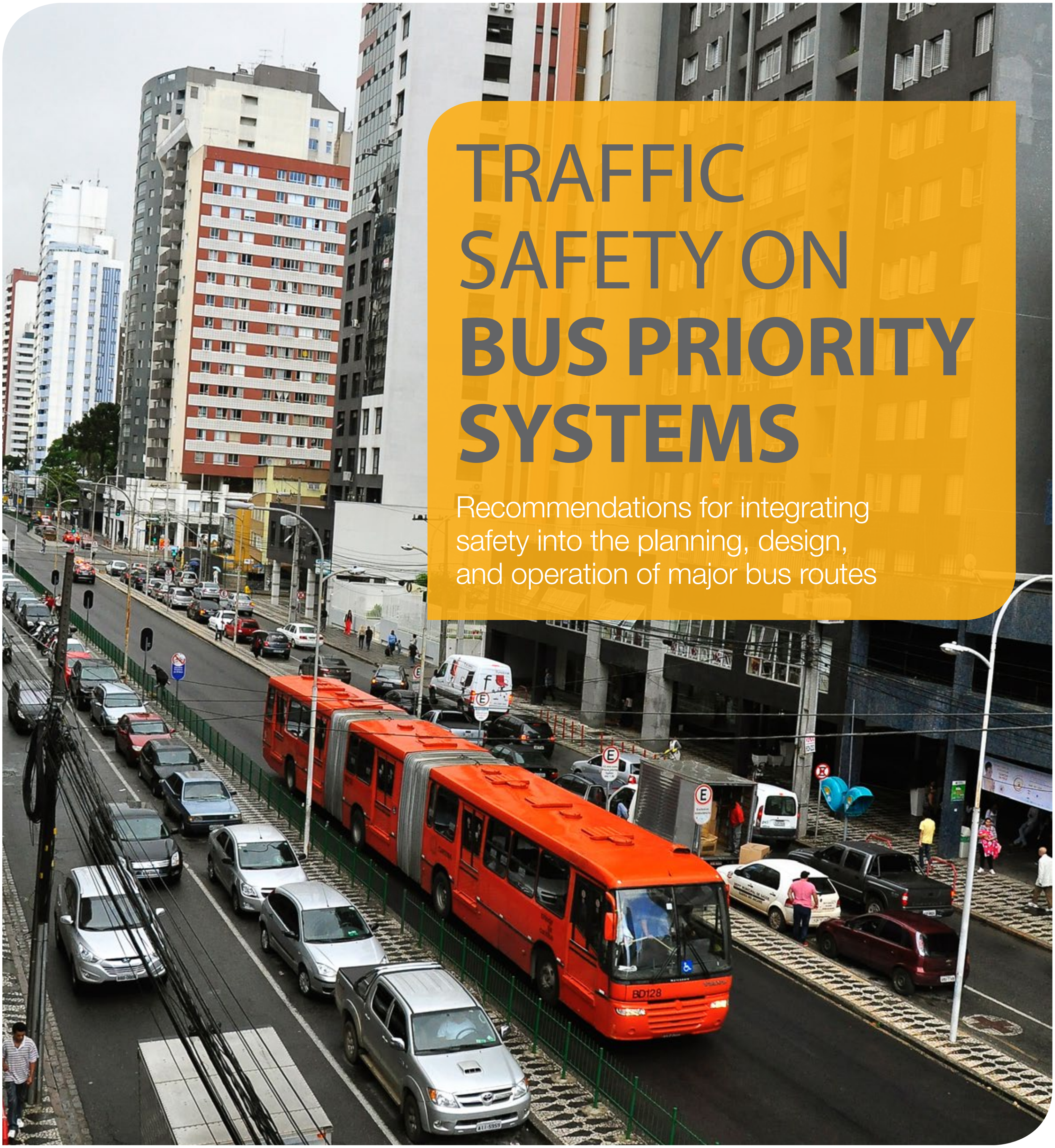
TRAFFIC SAFETY ON **BUS PRIORITY SYSTEMS**

Recommendations for integrating safety into the planning, design, and operation of major bus routes



A program of the
WORLD RESOURCES INSTITUTE

EMBARQ®
www.embarq.org

WORLD BANK GROUP

EMBARQ

Report by:

Nicolae Duduta
Associate Transport Planner,
EMBARQ, World Resources Institute
nduduta@gmail.com

Claudia Adriazola-Steil
Director of Health and Road Safety,
EMBARQ, World Resources Institute
cadriazola@wri.org

Carsten Wass
Technical Director, Consia Consultants
wass@consia.com

Dario Hidalgo
Director of Research and Practice,
EMBARQ, World Resources Institute
dhidalgo@embarq.org

Luis Antonio Lindau
Director, EMBARQ Brazil
tlindau@embarqbrasil.org

Vineet Sam John
Research Analyst,
EMBARQ, World Resources Institute
vjohn@wri.org

A Product of
The WRI Ross Center for Sustainable Cities

Design and layout by:
Carni Klirs, Graphic Designer
cklirs@wri.org

This report was made possible through funding from

Bloomberg Philanthropies

CONTENTS

CITIES AND BUS SYSTEMS COVERED IN THIS REPORT

ROAD SAFETY INSPECTIONS

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

CITYWIDE CRASH FREQUENCY MODELS

- Mexico City
- Guadalajara
- Porto Alegre
- Bogotá

ADDITIONAL DATA COLLECTION AND ANALYSIS

- Metrobús Line 2, Mexico City
- Macrobús, Guadalajara
- TransMilenio, Bogotá
- Megabús, Pereira
- BRT, Santiago de Cali
- SIT, Arequipa
- Busways, Belo Horizonte
- Boqueirao and South Line, Curitiba
- South East Busway, Brisbane
- BRTS, Delhi
- Busways, São Paulo
- Metrobüs BRT, Istanbul

ROAD SAFETY AUDITS ON BUS CORRIDORS

- Metrobús Lines 3, 4, and 5, Mexico City
- SIT, Arequipa, Peru
- C. Machado and Dom Pedro II Busways, Belo Horizonte
- Antonio Cerlos Busway, Belo Horizonte
- TransCarioca BRT, Rio de Janeiro
- TransOeste BRT, Rio de Janeiro
- BRT, Izmit, Turkey

DATA SOURCES

- Ministerio de Transporte, Colombia, 2011
- Transmilenio S.A. 2011
- Gobierno de la Ciudad de México 2011
- Secretaria 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
- Empressa 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
- Instituto Metropolitano Protransporte de Lima, 2012
- Istanbul Elektrik Tramvay ve Tunel (IETT)

FOREWORD

Investment in high quality public transport systems in developing world cities can help achieve significant traffic safety benefits, while meeting the growing mobility needs of city residents.

Over 1.2 million people die in traffic crashes on the world's roads every year, according to the World Health Organization, and the majority of these deaths occur in rapidly motorizing low and middle income countries. This situation is expected to worsen in the absence of policy interventions, and traffic crashes could become the fifth leading cause of premature mortality worldwide by 2030.

In response to this unacceptable trend, the United Nations declared 2011–2020 as the Decade of Action for Road Safety. EMBARQ and the World Bank have been closely involved in furthering the goals of the Decade of Action and helping achieve its ambitious goal of decreasing global road fatalities in half by 2020.

This report is an important part of this effort, as it highlights a unique opportunity to leverage the growing investment in Bus Rapid Transit and other bus priority systems in cities around the world to improve safety while meeting the growing mobility needs. Indeed, the number of new Bus Rapid Transit systems has increased in recent years, as the early experiences in Latin America have inspired cities in other regions of the world to improve their public transport systems. The recent commitment by eight multilateral development banks to direct $175 billion over ten years to sustainable transport will further contribute to this growth.

The evidence in this report clearly shows that high quality public transport systems can result in significant safety benefits on the streets where they are implemented, reducing injuries and fatalities by as much as 50 percent. But in order to achieve these benefits, it is important to ensure that the new systems being built incorporate high quality infrastructure and safety features. This report provides detailed, data driven recommendations for incorporating safety into the design, planning, and operation of different types of bus systems, drawing from data analysis and road safety audits and inspections of existing bus systems around the world.

We encourage planners, designers, engineers, and decision makers involved in the planning and implementation of new bus priority systems to use the recommendations in this report to make sure that the new public transport systems achieve their full potential for improving safety and quality of life.

Marc H. Juhel
Practice Manager, Transport
World Bank Group
Transport & ICT

Holger Dalkmann
Director
EMBARQ
World Resources Institute

Claudia Adriazola-Steil
Director, Health and Road Safety
EMBARQ
World Resources Institute

EXECUTIVE SUMMARY

Bus rapid transit (BRT) and bus priority systems have become an attractive solution to urban mobility needs in recent years because of their relatively low capital costs and short construction times compared to rail transit.

As these systems gain popularity,[1] a number of studies and planning guides have appeared, illustrating the different design options available and their impact on the operational performance of the systems, as well as outlining some of the institutional challenges to implementation (see Rickert 2007; Hidalgo and Carrigan 2010; and Moreno González, Romana, and Alvaro 2013).

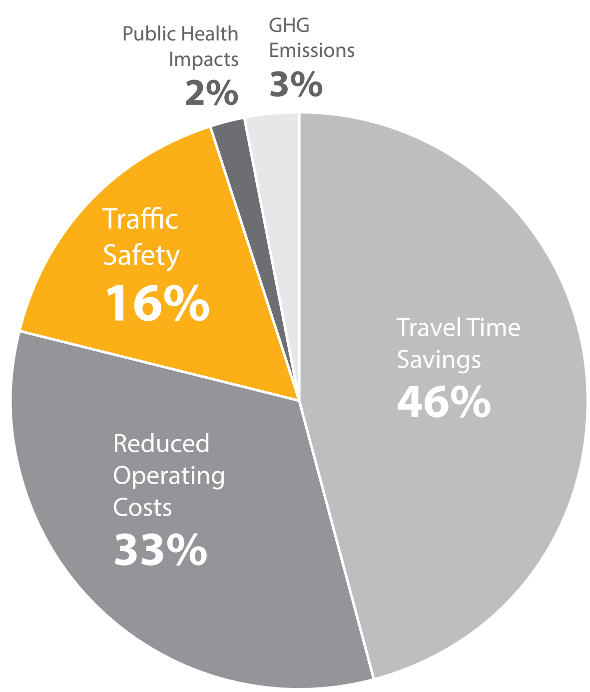
The traffic safety aspects of bus priority systems, however, are typically not as well understood as the better documented impacts on travel times, greenhouse gas and local pollutant emissions, or land values. Our research shows that bus priority systems have had significant positive impacts on traffic safety, reducing severe and fatal crashes on the streets where they were implemented by over 50% (Duduta, Lindau, and Adriazola-Steil 2013). From this, we estimate that safety impacts typically account for 8% to 16% of the total economic benefits on these types of systems (Figure 1).[2]

This report is based on an extensive research project on the traffic safety aspects of bus priority systems, based on data analysis, road safety audits and inspections on over thirty bus systems around the world, and microsimulation models testing the impact of safety countermeasures on operational performance.

Safety impacts account for up to 16% of total economic benefits of a typical Latin American BRT

This report 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 to high-capacity, multilane, and median-running BRTs. We identify the main risk factors and common crash situations, and suggest design concepts to address them. We also consider how the main design concepts impact the operational performance of the bus system, with a focus on passenger capacity, travel times, and fleet size requirements.

Figure 1 Safety impacts as a percentage of the total economic benefits of a typical Latin American BRT



HOW TO USE THIS GUIDEBOOK

This guidebook provides a comprehensive overview of the different aspects related to safety at different stages of planning, design, and operation of a bus priority system. It is primarily intended for use on high-capacity bus transit in cities of the developing world and mainly based on research from these regions. Nevertheless, many of the findings and recommendations in this guidebook are also applicable to cities in the developed world and to rail-based systems as well, particularly tramways and light rail.

Indeed, our findings suggest that the main safety risks on a transit corridor depend more on its geometric design than the type of technology used (bus or rail) or the region of the world where it is located. For instance, one of the most common types of collisions involving transit vehicles that operate along the median of an arterial street is a crash with turning traffic. This is true whether the transit system is a BRT in Rio de Janeiro or light rail in the United States (Duduta et al. 2012; Klaver Pecheux and Saporta 2009). This does not necessarily mean that the same countermeasures are applicable on all systems. The traffic mix, street design standards, and general compliance with traffic signs and regulations can vary widely from one location to another.

The **Research Overview** presents the key findings of the study. These are further explained in the section **Research and Analysis**, which discusses the overall safety impact that can be expected from the implementation of different types of bus systems. We discuss different methodologies for estimating safety impacts and for evaluating the economic benefits related to safety. We then illustrate the methodologies with examples from Bogotá, Mexico City, Guadalajara, Ahmedabad, and Melbourne. This is relevant for the early phases of project planning and for funding decisions, as it can provide guidance for including safety in a cost-benefit or alternatives analysis.

The **Design Recommendations** section provides annotated illustrations of common street and intersection configurations where bus priority systems are implemented. They are grouped into the following categories:

- **Street segments, midblock sections and crossings**
- **Intersections**
- **Stations**
- **Major Transfer Stations**

The design concepts are not site specific and are meant to be applicable to a range of different contexts. In addition, we use **case studies** to illustrate specific applications of these concepts. We use the **Rio de Janeiro** case study to analyze the impact of our safe design concepts on BRT operations, using microsimulation. The **Mexico City** case study shows an example of implementing bus priority on narrow streets in a historical center, while the **Istanbul** case study shows a BRT operating on an expressway. We also use the Istanbul Metrobüs BRT as a case study in station design for bus systems operating on expressways.

CHAPTER 1

RESEARCH OVERVIEW

The overall safety impact of implementing a bus priority system on a corridor varies depending on the characteristics of the system and the existing conditions on the street.

1.1 SAFETY IMPACTS OF IMPLEMENTING BUS PRIORITY

In cities of the developing world, the implementation of median-running BRT systems has generally proven to have a positive impact on safety (Table 1). Research from Australia indicates that bus priority systems (including signal priority and dedicated lanes) also had a positive safety impact. Other studies from the United States show opposite impacts—various types of bus lanes are shown to contribute to higher crash rates.

