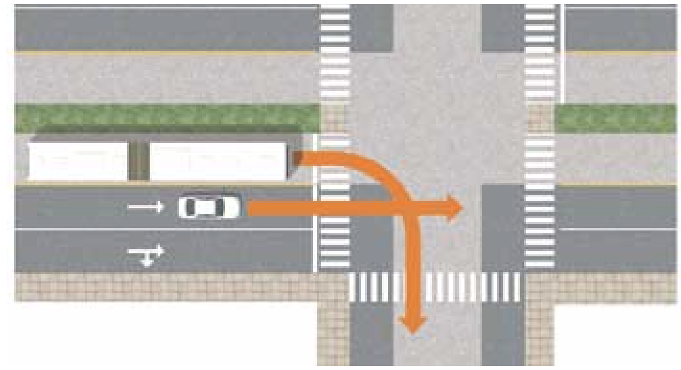
Under this type of configuration, there is a need to place multiple bus signals to serve each turning movement with a separate phase.



SAFETY

For transfer passengers, this is the safest option, since the there is no actual transfer involved, and passengers would simply choose the bus that takes them to their destination.

Because of the need to accommodate multiple bus turns, there is a risk that this layout could result in a large junction area, which could pose problems for pedestrians. This risk can be mitigated by using the narrowest turning radii possible for bus turns, and by adding pedestrian refuge islands in the center of the street.



Crash diagram illustrating a potential conflict between right turning buses and vehicles continuing straight. This type of crash has been reported on TransMilenio.

OPERATIONS

This type of transfer allows great flexibility in organizing bus routes. Offering BRT passengers a direct connection to their destination - rather than forcing them to walk to another station to transfer - can help attract more riders to the BRT system. But the downside is that the location where two BRT corridors intersect can become a major bottleneck.

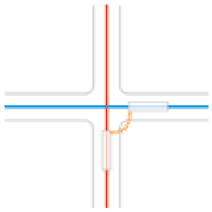
A multi-lane BRT corridor can have a maximum capacity of up to 43,000 pphpd (Hidalgo and Carrigan 2010). In this case, where the two corridors meet at an intersection, it is very difficult to achieve this capacity on both corridors. Because all the different bus movements would need their own signal phase, the g/C ratio (i.e. the ratio between the length of the green phase and that of the signal cycle) for each movement will be low.

This could be addressed by prioritizing one of the two corridors or one of the bus movements, by increasing the amount of green time available for that movement and decreasing for others. If both corridors have high passenger demand, it could be considered to create an overpass or underpass to connect the corridors, like in the case of the junction between NQS, Avenida Suba, and Calle 80 on TransMilenio

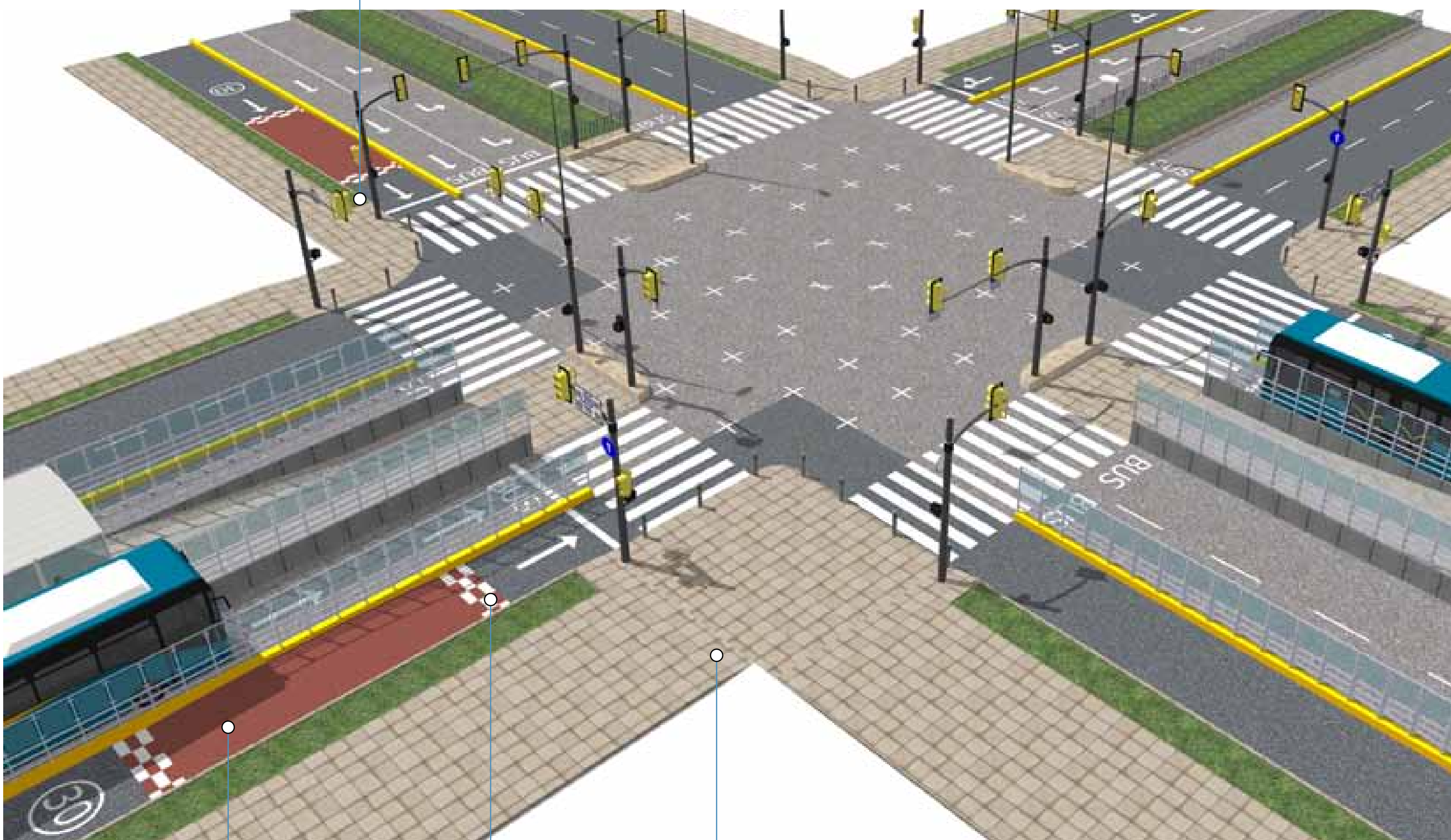
Junction between three TransMilenio corridors: NQS, Calle 80, and Avenida Suba. Bus connections between the three corridors are done via overpasses and underpasses, which maximizes capacity for all the movements and minimized potential conflicts between buses. Google Earth image.