Our research suggests that the differences in safety impacts are attributable not so much to the type of bus system being implemented as to the changes made to the street infrastructure in order to accommodate the bus infrastructure. The main reason that Latin American BRTs have had positive safety impacts is the fact that in order to accommodate the BRT infrastructure, the city removed lanes, introduced central medians, shortened crosswalks, and prohibited left turns at most intersections (Figure 2). Our crash frequency models indicate that all these infrastructure changes are associated with positive safety impacts (Table 2). Our safety impact analysis confirmed this for several BRTs that include all these features (e.g., Macrobús, Guadalajara, Figure 3).

Safety impacts beyond the corridor

The removal of traffic lanes when implementing bus priority reduces the capacity of the street for mixed traffic. Although one might worry that traffic diverted to parallel routes could lead to increased crashes on these other streets, our analysis of the data from Guadalajara suggests this was not the case. We selected a 3-km buffer zone on both sides of the corridor, to include several major arterials that run parallel to the BRT corridor. We found that 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. This indicates that the safety improvements observed on the corridor in Guadalajara (Table 3) were not offset by increases along parallel streets.

Table 1 Safety impact of bus priority

	% change in accidents	95% confidence interval	Source
Arterial BRT (Latin American countries)			
Fatalities	-47%	(-21%; -64%)	EMBARQ analysis
Injuries	-41%	(-35%; -46%)	
All crashes	-33%	(-29%; -36%)	
Arterial BRT (Latin America and India)			
Fatalities	-52%	(-39%; -63%)	EMBARQ analysis
Injuries	-39%	(-33%; -43%)	
All crashes	-33%	(-30%; -36%)	
Bus priority (Australia)			
All crashes	-18%	n/a	Goh et al. 2013
Peak-hour bus and high-occupancy vehicles (HOV) lanes (United States)			
Unspecified severity	+61%	(+51%; +71%)	Elvik and Vaa 2008
Peak-hour bus lanes (United States)			
Injury crashes	+12%	(+4%; +21%)	Elvik and Vaa 2008
Property damage crashes	+15%	(+3%; +28%)	
Permanent lanes for buses and taxis (United States)			
Injury crashes	+27%	(+8%; +49%)	Elvik and Vaa 2008
Unspecified severity	-4%	(-8%; 0)	

Figure 2 Changes to the street infrastructure to accommodate a typical Latin American BRT (here, Macrobús, Guadalajara) and their associated safety benefits

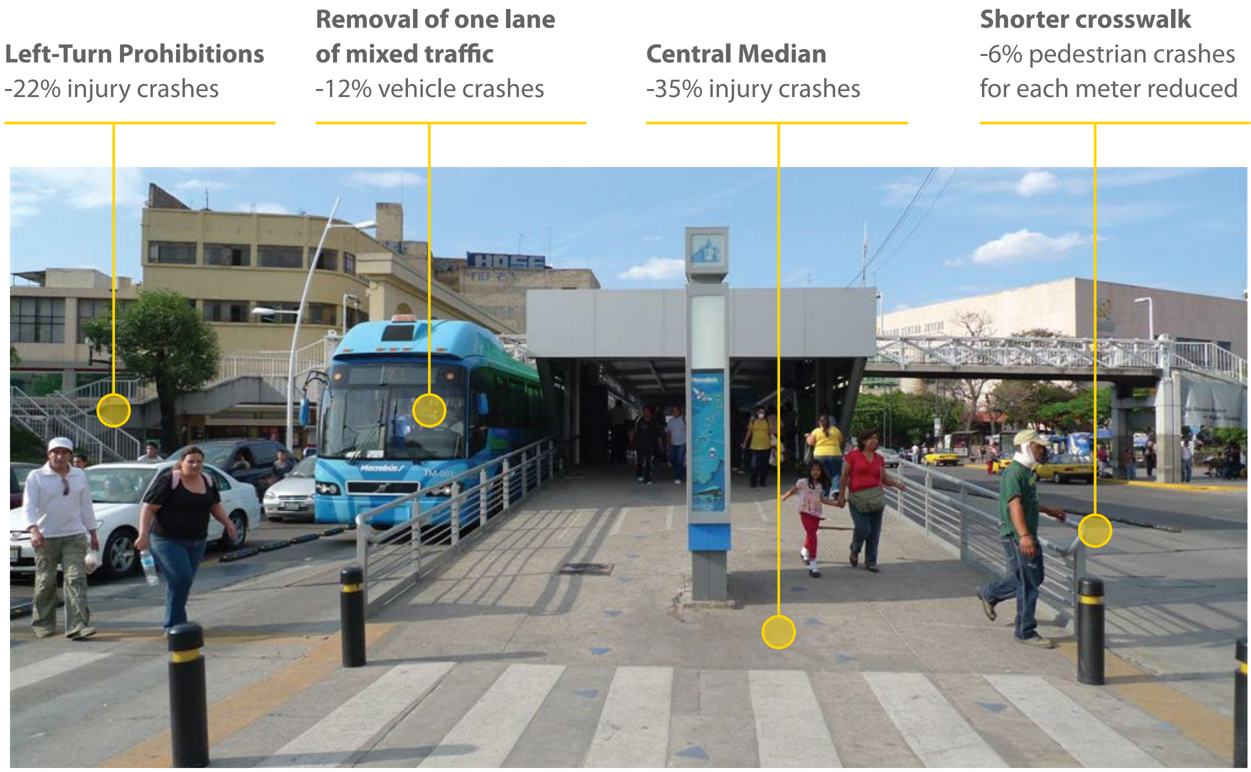
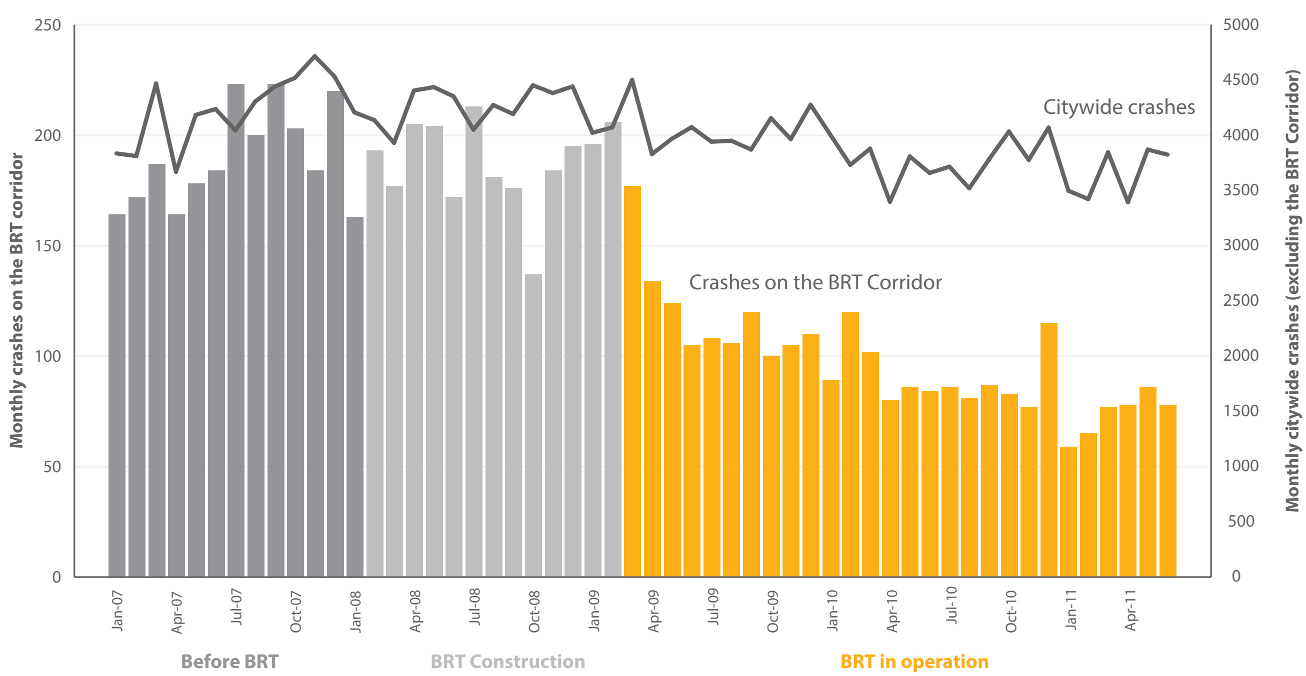


Figure 3 Crashes on Calzada Independencia, Guadalajara, 2007–2011



Source: Computed from statistics provided by Secretaría de Vialidad y Transporte de Jalisco 2011

Table 2 Safety impact of common infrastructure changes associated with implementing bus priority systems

	Crash type	% change in crashes	95% confidence interval
Converting a four-way intersection into two T-junctions	Severe	-66%	(-1%, -88%)
	All types	-57%	(-37%, -70%)
Removing a traffic lane	Severe	-15%	(-11%, -17%)
	Vehicle collisions	-12%	(-9%, -15%)
Shortening crosswalks (each additional meter removed)	Severe	-2%	(-0.04%, -4%)
	Pedestrian crashes	-6%	(-2%, -8%)
Prohibiting left turns on main corridors	Severe	-22%	(-12%, -32%)
	Vehicle collisions	-26%	(-10%, -43%)
Introducing a central median	Severe	-35%	(-8%, -55%)
	Vehicle collisions	-43%	(-26%, -56%)
Introducing a counterflow bus lane	Severe	+83%	(+23%, +171%)
	Vehicle collisions	+35%	(+0.02%, +86%)
	Pedestrian crashes	+146%	(+59%, +296%)
Reducing distance between traffic signals (for each 10m)	Severe	-3%	(-1%, -5%)
	All types	+2%	(+0.03%, +4%)
	Pedestrian crashes	-5%	(-1%, -7%)
Pedestrian bridge on expressway	Pedestrian crashes	-84%	(-55%, -94%)
Pedestrian bridge on arterial road	Pedestrian crashes	No statistically significant impact	(-23%, +262%)

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 had no impact on crashes in the neighborhood around the BRT corridor. But in at least one case the creation of the loop resulted in an increase in crashes at the intersections along it. This suggests that the design and planning of the BRT should extend beyond the corridor itself, and that it should consider and mitigate potential spillover effects. We address this in the Design Recommendations section.

Table 3 Results of safety impact assessment on bus priority systems in Latin America, India, and Australia[3]

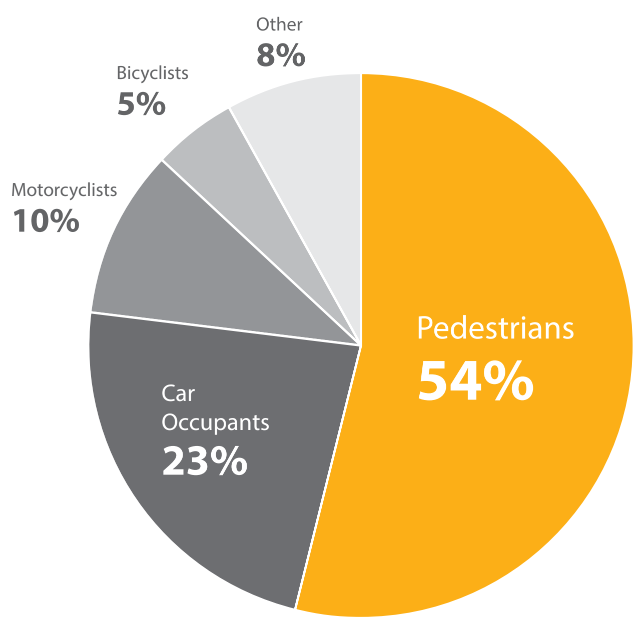
City	Change in Bus System	Safety impact		
		CRASHES	INJURIES	FATALITIES
Ahmedabad	Informal transit to single-lane, median-running BRT	-32%	-28%	-55%
Mexico City	Informal transit to single-lane, median-running BRT	+11%	-38%	-38%
Guadalajara	Curbside bus priority lanes to median-running BRT with overtaking lane at stations	-56%	-69%	-68%
Bogotá	Median busway to multilane BRT	n/a	-39%	-48%
Melbourne	Conventional bus service to bus priority using queue jumpers and signal priority	-11%	-25%	-100%

Severe crashes

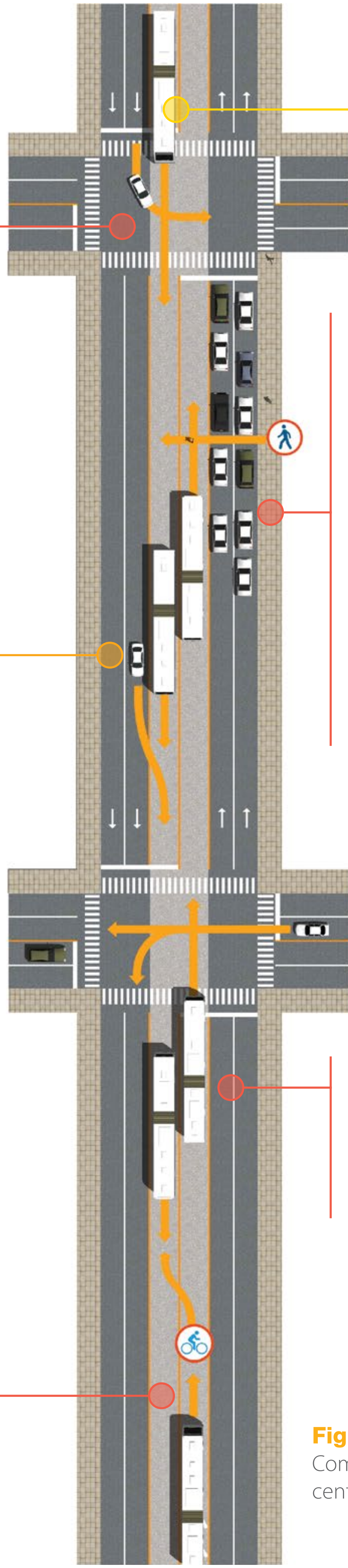
While accounting for only 7% of reported crashes on bus corridors (a low number that likely suggests underreporting), pedestrians represent over half of fatalities (Figure 4) across all the bus systems included in our database. Improving safety on bus corridors is therefore primarily an issue of preventing pedestrian crashes. In general, pedestrians are at risk when they cross the corridor in midblock, 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, and better provisions for pedestrian midblock crossings, can play a key role in improving safety on bus corridors.