TRANSFERS BETWEEN TRUNK LINES ON THE SAME SYSTEM

TRANSFER ACROSS AN INTERSECTION



It is also possible to use a combination of transfers across the intersection and bus turns. This is used in the case of the Av. Jimenez station in TransMilenio, where some transfers are made by buses connecting the two corridors, while other transfers are made by passengers walking from one station to another via an underpass. This type of solution can help reduce the number of signal phases required for the intersection.



We recommend using speed humps at least on the two approaches that cross the transfer path for pedestrians.

All turning movements that conflict with pedestrian access to the stations should be prohibited. The “no turns” sign should be accompanied by a sign indicating the loop replacing the left turn. The loop replacing the right turn should have started before this intersection and should no longer be indicated here.

Very high pedestrian volumes can be expected at this corner of the intersection. In addition to existing pedestrian traffic, passengers accessing either of the two stations as well as passengers transferring between the two stations will pass through here. We recommend taking out the curbside lane on both sides and extending the sidewalk to provide more space for pedestrians. A small plaza or pocket park near this street corner would also work well.

SAFETY

This is the simplest way to organize a transfer between routes, but also the one that puts transferring passengers at the greatest risk. There are several ways to mitigate this risk

PEDESTRIAN SAFETY IMPROVEMENTS AT THE INTERSECTION

This is the solution we illustrate in the image to the left. One lane is taken out for each of the two approaches that cross the path of transfer passengers, and speed humps are used to slow traffic down. We also recommend not allowing any turning movement that might conflict with pedestrians transferring between the two stations. If there are high volumes of transfer passengers, it could be considered to include a pedestrian only signal phase, to allow passengers to cross between the two stations in one phase.

PEDESTRIAN BRIDGE OR UNDERPASS CONNECTING THE TWO STATIONS

It is also possible to connect the two stations via a pedestrian bridge or an underpass. This would make the transfer less risky for pedestrians, and would have some operational benefits as well. If the stations were connected, they could operate as a single station, and there would be no issue with transfer passengers exiting and entering the station.

This type of solution has been implemented at the Avenida Jimenez transfer station on TransMilenio. An underpass has the advantage of requiring shorter ramps. When building an overpass between stations, it is important to provide sufficient height in order to allow buses and large trucks to pass under it. An overpass would require a height of 4.8 meters or higher.

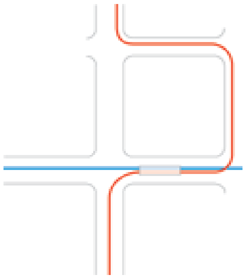
An underpass only needs to provide sufficient height for a person to pass, which can usually be done with a height of 3 meters. The 1.8 meter difference would translate into ramps that are about 18 meters shorter, assuming a slope of 10%. The choice between an underpass and an overpass would then depend on the amount of space available inside the station for accommodating the ramp and the cost of building an underground structure as opposed to a pedestrian bridge. Other issues to consider in the design of an underpass are lighting levels and security.