Pedestrians usually represent **over half of fatalities** on a bus corridor

Figure 4 Fatalities on bus corridors by type of road user (includes data from Mexico City, Guadalajara, Delhi, Ahmedabad, Curitiba, Porto Alegre, and Belo Horizonte)



1.2 COMMON CRASH TYPES



LEFT TURNS ACROSS BUS LANES

SEVERITY: HIGH

Depending on the speed of the approaching bus, the crash can be quite severe.

This is the most common type of collision between buses and general traffic on center-lane bus corridors. Even where prohibited, cars may attempt illegal left turns, leading to crashes.

Replacing turns with loops is a countermeasure for this conflict, discussed further on pages 39–40. For intersections with left turns, see page 43.

PEDESTRIANS CROSSING THROUGH TRAFFIC

SEVERITY: HIGH

This is one of the most common types of fatal crashes involving BRT vehicles.

Pedestrians have been observed attempting to cross midblock through stopped traffic. Even if the mixed lanes are congested, the bus lanes remain clear and have buses traveling at high speeds. The bus driver's view of people crossing through traffic is limited, and as a result the bus is often unable to avoid hitting the pedestrian.

Design recommendations for midblock crossings are discussed on page 24-26.

UNAUTHORIZED VEHICLES IN BUS LANES

SEVERITY: MODERATE

This is 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 BUSES AND CYCLISTS

SEVERITY: HIGH

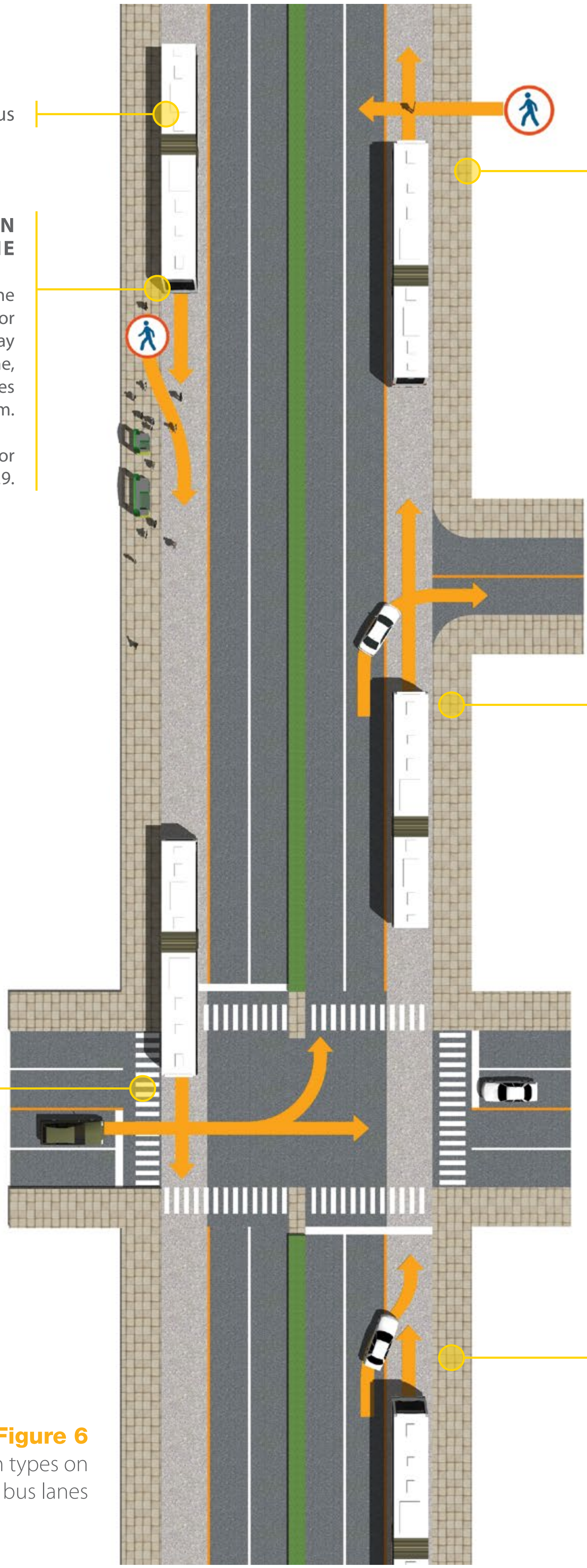
Cyclists often use the BRT lanes on bus corridors that do not have bike lanes, resulting in conflicts and crashes with buses. A particularly dangerous situation occurs when a cyclist observes an incoming BRT and attempts to get out of the way. The cyclist can be hit by another bus in the adjacent lane, or lose control and hit the lane separators, resulting in serious injuries.

RUNNING A RED LIGHT

SEVERITY: HIGH

This occurs when either a bus or other vehicle jumps a red light and crashes with cross traffic.

Figure 5
Common crash types on center-lane busways and BRTs



Articulated bus

PEDESTRIANS IN THE BUS LANE

In situations where the sidewalk is crowded or inadequate, pedestrians may choose to walk in the bus lane, leading to crashes with buses coming behind them.

See recommendations for sidewalks on page 29.

PEDESTRIANS CROSSING MIDBLOCK

Pedestrians may attempt to cross midblock, leading to severe, even fatal crashes.

RIGHT TURNS ACROSS THE BUS LANE

This is a potential conflict between buses and mixed traffic on curbside bus corridors.

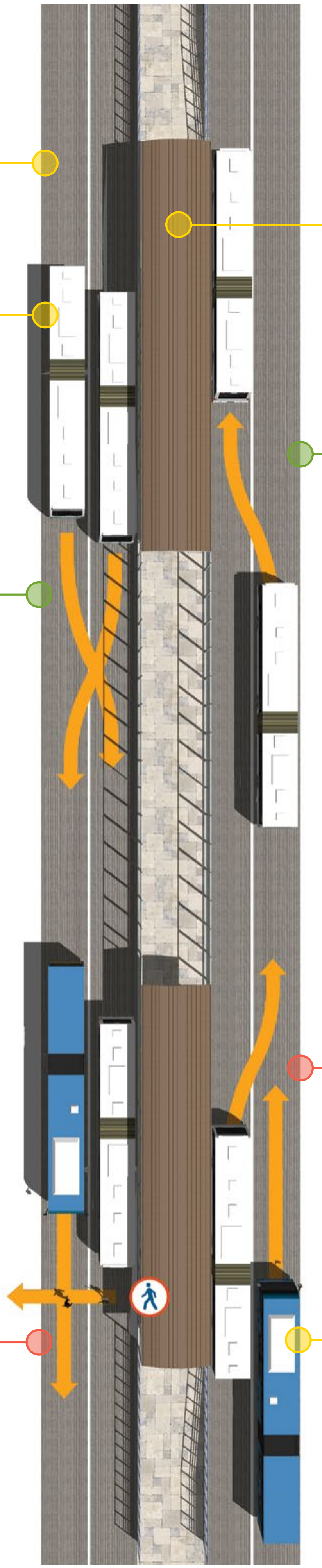
RUNNING A RED LIGHT

This occurs when either a bus or another vehicle ignores a red light and crashes with cross traffic.

UNAUTHORIZED VEHICLES IN BUS LANES

This is a common crash situation where there is no strong physical separation between the bus lanes and mixed traffic. The likelihood of unauthorized vehicles in the bus lane is higher for curbside bus lanes. In the case of curbside bus lanes, taxis may stop for passengers or vehicles may need to access properties or turns along the road. For guidelines on intersections with curbside bus lanes, see page 50–51.

Figure 6
Common crash types on curbside bus lanes



SIDE SWIPE BETWEEN BUSES AT A STATION

SEVERITY: LOW.
Usually does not result in injuries. Most common damage to buses includes broken side mirrors, occasionally broken windows.

Occurs when a bus is attempting to leave a station and another bus tries to access the station from the express lane.

CRASHES BETWEEN BUSES AND PEDESTRIANS IN THE BUS LANE

SEVERITY: HIGH.
This is the most common type of fatal crash involving BRT vehicles.

Severe crashes occur when pedestrians attempt to evade fares by entering and exiting the station illegally between the bus and the station. Pedestrians may also attempt to cross the bus lane as a shortcut or to avoid crowded platforms. Express buses may have their view of platform obscured by docked buses.

See case study on pedestrians crashes at stations in Istanbul on pages 74–79.

REAR-END CRASH AT A STATION PLATFORM

SEVERITY: LOW.
Occurs at low speeds and usually involves only minor damage to the buses.

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 the parked bus in front.

LOCAL BUSES MERGING INTO EXPRESS LANES AND COLLIDING WITH EXPRESS BUS

SEVERITY: HIGH
Due to the high speed differential as well as the high load factor of BRTs, a single crash of this type often results in dozens of injuries.

This is a potentially severe type of crash on multilane 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 higher speeds.

See recommendations for multilane BRT stations on page 68.

Figure 7
Common crash types at major stations on multilane BRTs

1.3 FACTORS INFLUENCING SAFETY

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 factors, along with the number of lanes per approach and the maximum pedestrian-crossing distance (Table 8, Table 4). 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 chapter 10.1.

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 (Table 4). The consistency of the results across the different models suggests that for bus systems, counterflow lanes are the most dangerous configuration of all those included in our study (see the detailed discussion on counterflow in chapter 10.1). 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 tend to indicate that curbside lanes may be problematic, though not as much as counterflow lanes.

Each additional approach into an intersection raises the risk of vehicle collisions by

65%

Adding a lane of traffic is associated with a

17%

increase in fatal and injury crashes

Each additional meter at a crosswalk increases the risk of pedestrian crashes by

6%

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 four-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 (Table 4, Table 8). Please refer to chapter 10.1, for more detailed information on crash data analysis.

Counterflow Lanes

can increase fatal and injury crashes by

83%

A central median can

reduce fatalities and injuries by

35%

Table 4 Safety impacts of busway lane configuration

	Weighted mean impact	% change in crashes	95% Confidence Interval
Presence of a central median	Fatal or injury crashes	-35%	(-55%, -8%)
	Vehicle Collisions	-43%	(-56%, -26%)
Counterflow bus lane	Fatal or injury crashes	83%	(+23%, +171%)
	Vehicle Collisions	35%	(+0.02%, +86%)
	Pedestrian Crashes	146%	(+59%, +296%)

Bus priority signal on Vesterbrogade, Copenhagen

DESIGN **RECOMMENDATIONS**

In this section, we provide detailed design, planning, and operational recommendations for ensuring that safety considerations are integrated into the planning and design process of a new transit priority scheme.

Metrobus Line 1 BRT corridor, Avenida Insurgentes, Mexico City

All our recommendations are based on either the findings from data analysis or common observations from road safety inspections presented in chapter 10.

We begin by providing overall recommendations on issues such as speed management that need to be considered for an entire corridor. We then look at specific street and intersection configurations and provide detailed design concepts.

Design guidelines are not meant to replace road safety audits and inspections. Rather, they should be seen as a complementary tool, to be consulted before planning a new bus corridor, and used as a reference throughout the design process. They can be very effective in improving safety, since they help planners, engineers, and designers integrate safety considerations throughout the planning and design of a corridor. Unlike audits and inspections, however, general guidelines cannot be site specific, so the recommendations they contain 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 to the specific site conditions, while considering the applicable design and signalization standards.

Finally in this chapter, we discuss the trade-offs between safety and the operational performance of a transit priority scheme, and we propose a methodology for evaluating the impact of safety countermeasures on commercial speed, travel times, and passenger capacity.

Bus corridor in Porto Alegre, Brazil

CHAPTER 2

SPEED MANAGEMENT

Good speed management is one of the keys to designing a safe street. Speed is one of the most important safety risks to consider, since it is one of the leading factors contributing to crash severity.

The probability that a crash involving pedestrians is fatal is strongly dependent on impact speed. The risk of death at an impact speed of 50 km/h is more than twice as high as the risk of death at 40 km/h (Rosén and Sander 2009). The average speed of traffic should therefore be appropriate for each type of street and context. Table 5 shows a range of recommended 85 percentile speeds for different types of roadways. The 85 percentile speed refers to the speed of a vehicle that is traveling faster than 85% of vehicles on that road.

Once a street has been assigned to one of the categories in Table 5 (a street can have different segments that fit into different categories) the next step is to put in place measures to ensure that the desired speed is not exceeded. Note that we are referring here to the actual speed of travel on a road and not to the posted speed limits. The target speed refers to both mixed traffic vehicles and transit vehicles, but the measures to achieve that speed limit can be slightly different for each group.

In particular, when there is a single operating agency for the transit system (and especially when that agency features an operations control center able to monitor bus speeds in real time) bus speeds can more easily be controlled through training and enforcement. For mixed traffic, however, a variety of other measures can be used to control speeds. We provide here an overview of the different measures to consider.

They are described in more detail in the following sections.

2.1 Speed humps and similar devices

Speed humps are one of the most effective means of controlling speeds. Speed humps are locations where the street pavement is slightly raised and can be driven over safely at speeds of up to 50 km/h. The length and height of the hump directly impact the speed for which it is designed. They should be visible on approach and clearly marked, typically with a different color pavement or reflectors and also with a vertical sign posting the appropriate speed, so that drivers can adjust their speed accordingly. Ideally, humps could be used for the entire length of a roadway, to control speeds throughout. In practice, this may not always be feasible, and in that case we recommend using humps on the approach to conflict points. The key conflict points include midblock pedestrian crossings and the approach to intersections, especially after a longer stretch of road.

Other devices similar to speed humps:

- A **raised crossing** is essentially a crosswalk placed on top of a speed hump. It can be an effective device to use for midblock crossings or for intersection crosswalks on narrower streets.
- A **raised intersection** refers to a situation where the entire area of an intersection is raised to sidewalk level, effectively functioning as a speed hump for all traffic. Raised intersections work well for relatively narrow intersections (no more than two lanes in total for each street). At wider intersections, raising the entire area may be less effective since vehicles could speed up while in the raised area.
- **Speed cushions** are narrower humps that do not span the entire road width. They are just wide enough to cause smaller vehicles like cars to slow down but compact enough to allow wide-axle vehicles like buses or emergency vehicles to pass over them without slowing down.

Speed humps, raised crosswalks, and raised intersections should be designed specifically for a desired speed. Poor, inappropriate, or haphazard designs for speed humps may be dangerous to drivers, and even more so to bicyclists and motorcyclists.

Table 5 Suggested 85 percentile speeds for different types of roadways*

Type of roadway	Suggested 85 percentile speed	Description of roadway environment
Expressway	80kmh or higher	A limited access road with no at-grade intersections or crosswalks
Arterial Road	50kmh	A major thoroughfare in an urban area, featuring signalized intersections and at grade pedestrian crosswalks
Street in a dense urban center	20 – 30kmh	A street in an area with very high pedestrian volumes (e.g. near a downtown, major market, etc.) with high volumes of pedestrians crossing at grade

* Speed recommendations must also consider other factors such as land-use in the surrounding area or high volumes of pedestrian or non- motorized traffic

2.2 Traffic signal spacing

The distance between traffic signals is one of the strongest predictors of travel speeds on a roadway. Streets with more closely spaced signalized intersections will tend to have lower travel speeds. Conversely, street sections with longer blocks will have higher travel speeds. The distance between signalized intersections has a different impact on crashes at different levels of severity. Our data analysis for streets in Guadalajara (Mexico) showed that for every 10 additional meters between intersections, there was a 2% decrease in overall crashes, but a 3% increase in injuries and fatalities (Table 2). In other words, there are fewer accidents overall, but they tend to be more severe. The explanation is that more intersections introduce more conflict points and therefore more crashes, but they also lower speeds and therefore the severity of crashes.

Every 10-meter increase in block length between intersections is correlated with a **3% increase in injuries and fatalities**

In practice, this translates to avoiding long stretches of roads with no traffic signals in urban areas. This is a risk at the urban periphery, especially in cases where the city has expanded considerably, and a road initially designed as a highway is turned into an urban street. This is a complex issue and there is no ideal recommendation for the best distance between traffic signals. On the one hand, the further apart signals are, the higher the likelihood that pedestrians will cross illegally and be hit by vehicles traveling at high speeds. On the other hand, if there are too many signalized midblock crossings, there is a risk that some drivers may disobey the red light (especially if the only conflict is with pedestrians). The recommendation here is to make a case-by-case assessment as to the ideal placement of a signalized midblock crossing to maximize opportunities for safe crossing while not creating an incentive for drivers to disobey the traffic lights. From this perspective, a major consideration would be land uses along the corridor. Locations near schools, shopping malls, or other major trip destinations are likely to have a higher demand for pedestrian crossings. We discuss this issue in more detail in the midblock design section.

2.3 Speed enforcement

Besides the design measures mentioned above, a wide range of technologies exist to enforce speeds on a given roadway. In addition to radars or speed cameras for mixed traffic, a transit operating agency can monitor bus speeds in real time, especially if it has an operations control center and if the buses are fitted with GPS equipment.

Mid-block crossing in Juiz de Fora, Brazil

CHAPTER 3

RECOMMENDATIONS FOR **STREET SEGMENTS, MIDBLOCK SECTIONS,** AND 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, because bus lanes have traffic lower traffic volume, pedestrians often perceive them as safer than the general traffic lanes and may walk in them or stop there to check for traffic when crossing the street. 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 midblock 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 midblock 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 jaywalking.

On the following pages, we present several design concepts for street segments that address the key safety issues we have discussed. The types of streets chosen, their width, and the types of bus systems featured are based on common street configurations found in the bus corridors included in our dataset.

Figure 8 Pedestrians crossing the Delhi BRTS corridor in midblock

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

We recommend using staggered midblock 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 midblock crossings is that vehicles may use them to make 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 midblock 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.

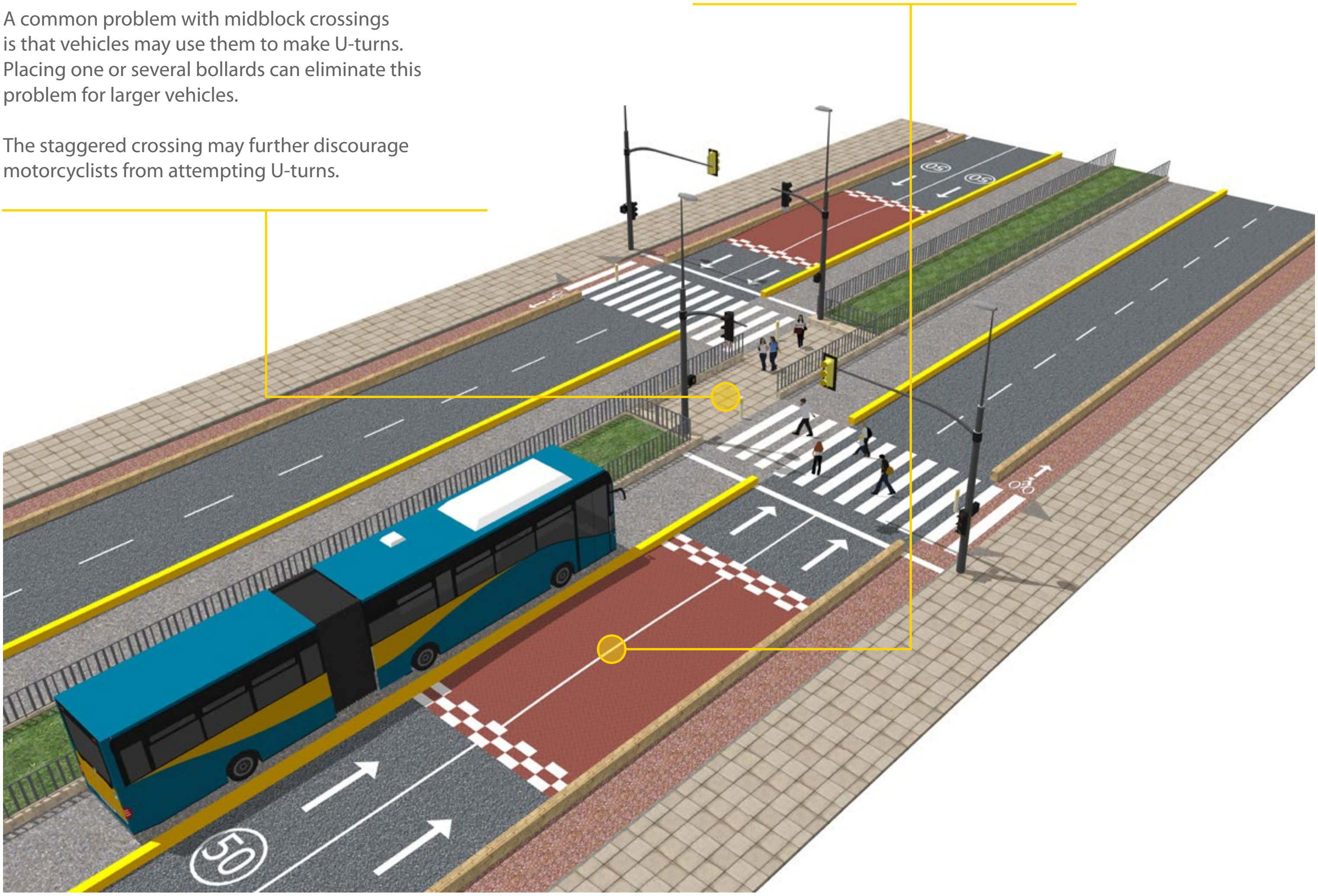


Figure 9 Midblock crossing on an urban arterial

3.1 Midblock crossing on an urban arterial

93% of pedestrian crashes occur mid-block in Porto Alegre (Figure 11). Midblock 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 (TRB 2010).

We also recommend using a central median and providing a pedestrian refuge island in the center of the crossing. A refuge island can reduce the distance that a pedestrian must cross in one attempt by as much as 10 meters on an urban arterial, which can reduce fatal and injury crashes at that location by as much as 35% (Table 4).

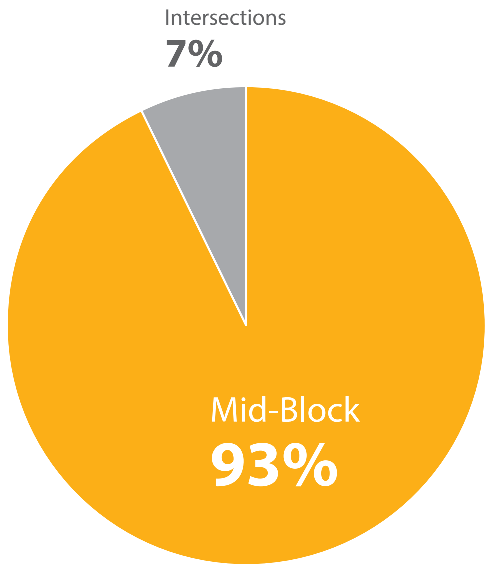


Figure 11 Crashes by location in Porto Alegre: Calculated from a crash database provided by Empresa Pública de Transporte e Circulação (EPTC), Porto Alegre, 2011

The design of the midblock crossing should take into account the general level of signal compliance among drivers. This is something that varies widely from one country to another, and even between different cities in the same country. In many cities in the developing world, drivers rarely stop at a red light if the only conflict is with pedestrians. In such cases, adding a speed hump on the approach to the midblock crossing can improve safety for pedestrians. Our observations from road safety inspections suggest that drivers are more likely to yield to pedestrians on a crosswalk when they are driving more slowly.

Figure 10 Pedestrians jaywalking across the bus lanes on the TransMilenio BRT in Bogotá

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 midblock 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 midblock pedestrian crossings.

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 sign should indicate the presence of the chicane to drivers.

Figure 12 Midblock crossing on a narrow street

2.3.2 Midblock crossing on a narrow street

On streets that only feature one mixed traffic lane per direction, it is possible to use another type of traffic calming device—a chicane (Figure 12). This type of layout has the advantage of breaking down the crossing distance even more than a median refuge.

3.3 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%, that also features resting areas (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 differently abled.

We used crash frequency models to examine the impact of bridges on both arterial roads and expressways. Our data analysis suggests that pedestrian bridges are not an effective safety countermeasure on urban arterials, but that they are very effective when used on expressways (Table 6).

Our observations from site inspections suggest that the reason bridges do not work on urban arterials (and on narrower streets in general) is that pedestrians find it more convenient to cross underneath them instead. Bridges should only be used on high-speed roads, such as expressways, in cases where it is not practical to place a signalized crosswalk. A good example of the use of pedestrian bridges on a BRT on an expressway is the Autopista Norte corridor on TransMilenio, in Bogotá.

If the street is narrower, pedestrians are more likely to 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.

Figure 13 Pedestrian bridge with ramp and resting area in León, Mexico

Figure 14 Pedestrians jumping over a guardrail and jaywalking across a busway in Delhi, next to a pedestrian bridge

Table 6 Safety impacts of pedestrian bridges

Pedestrian bridge over	Change in Pedestrian crashes	95% Confidence Interval
Expressway	-84%	(-94%, -55%)
Arterial road	Not statistically significant	

Curbside bus lanes are often used on narrower streets, where there is not enough space to add 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.

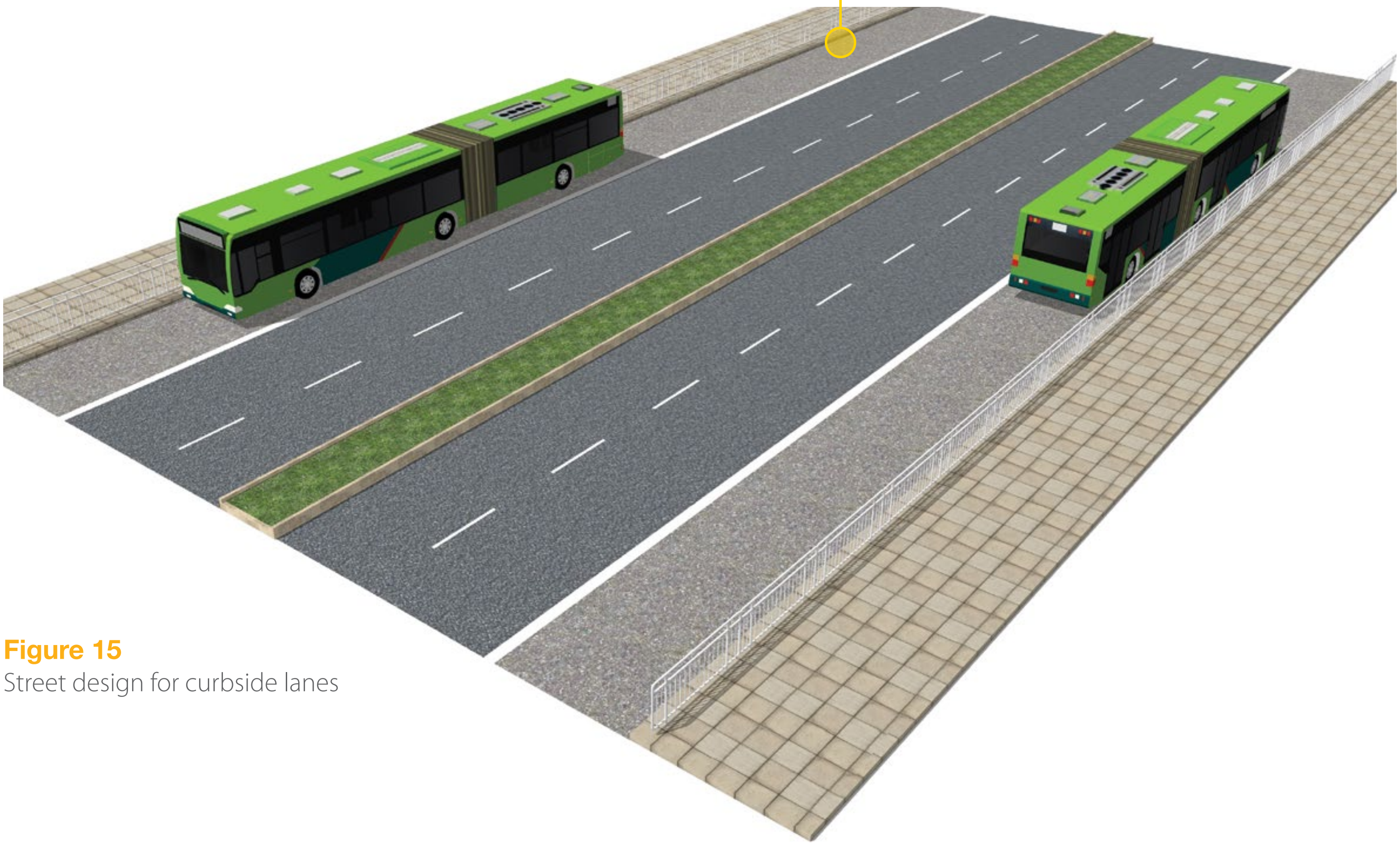


Figure 15
Street design for curbside lanes

3.4 Street design for curbside 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 result from crowding on the sidewalks. To some extent, this is an accessibility issue. People who need to push carts, for example, often prefer to use curbside bus lanes rather than go up the ramps to the sidewalk. There is also perhaps a perception that bus lanes are relatively safer to walk in, since they carry fewer vehicles than the general traffic lanes. In order to address this issue, we recommend ensuring that sidewalks along the corridor are in good condition, without level changes, steep ramps, or objects blocking access to ramps, and that their dimensions are appropriate for the level of pedestrian traffic on them.