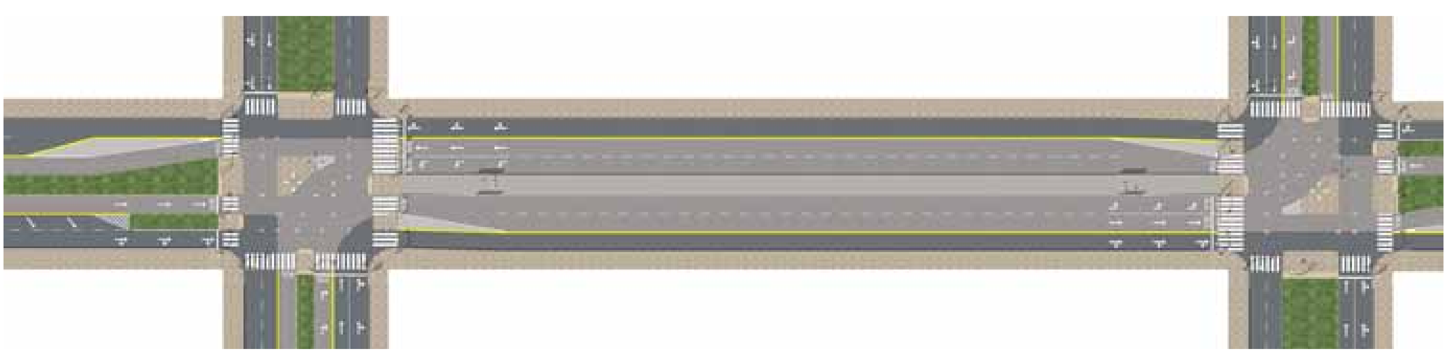
OPERATIONS

Without an overpass or underpass, this type of transfer would require passengers to exit at one station and re-enter at the next one. This will require making a decision about how this would impact the fare that transfer passengers pay for their trip.

While posing some problems in terms of collecting fares from transfer passengers and risking that transfer passengers may choose other modes because of the difficulty of the transfer, this option offers an advantage from the point of view of capacity. Unlike the previous example, this would not constitute a bottleneck, as the capacity of the intersection would be higher than that of the two stations. The two corridors can handle higher volumes of passengers per lane under this configuration, compared to the scenario where transfers are made by direct routes intersecting at grade.

DETOUR ON ONE LINE TO ALLOW CROSS PLATFORM TRANSFERS





SAFETY

This option would allow cross-platform transfers between two corridors, even though there is only one line operating on each corridor. This would have the safety benefits of the direct routes option, and the operational simplicity of a system with one route per corridor.

There are more possible combinations. This transfer could be redesigned so that some buses continue straight on one line, while some make a detour via the other line. This would allow time savings for through passengers as well as transfer passengers.

The main safety issue to consider is the design of the intersections where one of the BRT corridors takes the detour. On the section where both lines share the same street, it is important to provide separate lanes for each turning movement at the intersection, to avoid delays. This is an operational issue, but the safety implication is that lane balance and lane alignment must be maintained for all movements through the intersection. This will be somewhat complex and will require use of medians of varying width, ghost islands, hatch markings, etc. The risk is that if the intersections are poorly designed, this would offset the safety benefits of the cross platform transfers.

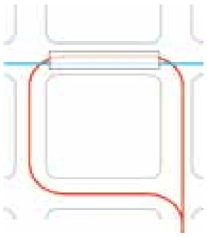
OPERATIONS

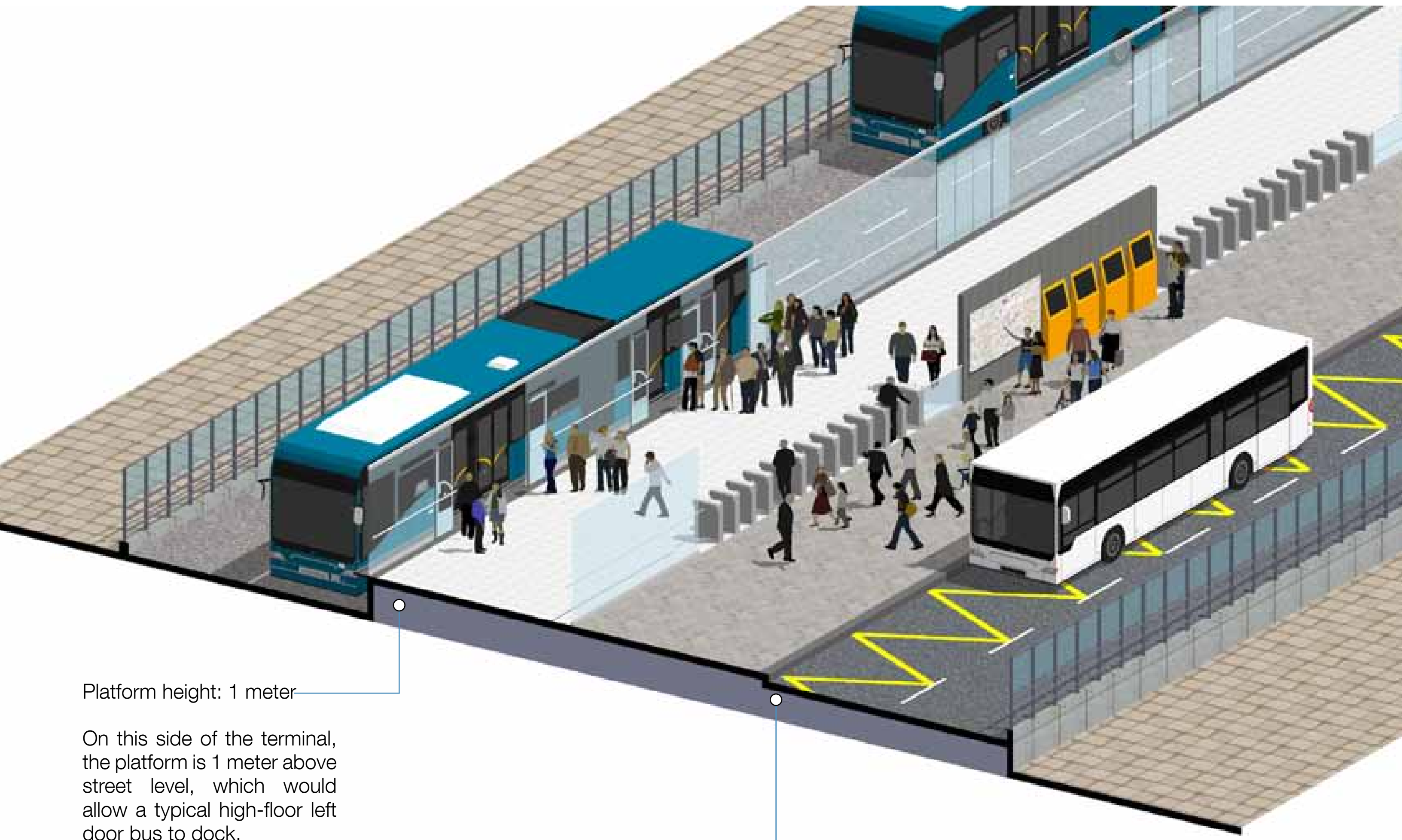
On this type of transfer, the capacity is likely to be limited by the intersection, rather than the station.

A key design feature for improving operations in this case is to provide dedicated lanes for bus turns and for buses continuing straight on one of the two BRT corridors. These movements will not share the same signal phases, and if they do not have separate lanes, they may end up blocking each other at the intersection.

The intersection needs three phases, one for bus turns from one corridor to the other, and two for through traffic on each corridor. We recommend not allowing any left turns for mixed traffic, as this would increase the number of signal phases required and would lower the capacity for both BRT corridors.

INTEGRATED TERMINAL





Platform height: 1 meter

On this side of the terminal, the platform is 1 meter above street level, which would allow a typical high-floor left door bus to dock.

This side of the terminal should be used by high-floor BRT vehicles, It will likely be closed and feature off-board fare collection.

Platform height: 30 cm

The bus lanes on this side of the terminal are raised 70 cm above street level, so that the central platform can service low-floor buses on this side.

This side of the terminal should be used by conventional right-door buses. It can be open and feature on-board fare collection, but there must be guardrails on the outside of the terminal, to prevent pedestrians from crossing the bus lanes.

It is important to size the platform correctly so that it does not get overcrowded. Otherwise, there is a serious risk that some passengers will walk in the bus lanes to avoid overcrowding on the platform.

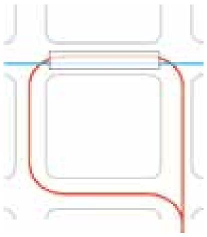
SAFETY

This is a very safe transfer option for passengers. The main safety risk to consider is the access point to the terminal for buses. It is important to avoid bottlenecks and to clearly separate different directions of traffic. TransMilenio recorded a fatal crash occurrence at the Portal de Usme terminal when a trunk line and a feeder line collided head-on at the entrance to the terminal, injuring several passengers and killing one.

For the terminal platforms, the key safety issue is to provide sufficient width to accommodate the expected volumes of passengers. If the platforms become overcrowded, there is a risk that passengers will end up walking in the bus lanes - particularly on the side of the terminal with low platforms.

Images showing a typical layout for a TransMilenio terminal. Above: the green feeder buses stop on the left side of the platform. Below: the articulated red trunk line buses top on the right side of the same platform. EMBARQ photos.

INTEGRATED TERMINAL: ACCESS POINTS



In downtown areas, many of these passengers may begin or end their journeys at the terminal, instead of transferring between lines. The pedestrian access points should be able to accommodate the expected passenger volumes per signal cycle. Also consider using underpasses or overpasses for very large pedestrian volumes.

Pedestrian area filled to capacity at the exit of the Calle 72 station on TransMilenio.

SAFETY

The design of the access points to the terminal should aim to minimize conflicts between different buses, and also to ensure safe pedestrian access.

The image on the left shows a possible design solution for one of the more challenging contexts for terminals: a terminal in a downtown area, with at-grade access for both buses and pedestrians. Conflicts between buses are dealt with by allowing trunk and feeder buses to enter the terminal on different signal phases. Pedestrians are provided with ample waiting space and wide crosswalks. It is, however, strongly recommended to provide pedestrian access to the terminal via an underpass or overpass, to eliminate conflicts between pedestrians and buses.

OPERATIONS

Capacity at this intersection would be slightly higher than the practical capacity of the system, meaning that this would not constitute a bottleneck. However, this configuration is likely to lead to high pedestrian delays, and a likelihood that pedestrians will cross on red. This could be addressed by ensuring pedestrian access via an underpass or overpass.

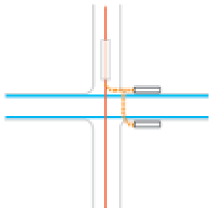
EXAMPLES OF TERMINAL CONFIGURATIONS

PORTAL DEL NORTE, TRANSMILENIO
Situated in the central reserve of Autopista Norte. Buses have at-grade access points directly from the expressway, while pedestrians access the terminal via an overpass. Two parallel platforms, with trunks and feeders stopping on both sides of each platform. Access points for buses to the terminal are not signalized, relying on drivers to yield to each other. Google Earth image

PORTAL TUNAL, TRANSMILENIO
Situated off an urban arterial, with at-grade access for buses, and via an overpass by pedestrians. It features a single platform, with buses docking on both sides. Google Earth image

PORTAL DEL SUR, TRANSMILENIO
This is a better layout for both safety and operations, though it is considerably more expensive: located just off an expressway, it is accessed by buses from both directions via overpasses. This eliminates many of the conflicts from the other two configurations shown above. Google Earth image

TRANSFER TO LOCAL BUS SERVICES



SAFETY

This type of transfer usually occurs between bus services that are not operated by the same agency. It is always difficult to coordinate transfers in such cases, but the key safety issue is to minimize the walking distance for transferring passengers, and to make the transfer path as safe as possible.