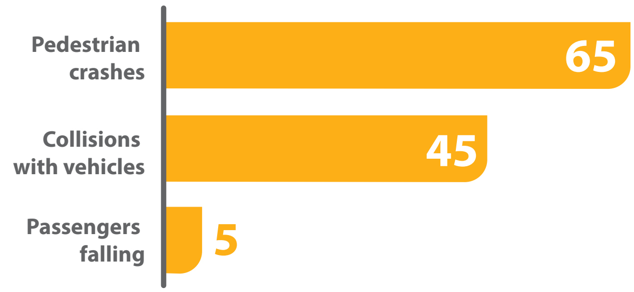


Figure 17 Accidents involving buses, by type, on the Eje Central curbside bus corridor, Mexico City (2006–2010)

Figure 16 Pedestrians walking in the curbside bus lane on Eje 1 Oriente, Mexico City

Figure 18 Person pushing a cart of goods on a curbside bus lane on Eje Central, Mexico City

Figure 19 The TransOeste BRT in Rio de Janeiro

CASE STUDY

TRANSOESTE BRT, RIO DE JANEIRO

MEASURING IMPACTS OF SAFETY IMPROVEMENTS ON OPERATIONAL PERFORMANCE

The safety recommendations discussed until this point include speed reductions and the addition of signalized midblock crossings. These can have negative impacts on the operational performance of the bus system. In order to address potential trade-offs between safety and operational performance, it is important to have an accurate estimate of the impact of safety countermeasures on operations. We suggest here a methodology for addressing potential trade-offs, and we show the results from applying this methodology to the TransOeste BRT in Rio de Janeiro.

OVERVIEW OF THE TRANSOESTE BRT

The TransOeste BRT corridor in Rio de Janeiro began operations in June 2012, the first line of a planned BRT network of over 150 km, including TransCarioca, TransOlímpica, and TransBrasil, designed as part of the infrastructure investments for the 2014 World Cup and the 2016 Summer Olympic Games. TransOeste connects Barra da Tijuca—a neighborhood in the south of Rio and the site of the Olympic Village in 2016—to Santa Cruz—a western suburb situated some 40 km from Barra. Unlike most other examples discussed in this report, phase 1 of TransOeste operates less as an urban transit system and more like a commuter transit service. Demand is heavily concentrated in the peak hours, and most passengers use the system to commute to and from jobs in Barra da Tijuca. While the two ends of the corridor are relatively dense urban centers, most of the middle section of TransOeste is currently a greenfield area.

The BRT operates in the center of Avenida das Américas—a typical thoroughfare in Rio de Janeiro, featuring high speed limits of 70 to 80 km/h, and a wide right-of-way of 60 to 90 meters, depending on location. There are few traffic signals along the route, with an average distance between them of over 600 meters. The high speed limits and relatively long distances between traffic signals allow TransOeste to feature commercial speeds above the average for arterial-running BRTs.

The local service, which makes all the stops, has a commercial speed of 28 km/h, while the expresso service, which bypasses most stations via overtaking lanes, has a commercial speed of 35 km/h.

METHODOLOGY

Safety countermeasures are site specific and the result of careful evaluation of conditions on a given roadway. For the purposes of this case study, we will focus on several common recommendations also applicable to Rio de Janeiro given the issues related to its street network discussed in the previous section.

- Lowering speed limits for all traffic on Avenida das Américas (including the BRT) to 60 km/h
- Lowering speed limits for express buses passing through stations in overtaking lanes to 30 km/h, to minimize conflicts with pedestrians who may jaywalk to and from the station, and to give drivers more time to react to potential conflicts between local and express buses
- Placing additional signalized midblock crossings to lower the average distance between crossings
- Reconfiguring signals to minimize pedestrian delay

IMPACT OF COUNTERMEASURES ON CRASH FREQUENCIES

We tested the impact of the design concepts mentioned above on operational performance of the BRT by looking at three main indicators:

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

We developed the model using the EMBARQ BRT Simulator—a macroscopic simulation tool designed specifically for high-capacity bus operations. This software allows for the detailed modeling of BRT routes, including terminal layouts, terminal holding zones, signalized intersections, and complex station configurations with multiple substops and a combination of local and express services.[4] We started by developing a baseline scenario, designed to replicate actual conditions on the BRT corridor at the time of the study, and a series of "project" scenarios, representing various combinations of safety countermeasures. The operating conditions we found on the corridor in 2012 are likely to change considerably by the time the BRT network is fully built out in 2016. In particular, the connections to the future TransOlímpica and TransCarioca corridors are likely to increase demand on TransOeste. As a result, it seemed necessary to compare the baseline and project scenarios not only in the 2012 operating conditions, but also in 2016, when both passenger demand and bus frequencies are likely to be higher on the corridor. We present here only the results of

the 2016 simulations. More details on the modeling approach, as well as the model specification and calibration for this case study can be found in Duduta et al. 2013.

SIMULATION RESULTS FOR 2016 SCENARIOS

We tested three different project scenarios. In the "60 km/h" scenario, the only change introduced is the reduction in overall speed limits to 60 km/h for all traffic on Avenida das Américas. The "60/30" scenario further restricts speeds for all buses approaching stations to 30 km/h (including buses not stopping at those stations). Finally, the "complete" scenario also includes the additional signalized midblock crossings as well as the speed reductions.

The columns from left to right in Table 7 show the impact of adding each safety countermeasure on the different performance indicators. The reduction in speed limits results in slightly higher commercial speeds for buses and higher travel times for passengers. They also reduce speed variability, however, meaning that the service is more reliable and bus frequency is better maintained throughout the route. The traffic signals have a negative impact on commercial speed, which is offset by another feature of the "complete" scenario: a slight increase in speed limits to 70 km/h in a greenfield section of the corridor (i.e., a section with no development along it).

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

Table 7 Simulation results for 2016 scenarios

Indicator	Type of service	Baseline	60km/h	60/30km/h	Complete	Difference
Commercial speed (km/h)	Express	32	31.5	29.6	29.6	2.4
	Local	25.6	25.6	25.45	25.43	0.17
Travel time (min)	Express	71	72	77	77	6
	Local	89	89	89	89	0
Speed variance (km/h)	Express	37	31.3	22.33	15.57	21.43
	Local	16	14.94	14.85	15.57	0.43
Speed variability coef.	Express	0.19	0.18	0.16	0.16	0.03
	Local	0.16	0.15	0.15	0.16	0

BRT corridor in Curitiba, Brazil

CHAPTER 5

RECOMMENDATIONS FOR **INTERSECTIONS**

5.1 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 severe crashes by up to 17% (Table 8).

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.

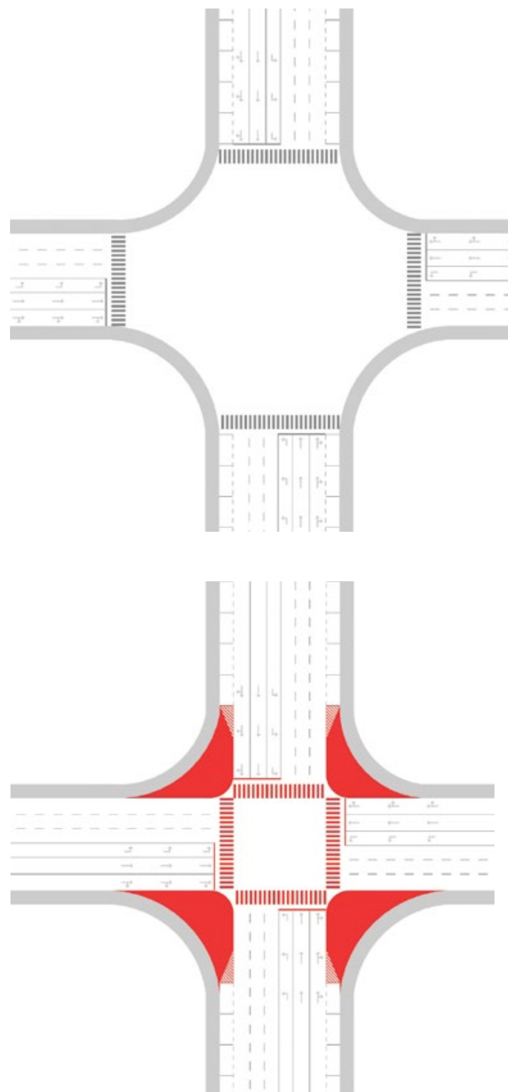


Figure 20 Diagram illustrating how narrower turning radii and curb extensions (in red) can be used to reduce the area of an intersection

Table 8 Safety impacts of street and intersection design elements

		% change in crashes	95% Confidence Interval
Each additional approach	Fatal or injury crashes	+78%	(+56%, +103%)
	Vehicle Collisions	+65%	(+46%, +87%)
Each Additional Lane	Fatal or injury crashes	+17%	(+12%, +21%)
	Vehicle Collisions	+14%	(+10%, + 18%)
Crosswalk length	Fatal or injury crashes	+2%	(+0.04%, + 4%)
(each additional meter)	Pedestrian Crashes	+6%	(+2%, +9%)
Allowing left turns	Fatal or injury crashes	+28%	(+14%, +48%)
	Vehicle Collisions	+35%	(+11%, +75%)

Left turns

We found that intersections which prohibited left turns had a better safety record than those that allowed the turns (Table 8). 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 occurs 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.

Pedestrian crossings

Our model results indicate that each additional meter in a pedestrian crosswalk is correlated with a 6% increase in the number of pedestrian crashes (Table 8). 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.

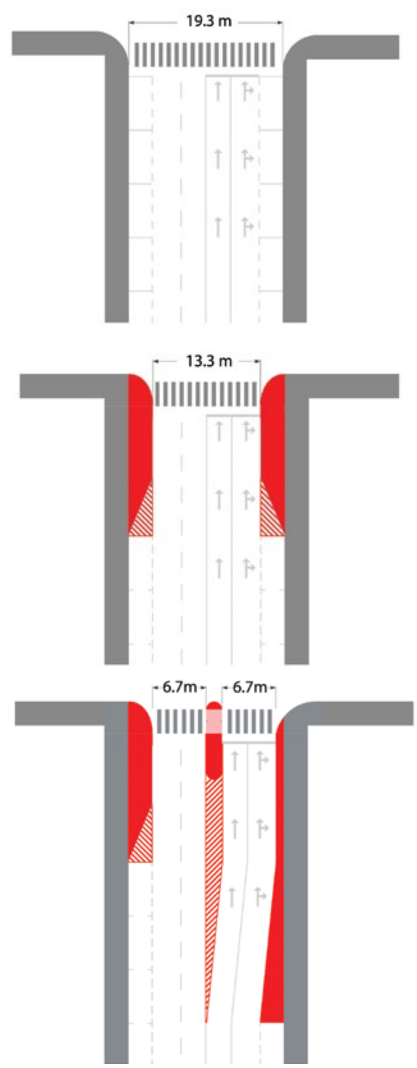


Figure 21 Daylighting and refuge islands

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 meters. It also improves visibility for both drivers and pedestrians. If a row of parked cars extends all the way to the crosswalk, pedestrians may appear unexpectedly from behind parked cars. This is a common contributing factor to pedestrian crashes. If parking spaces in advance of the intersection are removed (a practice 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.

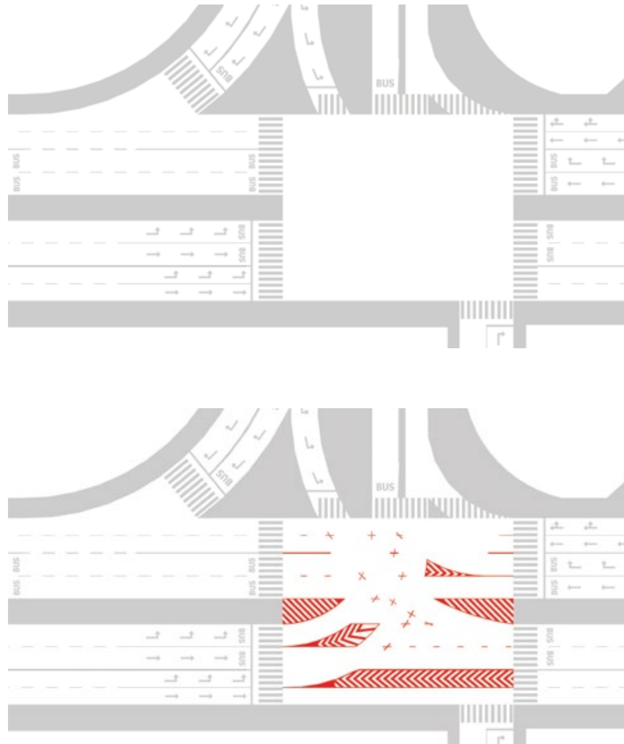


Figure 22 Example of an intersection with and without junction markings

Protected pedestrian space

Wherever a pedestrian waiting area—such as a refuge island—is 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 curb instead of 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 to find 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. Lane imbalance requires vehicles to converge on fewer lanes and some drivers may react by changing lanes suddenly, which could result in crashes.