The BRT station should be located as close as possible to the intersection with the other bus corridor.

We recommend not allowing any turns at this intersection that may conflict with the path of transfer passengers. The crosswalk along the median that was shown for previous BRT station designs is particularly important here. If the local bus services have longer headways, there is a risk that transfer passengers leaving the BRT station would cross on red to catch their bus. Providing the median crossing would give passengers the opportunity to cross during both signal phases.

SAFETY

This design concept illustrates a possible way to integrate a BRT corridor with a cycling network without providing cycle infrastructure on the corridor itself. In this case, the cross street features cycle tracks and bike parking at all four street corners. Cyclists accessing the BRT station could leave their bicycle at one of the bike parking locations, and then cross on foot to the station.

The right turn from the cross street that conflicts with pedestrian access to the station is prohibited. Note that the cycle tracks are placed on a minor cross street with only one lane per direction and not on an urban arterial.

If parking is provided on the cross street, we recommend placing the cycle track between the row of on-street parking and the sidewalk, with a small buffer space (a curb or a median) to protect cyclists from the opening of vehicle doors.

CRASH DATA ANALYSIS

DATA COLLECTION

There were no publicly available datasets on crashes on BRT and Busway corridors in any of the cities we used for our study. For this reason, we compiled crash datasets for each city using the different local data sources available. In Brazilian cities, crash data were provided by the local public transport agencies. In Mexico, data were provided by the Jalisco State Secretariat for Transport and by the Mexico City Government. We obtained data for Colombian cities from the national Ministry of Transport, and for Indian cities from the local police departments.

For Bogotá, we also used a crash dataset provided by TRANSMILENIO S.A., which is one of the few BRT operating agencies to have compiled its own traffic crash database. This dataset includes crashes involving TransMilenio vehicles, and all minor incidents involving buses, which are usually not reported to the police. These are relatively minor events, but which contribute to a better understanding of safety issues related to BRT operations (e.g. sudden braking by the bus driver resulting in passengers falling inside the bus, or buses docking improperly at stations, resulting in minor damage to the vehicles).

All the datasets contain detailed information on every event that occurred on each bus corridor for a period ranging from three to seven years, depending on the city.

STUDY METHODOLOGY

The key component of our evaluation was crash data analysis. Due to the considerable differences in crash reporting standards and even in the definitions of what constitutes a crash, or an injury, it was not possible to carry out relevant comparisons between different cities. For this reason, we structured our analysis by case study, where each case study represents a city. For each city, we analyzed crash data for the different bus systems with the goal of determining which factors influence the number of crashes (e.g. the length of pedestrian crossings, or the presence of a central median). We then aimed to confirm or reject the findings from one case study by applying the same methodology to other cities. For some design characteristics, such as the number of approaches per intersection, we were able to get highly significant and consistent results across multiple case studies. For others, such as the number of left turns allowed at each intersection, the results were not as consistent.

We developed crash frequency models to explain differences in crash rates at different locations using factors such as road and intersection geometry, bus system design, and land use, after controlling for exposure –i.e. the number of vehicles or pedestrians.

Crash data are count variables, which are usually best represented by a Poisson distribution (Ladron de Guevara et al. 2004). However, previous studies have noted that crash data are also over-dispersed (i.e. the variance is much larger than the mean) and therefore are better represented by a negative binomial distribution, which, unlike Poisson, allows the variance to differ from the mean (Dumbaugh and Rae 2009, Viola et al. 2010). For this reason the negative binomial (NB) is the preferred probability distribution for modeling crash frequencies in most cases (Ladron de Guevara et al. 2004, Dumbaugh and Rae 2009). We used NB regressions for the majority of our models, with the exception of the Guadalajara pedestrian crash model, where the dependent variable was not sufficiently over-dispersed, in which case we used a Poisson regression instead.

An important decision regarded the scale at which to develop the models. Previous studies have developed crash frequency models at very different scales, ranging from intersection models (Almonte and Abdel-Aty 2010) to neighborhood models (Dumbaugh and Rae 2009), all the way to zip-code level crash models (Viola et al. 2010). Since our goal was to understand the detailed impact of design choices on crashes, we used the smallest scale possible: intersections or street segments. This choice was also influenced by the structure of the dataset, and particularly the way in which locations are reported. In most cities in our sample, with the exception of some Brazilian cities, crash locations are reported by listing the main street on which the crash occurred, and then listing the nearest cross street. Crashes are therefore grouped by the nearest intersection to the location where they occurred, with no possibility of separating intersection and mid-block crashes. As a result, each observation in our dataset corresponds to an intersection plus the approaches leading up to it along the main street. Since we were not able to separate intersection and mid-block crashes, we decided to create separate variables for intersection and street design characteristics, to separate their impact on crashes.

VARIABLES

In addition to variables for street and intersection design, exposure, and land use, we created four dummy variables for bus systems, based on the types of bus corridors present in our database: center-lane BRT, central Busway, counterflow lanes, and bus priority lanes.