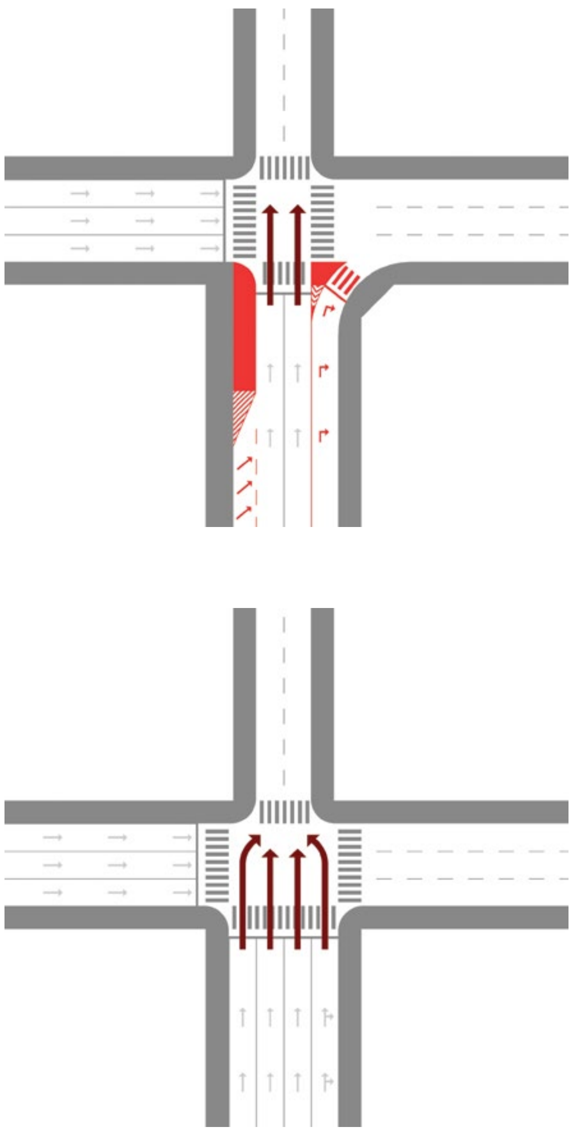


Figure 23 Example of how lane imbalance can be addressed by taking out lanes on one approach, or creating turn only lanes

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 midblock, with advance warning to drivers.

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 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 drivers 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 replaces a left turn with one right turn and two left turns on a parallel street, which 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.

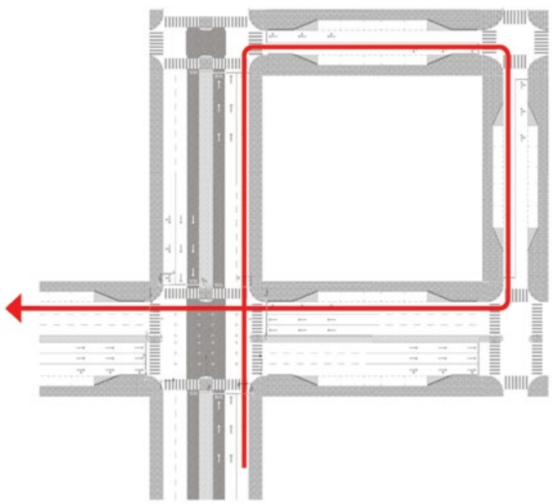


Figure 24 Loop option 1: Starting after the intersection with the left-turn prohibition

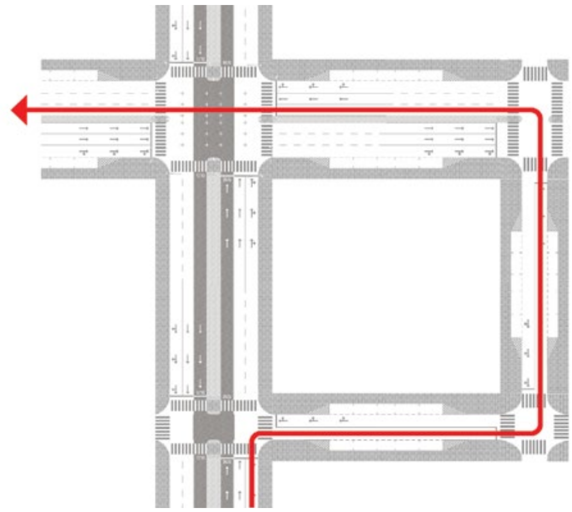


Figure 25 Loop option 2: Starting before the intersection with the left-turn prohibition

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. In the case of option 2, the sign must be placed before the previous intersection to allow the driver to make a right turn to begin the loop before the intersection where the left turn is prohibited.
- 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 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.
- The sign 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.

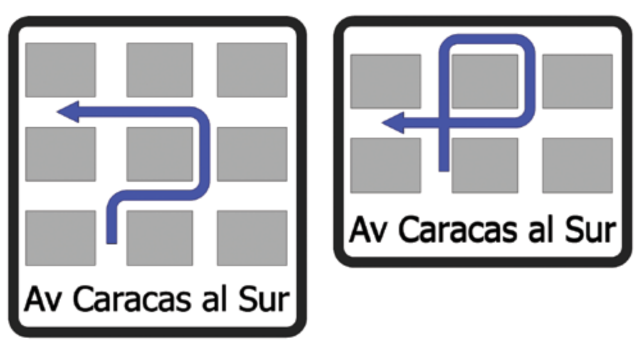


Figure 26 Recommended design for the two loop options. Note that the design includes the minimum amount of information needed for comprehension, and that the only street name listed is the one of the cross street where left turns are prohibited.

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 reduce intersection through capacity, and can be very effective in improving safety for pedestrians.

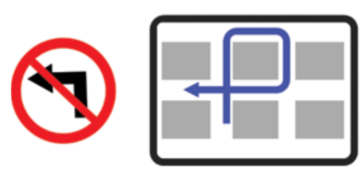
It can also help eliminate conflicts between vehicles maneuvering in and out of the parking lane on the cross street and vehicles turning right from the BRT corridor.

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

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

Figure 27 Major four-way intersection, no left turns

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



Provide 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, so they can be understood by a driver passing through the intersection.

5.2 MAJOR FOUR-WAY INTERSECTION, NO LEFT TURNS

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 in Figure 27 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 that cyclists will use the bus lanes. If a high volume of cyclists can be expected to use the corridors, we recommend including cycle tracks.

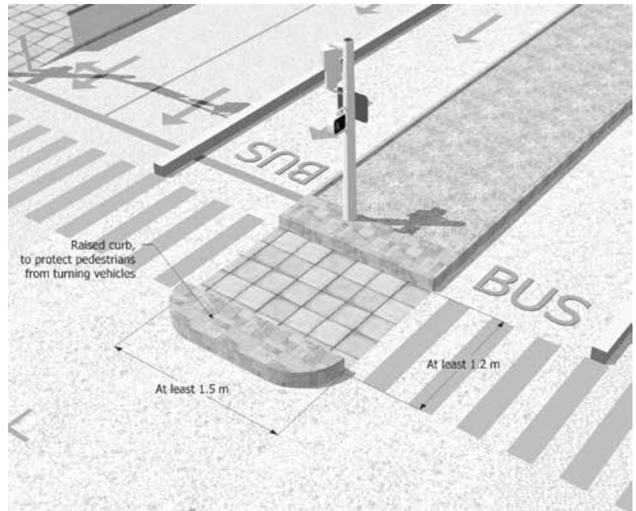


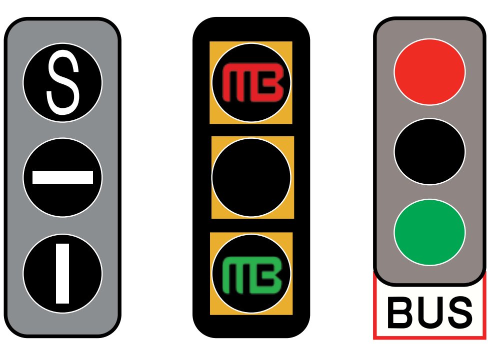
Figure 28 Detail of the pedestrian refuge island. The island should be at grade with the pavement and protected from traffic by a raised curb. It should provide sufficient space for the expected volume of pedestrians and at a minimum should accommodate a person with a stroller.

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.

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 Bogotá 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.

Figure 29 Major four-way intersection, with left turns

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: Metrobús signal from Mexico City; right: standard signal with a "BUS" sign).

Table 9 Potential safety impact of removing a left turn from an intersection

Weighted mean impact of removing a left turn	% change in crashes	95% confidence interval
Injury and fatal crashes	-22%	(-12%, -32%)
Vehicle collisions	-26%	(-10%, -43%)

5.3 MAJOR FOUR-WAY INTERSECTION, WITH LEFT TURNS

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 cannot be accommodated on adjacent or nearby streets, making a loop infeasible.
- 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 Bogotá, Mexico City, and Guadalajara suggest that when vehicles from the mixed traffic lanes enter the bus lanes this often results in collisions with buses.

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, 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.

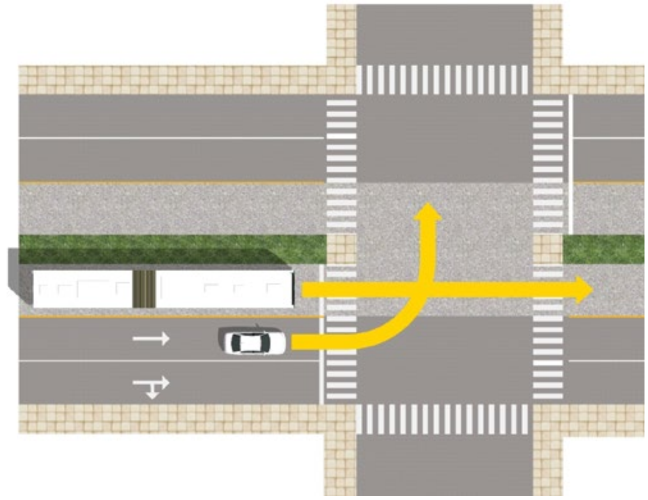
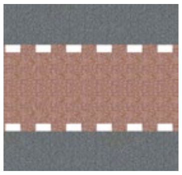


Figure 30 Crash diagram: The most common type of crash involving buses on center-lane BRT or busway corridors: Cars making illegal left turns in front of buses.

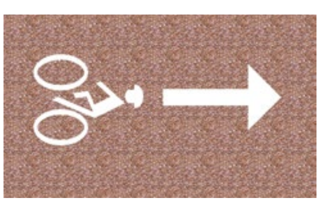
Left turns are one of the issues where the same recommendations improve both safety and operations. Prohibiting left turns eliminates a dangerous movement, while minimizing the number of required signal phases, thus maximizing the capacity of the bus corridor.



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

Figure 31 Intersection with cycle tracks

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.

5.4 MAJOR FOUR-WAY INTERSECTION, WITH CYCLE TRACKS

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 large physical barriers such as fences along the cycle track several meters in advance of the intersection, to ensure better visibility. Smaller curb height barriers can be used leading up to the intersection.

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.

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.

Figure 32 Example of bike lane signs and markings

Figure 33 Minor four-way intersection, through cross street

5.5 MINOR FOUR-WAY INTERSECTION, THROUGH CROSS STREET

We have already covered most of the safety problems related to this type of intersection. 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.

Table 10 Safety impacts of converting an intersection into two T-junctions

		% Change in crashes	95% Confidence Interval
Converting a 4-way intersection into two T-junctions	Fatal or injury crashes	-66%	(-88%, -1%)
	All crashes	-57%	(-70%, -37%)

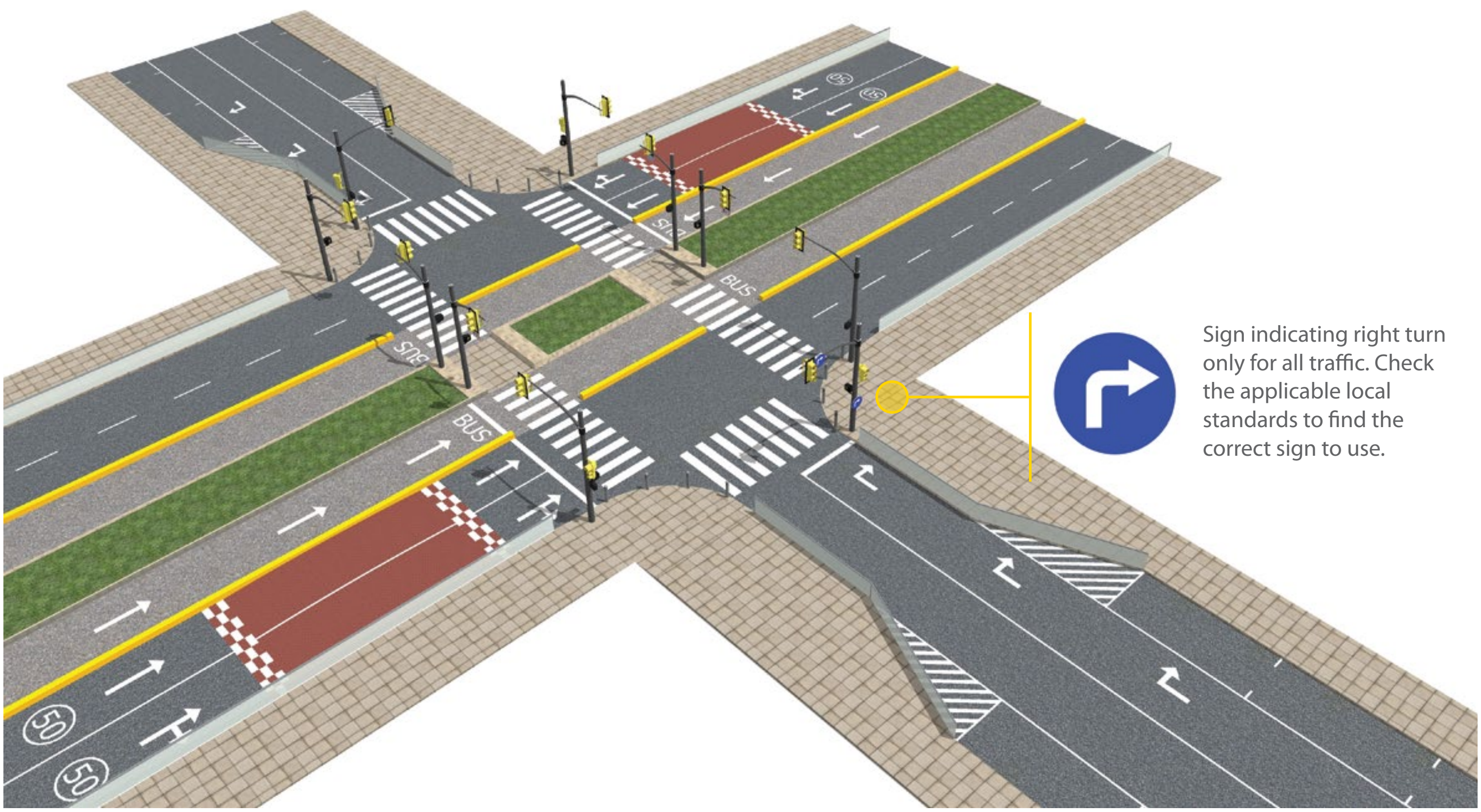


Figure 34 Blocked cross street

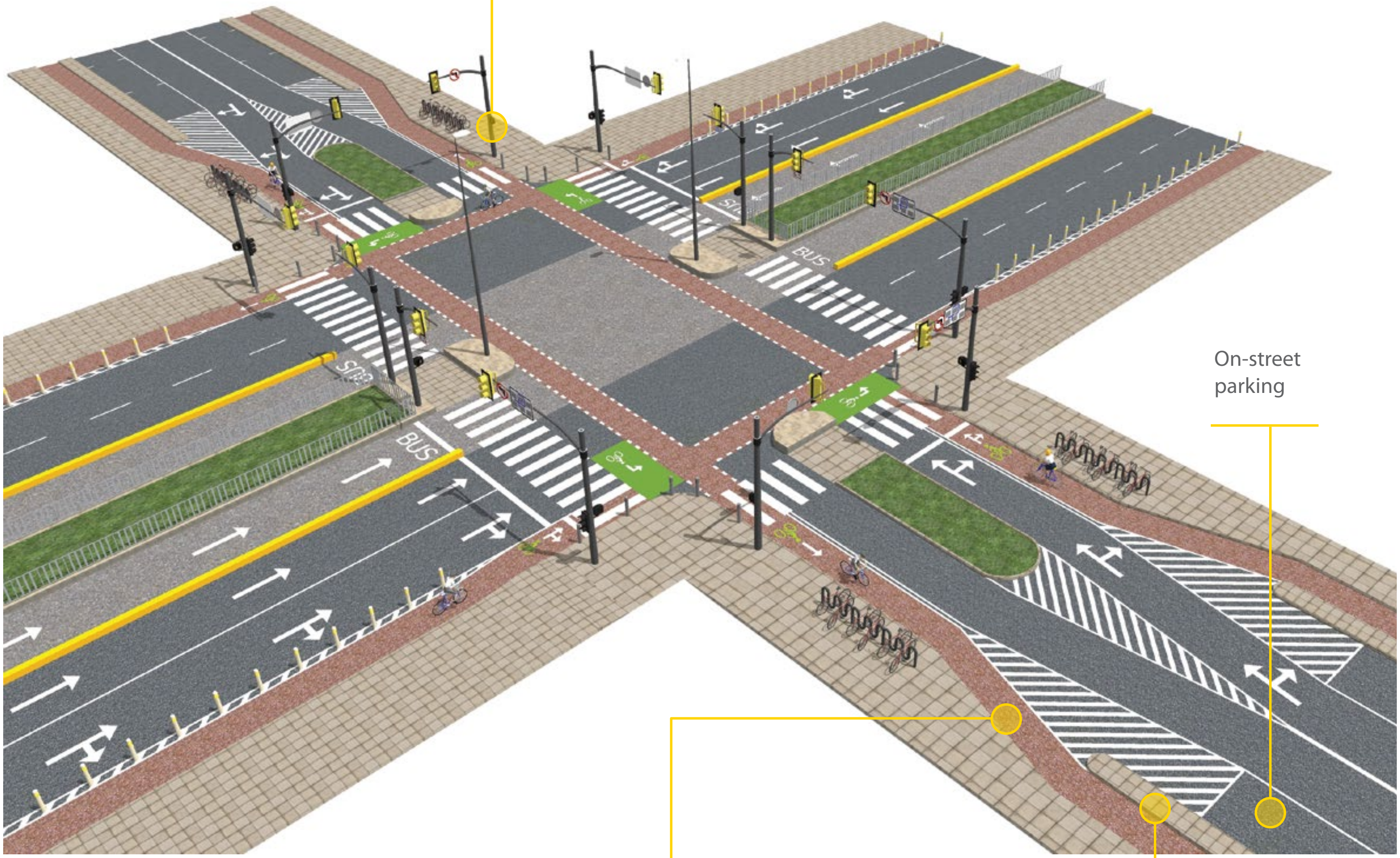
5.6 MINOR FOUR-WAY INTERSECTION, BLOCKED CROSS STREET/T-JUNCTION

Blocking off through traffic on the cross street can reduce crashes at this intersection by up to 57% (Table 10). 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.

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, all other things being 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 of eliminating crosswalks and signals at these locations. This implies a trade-off between operating speeds and pedestrian safety. At a minimum, we recommend having one signalized pedestrian crossing every 300 meters.

5.7 MINOR FOUR-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 will rely exclusively on the secondary one.



On-street parking

Figure 35 Minor four-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 will rely exclusively on the secondary one.

A buffer zone between parking lane and cycle track can help protect cyclists from parked car doors opening unexpectedly—a common safety concern for cyclists.

5.8 INTERSECTIONS WITH BICYCLE INFRASTRUCTURE

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, which we illustrate in Figures 36 and 37. Note 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 cross the BRT corridor with the rest of the traffic.

This common design solution (NACTO 2011) is also the option that best 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, no safety benefits may accrue from introducing it. For other options for accommodating left turns for cyclists, refer to NACTO 2011.

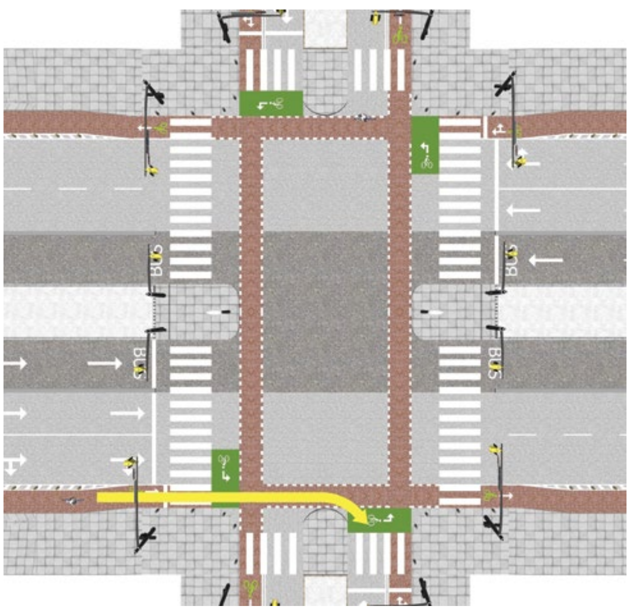


Figure 36 First stage of the left turn: Cyclists should continue straight along the BRT corridor on the green light, stop in the queue box to their right, and wait there for the light to change.

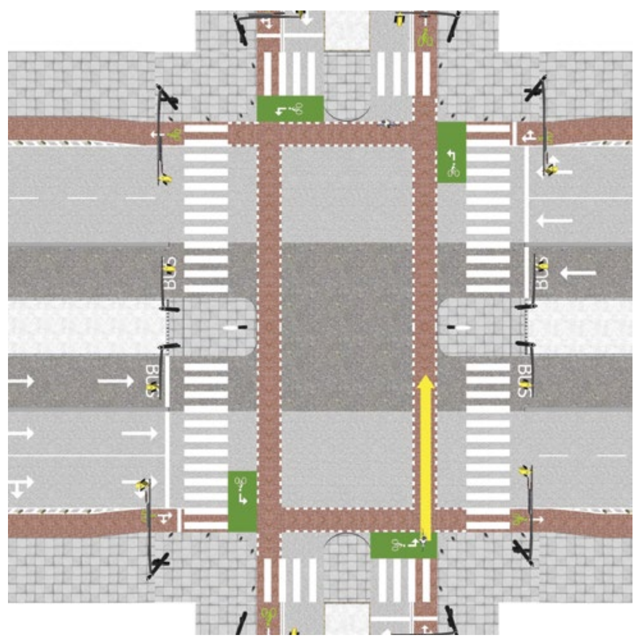


Figure 37 Second stage of the left turn: When the light turns green for the cross street, cyclists can cross the BRT corridor along with the rest of the traffic. Note the importance of the secondary traffic signal here. Cyclists will not be able to see the primary signal and will rely exclusively on the secondary one, situated on the far side of the intersection.

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 small, 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. However, a small turning radius should not be used when some vehicles might need to turn right directly into the bus lane (e.g., maintenance vehicles, local bus services sharing the bus lane, ambulances, etc.)

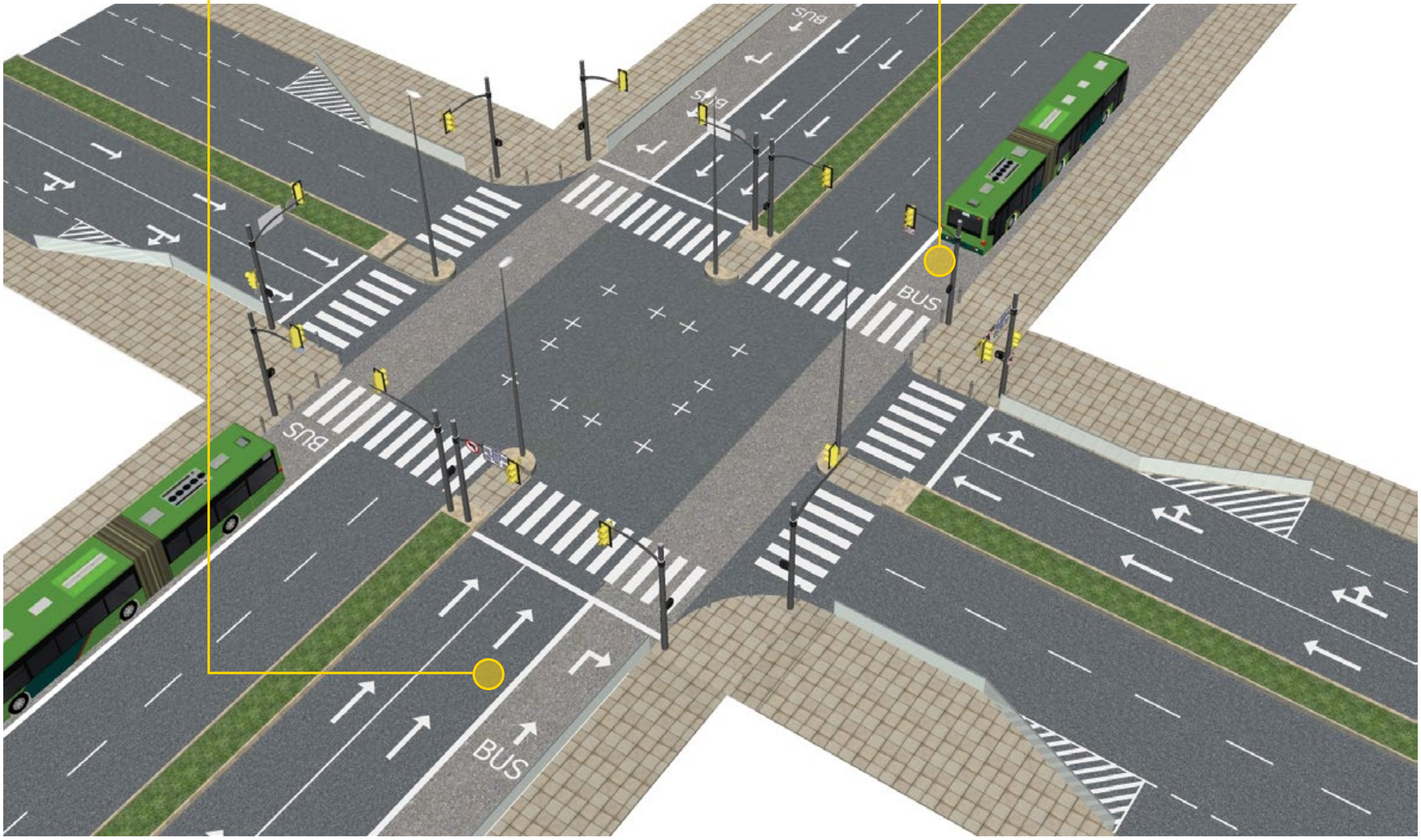


Figure 38
Curbside BRT intersection

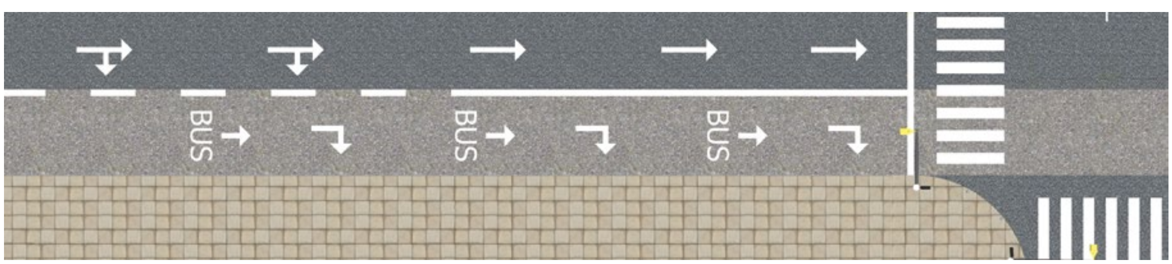


Figure 39 Plan view of one approach to the intersection along the bus corridor. Right-turning vehicles can merge into the curbside bus lane in advance of the intersection and then turn right from the bus lane. The space for merging into the bus lane should be at least 50 meters long.

5.9 MAJOR FOUR-WAY INTERSECTION, CURBSIDE BRT/BUSWAY

One of the main safety issues at intersections with curbside bus lanes is how to address right turns. Prohibiting right turns across a curbside bus lane would severely restrict mobility and access to adjacent property. Mixed traffic should therefore either merge with the bus lanes to make turns or make turns from the adjacent lane across the bus lane, but with a protected turn phase.