TABLE A1 Vehicle collision and pedestrian crash frequency model results, Mexico City

	Vehicle collision model (NB)	Pedestrian crash model (NB)
	Coef.	Coef.
Constant	-1.518***	-1.857***
Number of legs	0.374***	0.252***
Number of lanes per leg	0.374***	0.341***
Left turns per approach	1.705***	1.268**
Market area	-	0.664***
Maximum pedestrian crossing distance (m)	-	0.026**
Pedestrian overpass	-	-0.147
Center-lane BRT (Metrobus Line 1)	-0.029	-0.299
Counterflow bus lane	0.554***	0.389**
Curbside bus lane	-0.176	-0.087
No. of observations	216	216
Log likelihood	-618.475	-518.539
LR chi2	139.99	104.88
Prob > chi2	0.000	0.000
chibar2(01)	367.14	231.39
Prob >=chibar2	0.000	0.000

**** p<=0.001, ** p<=0.05, * p<=0.1, - variable not included in the model*

TABLE A2 Vehicle collision and pedestrian crash frequency model results, Guadalajara

	Vehicle collision model (NB)	Pedestrian crash model (Poisson)
	Coef.	Coef.
Constant	-0.266	-2.822***
Number of legs	0.392***	0.204**
Number of lanes per leg	0.408***	-
Central median	-0.146*	-0.488**
Poor lane alignment	-	0.527**
Market area	-	2.989***
Big box retail	0.344*	-
Maximum pedestrian crossing distance (m)	-	0.047**
Major T junction	0.754***	-
Cross street is through street	0.570***	-
Curbside bus lane	0.942***	1.262***
No. of observations	164	164
Log likelihood	-708.075	-164.481
LR chi2	231.84	117.5
Prob > chi2	0.000	0.000
chibar2(01)	1111.59	n/a
Prob >=chibar2	0.000	n/a

**** p<=0.001, ** p<=0.05, * p<=0.1, - variable not included in the model*

TABLE A3: Vehicle collision frequency model results, Porto Alegre

	Vehicle collision model (NB)
	Coef.
Constant	-2.877***
Number of legs	1.001***
Number of lanes per leg	0.662***
Left turns per approach	0.888**
Center median	-0.592**
Center-lane Busway	0.039
Counterflow Busway	0.740**
No. of observations	183
Log likelihood	-684.777
LR chi2(6)	187.2
Prob > chi2	0.000
chibar2(01)	1599.3
Prob >=chibar2	0.000

**** p<=0.001, ** p<=0.05*

TABLE A4: Vehicle collision and pedestrian crash frequency model results, Bogota

	Vehicle collision model (NB)	Pedestrian crash model (NB)
	Coef.	Coef.
Constant	-0.336	-3.220***
Number of legs	0.467***	0.616**
Number of lanes per leg	0.250***	-
Maximum pedestrian crossing distance (m)	-	0.056**
Pedestrian bridge	-	-1.977**
Major T junction	0.533**	-
Urban arterial	-0.082	0.699**
Center-lane BRT (TransMilenio)	-0.218	-0.102
TransMilenio station	-	-0.360
No. of observations	127	124
Log likelihood	-421.663	-207.063
LR chi2	51.41	23.82
Prob > chi2	0.000	0.000
chibar2(01)	395.22	55.22
Prob >=chibar2	0.000	0.000

**** p<=0.001, ** p<=0.05, - variable not included in the model*

IMPACT OF STREET AND INTERSECTION DESIGN ON CRASH FREQUENCIES

Given that the majority of crashes on BRT corridors occur in the general traffic lanes, we had expected the overall design of the roadway to be the main predictor of crash frequencies, regardless of the configuration of the bus system. The model results confirmed this, indicating that road width as well as intersection size and complexity were the most important predictors of crash rates.

The number of approaches per intersection is one of the key issues, along with the number of lanes per approach, and the maximum pedestrian crossing distance. Intersections where traffic on the cross streets is allowed to cross the bus corridor are more dangerous than intersections where only right turns are allowed (table A2). In other words, turning a standard 4-way intersection into two T junctions by continuing the median on the main street should improve safety. This suggests that some of the minor intersections along a center-lane corridor could be changed to T junctions.

THE IMPACT OF BUS SYSTEM CONFIGURATION ON CRASH FREQUENCIES

Counterflow bus lanes in Mexico City and Porto Alegre were found to be significantly correlated with higher crash rates for both vehicles and pedestrians (tables A1 and A3). The consistency of the results across the different models suggests that counterflow lanes are the most dangerous configuration for bus systems, of all those included in our study. This was also confirmed by data analysis in cities where we could not develop statistical models. For example, a section of the South Line in Curitiba which features a counterflow lane has four times the number of crashes per lane-km than the rest of the South Line, which has a center-lane configuration.

We also found that curbside bus lanes in Guadalajara increased both vehicle and pedestrian crash rates, while in Mexico City they did not have a statistically significant impact on crash frequencies (tables A1 and A2). While the results are not always significant, they generally tend to indicate that curbside lanes may be problematic, though not as much as counterflow lanes.

Assessing the safety impact of center-lane systems is slightly more complex, since the changes introduced by a center-lane BRT on a street are measured by several variables. Unlike curbside bus corridors, which usually only replace one traffic (or parking) lane with a bus lane, center-lane systems imply a more significant reconfiguration of the street. Typically, this involves introducing a central median to replace a traffic lane, shortening the pedestrian crossing distance by creating a pedestrian refuge in the center of the street, and creating more T intersections and fewer 4-way intersections along the corridor. While the variable accounting for the presence of the center-lane BRT in Mexico City was not significant, the variables accounting for number of lanes, central median, crossing distance, and number of legs, were all correlated with lower crash rates and were significant across the different models (tables A1, A2, A3, and A4).

We conclude that center-lane systems are likely to have more safety benefits than curbside systems, due to the changes they introduce in the overall street configuration. The crash data are not detailed enough to allow us to explore which types of crashes might be more frequent on curbside versus center-lane bus corridors. However, the road safety inspections allowed us to gain a better understanding of this issue.

A common observation from the inspections was that curbside bus lanes introduce more conflicts than center lanes. In particular, vehicles turning right will always need to cross the bus lanes, increasing the chances of a crash with a bus going straight. Similarly, left turns are problematic on center-lane systems, but it is easier to eliminate left turns and replace them with loops rather than eliminating all right turns on a street. Moreover, cyclists have been observed to use the dedicated bus lanes and this type of behavior appeared to be more common on curbside lanes.

THE IMPACT OF LAND USE ALONG THE CORRIDORS ON CRASH FREQUENCIES

The presence of a major market near the corridor was one of the strongest predictors of pedestrian crashes in both Mexico City and Guadalajara (tables A1 and A2). This is not only due to higher pedestrian volumes, but also to additional risks resulting from the configuration of the market. In the area of the Merced market in Mexico City, for example, vendors often take up all or most of the space on the sidewalks, leaving insufficient capacity for the existing pedestrian volumes and forcing some pedestrians to walk in the traffic lanes. The presence of kiosks on the sidewalk also reduces visibility for drivers, as they are less likely to notice driveways, entrances to parking garages, or pedestrians attempting to cross the street.

ACKNOWLEDGEMENTS

This research project was funded with support from Bloomberg Philanthropies.

The authors would like to acknowledge all those who participated in the data collection and analysis effort, as well as those who shared their knowledge, provided comments, or participated in site inspections.

Rebecca Jaffe of Rice University contributed to data collection and analysis for Porto Alegre, Mexico City, and Bogotá.

Saúl Alveano Aguerrebere, Marco Tulio Priego Adriano, and Yorgos Voukas, from EMBARQ México, coordinated data collection efforts for the Metrobús BRT system in Mexico City and for the Macrobús BRT corridor in Guadalajara. Jesús Alberto Leyva Gutierrez and Diego Monraz Villaseñor of the Secretaría de Vialidad y Transporte de Jalisco provided us with crash data for the Guadalajara metropolitan area, while Joel Ivan Zúñiga Gosálvez of EPS (Estudios, Proyectos y Señalización Vial S.A. de C.V.) shared traffic counts for the city of Guadalajara.

Jorge Coxtinica Aguilar, Director of Operations for Metrobús in Mexico City, along with Technical Director Jorge Casahonda Zentella and David Escalante Sánchez met with EMBARQ staff and shared their experience with crashes on the Metrobús system.

Mario Valbuena, Director of Operations, along with Safety Director Carlos Gutierrez, as well as Martín Salamanca, and Jaison Lucumí of TRANSMILENIO S.A. shared with us their crash database for the TransMilenio BRT system in Bogotá and accompanied EMBARQ staff on an inspection of a TransMilenio corridor. Myriam Haidee Carvajal Lopez and Beatriz Elena Jurado Flóres, from the Colombian Ministry of Transport, gave us access to information from the Colombian national road safety database, including the cities of Bogotá, Cali, and Pereira.

Brenda Medeiros and Marta Obelheiro of EMBARQ Brasil coordinated data collection in Brazilian cities. Empresa Pública de Transporte e Circulação (EPTC) and Matricial Engenharia Consultiva Ltda provided us with crash data and traffic counts for the city of Porto Alegre. Urbanização de Curitiba S.A. (URBS) provided crash data for BRT corridors in Curitiba. Empresa de Transporte e Trânsito de Belo Horizonte S.A. (BHTrans) provided crash data for several bus corridors in Belo Horizonte, while Companhia de Engenharia de Tráfego de São Paulo (CET-SP) provided crash data for Busways in Sao Paulo. Madhav Pai and Binoy Mascarenhas of EMBARQ India coordinated data collection efforts for Indian cities including the BRTS corridor in Delhi and the Janmarg BRT in Ahmedabad.

Judy Raski of the Insurance Corporation of British Colombia (ICBC) kindly shared with us a dataset of crashes for the city of Vancouver, including the TransLink Route 97 and 99 dedicated bus lanes.

Rob McInerney from the International Road Assessment Programme (iRAP) provided us with data on pedestrian crashes on the Southeast Busway in Brisbane, Queensland, Australia.

Ricardo Rivera Salas and Vladimir Americo García Valverde from Instituto Metropolitano Protransporte de Lima shared with us a database of crashes on the Metropolitano BRT in Lima.

The authors would also like acknowledge valuable comments by Fred Wegman and Jacques Commandeur (SWOV – The Dutch National Institute for Road Safety Research), Steve Lawson (iRAP), Tony Bliss, Sam Zimmerman, and Said Dahdah (World Bank), Gerhard Menckhoff (Institute for Transportation and Development Policy), Juan Carlos Muñoz Abogabir and Luis Ignacio Rizzi (Pontificía Universidad Católica de Chile), Alexandra Rojas and Claudia Puentes (Fondo de Prevencion Vial de Colombia), Holger Dalkmann, Clayton Lane, Benjamin Welle, Aileen Carrigan, Aaron Minnick, Heshuang Zeng, and Katherine Filardo (EMBARQ), Janet Ranganathan, and David Tomberlin (World Resources Institute).

Almonte, A.M., M.A. Abdel-Aty. *Exploring the Level of Service and Traffic Safety Relationship at Signalized Intersections*. Institute of Transportation Engineers Journal, vol. 80, no. 6, June 2010.

CERTU. *Bus à haut niveau de service : du choix du système à sa mise en œuvre.* Centre d'études sur les réseaux, les transports, l'urbanisme, et les constructions publiques, Lyon, 2009.

Chias Becerril L., A. Cervantes Trejo. *Diagnóstico Espacial de los Accidentes de Transito en el Distrito Federa*l. Secretaría de Salud, Mexico City, 2008.

Dumbaugh, E., R. Rae. *Safe Urban Form: Revisiting the Relationship Between Community Design and Traffic Safety.* Journal of the American Planning Association, 75: 3, 309-329, 2009.

Diogenes, M.C., L.A. Lindau. *Evaluating Pedestrian Safety at Midblock Crossings in Porto Alegre, Brazil.* Transportation Research Record: Journal of the Transportation Research Board, no. 2193, pp.37-43, 2009.

Duduta, N., C. Adriazola, D. Hidalgo, L.A. Lindau, R. Jaffe. *Understanding the Road Safety Impact of High Performance BRT and Busway Design Features*. Transportation Research Record, forthcoming 2012.

EMBARQ. *Bus Karo. A Guidebook on Bus Planning and Operations.* EMBARQ Center for Sustainable Transport, Mumbai, 2011.

FTA. *Characteristics of Bus Rapid Transit for Decision-Making.* Federal Transit Administration, Washington DC. 2004.

Gardner, G., P. Cornwell, J. Cracknell. *The Performance of Busway Transit in Developing Countries.* TRRL Research Report 329, Crowthorne UK, 1991.

Hidalgo, D., A. Carrigan. *Modernizing Public Transportation. Lessons learned from major bus improvements in Latin America and Asia.* World Resources Institute Report. Washington DC, 2010.

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

Ladrón de Guevara, F., S.P. Washington, and J. Oh. *Forecasting Crashes at the Planning Level. Simultaneous Negative Binomial Crash Model Applied in Tucson, Arizona.* Transportation Research Record: Journal of the Transportation Research Board, No. 1987, TRB, National Research Council, Washington D.C., pp. 191-199, 2004.

Levinson, H., et al. *Bus Rapid Transit: Case Studies in Bus Rapid Transit*. Transit Cooperative Research Program – Report 90, Vol. I, Transportation Research Board, National Academies, Washington DC, 2003.

Lindau, L.A., D. Hidalgo, D. Facchini. *Curitiba, the Cradle of Bus Rapid Transit.* Built Environment 36, 274-283.

Lindau, L.A., B.M. 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, 2011.

NACTO. *Urban Bikeway Design Guide*. National Association of City Transportation Officials. 2011

NTU. *Conceitos e Elementos de Custos de Sistemas BRT.* Associação Nacional das Empresas de Transportes Urbanos, Brasília, 2010.

Transportation Research Board. *Highway Capacity Manual 2010.* Washington DC, 2010.

Rickert, T. *Bus Rapid Transit Accessibility Guidelines.* 2007.

Viola, R., M. Roe, H. Shin. 2010. *The New York City Pedestrian Safety Study and Action Plan.* New York City Department of Transportation, 2010.

Vuchic, V. *Urban Transit. Systems and Technology.* Hoboken, New Jersey: John Wiley and Sons, 2007.

Wright, L., W. Hook, Eds. *Bus Rapid Transit Planning Guide.*, 3rd edition. Institute for Transportation and Development Policy (ITDP), New York. 2007.

EMBARQ's mission is to catalyze and help implement environmentally and financially sustainable transport solutions to improve quality of life in cities. Since 2002, the EMBARQ network has expanded to the following countries and regions: Mexico, Brazil, India, Turkey, the Andean Region, and China. The network employs more than 100 experts in fields ranging from architecture to air quality management; geography to journalism; and sociology to civil and transport engineering.

EMBARQ
10 G Street, NE,
Suite 800
Washington, DC 20002
USA
+1 (202) 729-7600

EMBARQ ANDINO
Palacio Viejo 216, Oficina 702
Arequipa, Perú
+51 54283393

EMBARQ MEXICO
Calle Belisario Dominguez #8, Planta Alta
Colonia Villa Coyoacán, C.P. 04000
Delegacion Coyoacán, México D.F.
+52 (55) 3096-5742

EMBARQ INDIA
Godrej and Boyce Premises
Gaswork Lane, Lalbaug
Parel, Mumbai 400012
+91 22 24713565

EMBARQ BRAZIL
Rua Luciana de Abreu, 471/801
90570-060 Porto Alegre/RS
Brasil
+55 51 3312 6324

EMBARQ CHINA
Unit 0902, Chaowai SOHO Tower A
Yi No. 6
Chaowai Dajie, Chaoyang District
Beijing 100020, China
+86 10 5900 2566

EMBARQ TURKEY
Tersane Cad. No:104 K:5 Ozdalli Is Merkezi 34420
Karakoy, Beyoglu ISTANBUL
+90 (212) 244 74 10