Figure 41 Intersections with bus priority lanes or mixed traffic

5.10 MAJOR FOUR-WAY INTERSECTION, BLOCKS UNDER 200 METERS: CURBSIDE BRT/BUSWAY

When block lengths are less than 200 meters (common in dense downtown areas) a curbside bus corridor will operate more like a conventional bus system in mixed traffic.

Crash data analysis suggests that the safety record of curbside bus priority systems is not as good as that of center-lane systems, though it can still represent an improvement over conventional bus service. As we mentioned in the research overview section, this is not necessarily due to the configuration of the bus system itself. Rather, the typical implementation of curbside bus priority does not include features such as adding a median, shortening crosswalks, or prohibiting left turns—the typical features of center-lane systems that are also shown to improve safety.

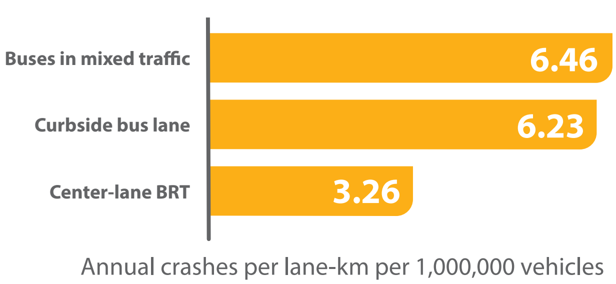


Figure 40 Comparison of road safety record for three types of bus corridors in Guadalajara, Mexico

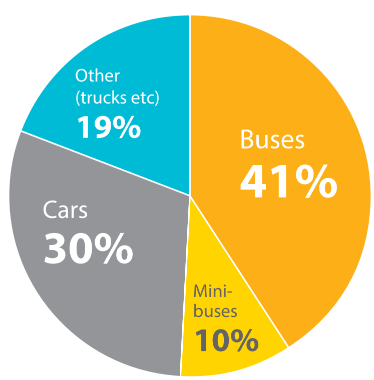


Figure 42 Vehicles involved in crashes on a curbside bus corridor in Guadalajara (Avenida Alcalde)

5.11 UNDERSTANDING PEDESTRIAN SIGNAL COMPLIANCE

In chapters 3 (midblock segments) and 5 (intersections), we recommended that all at-grade pedestrian crossings on urban arterials be signalized in order to provide a safe crossing environment. It is also important to pay careful attention to the configuration of the signal and to understand the factors that contribute to pedestrian compliance. A signalized crossing where the majority of pedestrians do not comply with the signal may not offer any significant safety benefits. In most of the cities we studied for this report, the majority of traffic signals are designed based almost exclusively on concerns for traffic capacity. Pedestrian behavior is not usually accounted for, which results in complex signal configurations and long waiting times, both of which contribute to low signal compliance levels. The incidence of pedestrians crossing on red is generally high in most cities that we studied (Figure 43), and this is a clear safety concern.

While there is certainly an enforcement and educational aspect to the problem of pedestrians crossing on red, research has also shown that the physical design of the intersection and especially the configuration of the traffic signals can have a strong impact on signal compliance levels (e.g., Zhou et al. 2011; Cooper et al. 2012).

As part of the research for this report, we carried out a study of pedestrian behavior at signalized intersections and studied how common intersection designs and signal configurations impact pedestrians' decision to cross on red. A detailed description of the data collection and analysis methodology for this study can be found in Duduta, Zhang, and Kroneberger 2014. We present here the main findings and the implications for intersection and signal design.

Figure 43 Pedestrians crossing with the red signal at the Eminönü transit hub in Istanbul (left image) and at the Salvador Allende express bus station in Rio de Janeiro (right image)

Table 11 Binary logit model predicting pedestrians' choice to cross on red at signalized intersections (a positive sign indicates a higher probability of crossing on red)

	Coefficient	P
Person of restricted mobility (=1 if yes, =0 otherwise)	-3.813	0.000
Traffic gap (seconds until next vehicle)	0.037	0.000
Traffic volumes (vehicles / second / lane)	-12.525	0.000
Average pedestrian delay (HCM formula, seconds)	0.012	0.023
Conflict with left turns (=1 if true, =0 otherwise)	0.873	0.000
All red (clearance) phase (=1 if yes, =0 otherwise)	1.02	0.001
Crosswalk length (meters)	-0.298	0.000
Constant	1.576	0.000
No. of observations	1570	
Log likelihood	-494.342	
LR chi2 (prob > chi2)	294.16 (0.000)	

Source: Duduta, Zhang, and Kroneberger 2014

One of the key findings from the results in Table 11 is that the average pedestrian delay is a significant predictor of signal compliance. Signal delay is essentially a function of the length of the pedestrian green phase and the length of the signal cycle:

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

(Eq. 18-71, Highway Capacity Manual)

Where d_p is pedestrian delay, C is the length of the signal cycle, $g_{Walk,mi}$ is the effective walk time for the signal phase serving the minor street (calculated as the green phase plus 4 seconds), and all measurements are in seconds. The pedestrian delay is higher when the signal cycle is longer and also when the pedestrian green phase is shorter. The Highway Capacity Manual (HCM) provides only an approximate way of interpreting the value of the delay in making a judgment about pedestrian compliance with the signal. It notes that pedestrians will be very likely to cross on red for delays of over 30 seconds, and very likely to wait for green when the delay is under 10 seconds. Table 12 shows possible values for the pedestrian phase and signal cycle length that would result in delay values just under 10 and 30 seconds, respectively.

Example A is a common configuration for a pedestrian crossing along a major arterial, allowing pedestrians to take advantage of the priority given to traffic. We predict a high level of pedestrian signal compliance in this case. Example B shows a case where the pedestrian phase corresponds to the green phase for the minor approach at a large intersection. This is more challenging, since the cycle length is long to accommodate multiple phases, making pedestrians less likely to comply with the signal. Example C is an extreme case of high pedestrian delay, with a cycle length typical of major intersections in Indian megacities.

Table 12 Examples of signal configurations and corresponding pedestrian delay

Examples	Pedestrian delay (d_p)	Pedestrian green phase length	Signal cycle length
A	12	40	85
B	76	15	180
C	191	30	440

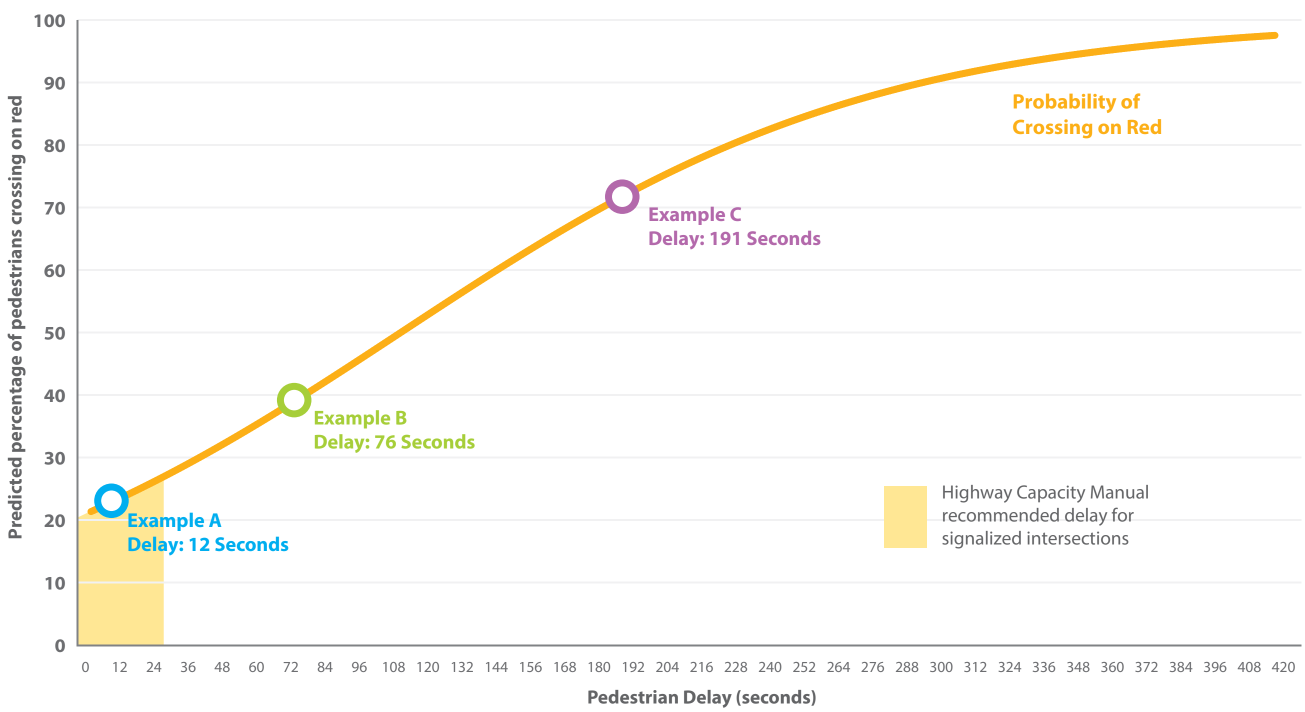


Figure 44 Percentage of pedestrians crossing on red at a signalized intersection, based on pedestrian signal delay (based on Duduta, Zhang, Kroneberger 2014)

Aside from the length of the different signal phases, the type of phases present at an intersection also have an impact on the probability that pedestrians will cross on red. Pedestrians are most likely to wait for green if the main conflict during the red phase is with cross traffic. When cross traffic is stopped, and some other turning movement is allowed, pedestrians are more likely to choose to cross on red. We tested the impact of different types of signal phases on the probability of crossing on red and found that the highest probability of crossing was associated with protected left turns for vehicles (Table 11). Note that we refer here to those left turns that conflict with pedestrian movements.

The physical design of the intersection also has an impact on signal compliance levels. Pedestrians are more likely to cross on red when the crosswalk length is shorter. It is important here to make the distinction between designs that lead to better compliance and designs that are safer. While fewer pedestrians may cross on red at larger intersections, more pedestrians be injured or killed there. Indeed, we found longer crosswalks to be associated with a higher incidence of pedestrian crashes (Table 8). This indicates that as an intersection is made safer by shortening the crossing distance, pedestrians are more likely to engage in risky behavior under the safer conditions.

DESIGN RECOMMENDATIONS FOR IMPROVING PEDESTRIAN SIGNAL COMPLIANCE

Perhaps the most important takeaway from the model results is that in order to minimize crossing on red, signal cycles should be kept as short and as simple as possible. Adding phases to accommodate additional turning movements or extending phases to increase capacity for vehicles will result in either longer pedestrian delays or more complex signal configurations. Both of these situations are likely to result in a higher percentage of pedestrians crossing on red, according to our findings.

Despite their association with a lower signal compliance level, shorter crosswalks should always be preferred, since they have a better safety record, and safety is clearly a more important performance indicator for pedestrian infrastructure than crossing on red. We would simply point out that urban designers and transport engineers should be aware that narrowing the road is likely to also make pedestrians more likely to not comply with the signal, which might offset some of the safety benefits. A good practice from this perspective would be to couple road narrowing with additional traffic calming devices, such as speed humps, or to make sure to reduce the signal delay even more on narrower crosswalks to improve pedestrian signal compliance.

Figure 45 Pedestrians in Rio de Janeiro crossing on red in the absence of oncoming traffic

Figure 47 Typical intersection design and transit service in the historic center of Mexico City after the implementation of Metrobús Line 4

CASE STUDY

METROBÚS LINE 4, MEXICO CITY

BUS PRIORITY IN A HISTORIC CITY CENTER:

Line 4 is part of Metrobús's growing BRT network in Mexico City, which in 2013 covered 95 km and served over 700,000 passenger trips daily. While the previous three lines of the system are median-running BRTs operating on major urban arterials, Line 4 operates on narrow streets in the city's historic center, connecting two major regional transit hubs (Buenavista and San Lázaro) with Mexico City's international airport. The narrow street widths in the historic center posed a significant design challenge. It was not possible to create dedicated bus lanes, as on the other Metrobús lines, because access to local properties and parking garages had to be maintained. Line 4 therefore operates on bus priority lanes that it shares with local traffic on the narrower sections, and on dedicated lanes whenever there is sufficient right-of-way to accommodate them. This is a somewhat complex configuration in which other road users are sometimes allowed to share the bus lanes and sometimes not. This required careful design, use of vertical and pavement markings, as well as enforcement to help road users understand the new street configuration (Figure 46).

Another important concern was the need both to accommodate the transit priority features and to allow sufficient space for the many pedestrians present in the historic center. The design of Metrobús Line 4 includes a number of significant safety provisions for pedestrians that were not common on streets in Mexico City before, including pedestrian signals, protected refuge islands, bollards along the sidewalk edge to prevent cars from parking on sidewalks, and improvements to pavement and signage, some of which can be seen in Figure 47. The new crosswalks and stop line markings are a notable design improvement on Line 4, as they help make intersections crosswalks more visible for drivers in advance.

Figure 46 New traffic signs and pavement markings indicating the end of a shared lane and the beginning of a dedicated bus lane, where mixed traffic must turn right

Station along the TransOeste BRT corridor in Rio de Janeiro, Brazil

CHAPTER 7

RECOMMENDATIONS FOR STATIONS

7.1 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 higher risk of pedestrian crashes here results not only from increased exposure but also from dangerous behavior, 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.

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.

On the following pages, we present several design concepts for bus stations that address the key safety issues we have just discussed. The main goal is the same regardless of the type of station: controlling pedestrian movements and discouraging people from crossing illegally. But the design solutions for achieving this differ 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 into two parts, the first dealing with pedestrian access to the station and the second with detailed station and platform design. For a design concept of bicycle access to a BRT station, refer to the following section (transfers and terminals). We then show a special case of median stations—those common on high-capacity systems like TransMilenio and that feature multiple substops 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 also illustrate concepts for bus stations on corridors that do not use offboard fare collection—such as open busways, curbside bus lanes, or conventional bus service in mixed traffic.

In a Latin American context, it may be better to prohibit both left and right turns at intersections featuring BRT stations. This could ensure safe pedestrian access, especially at stations with large pedestrian volumes. Right turns can be replaced with loops, which would need to start one block before the intersection.

Figure 49 Station access on an urban arterial

It is common in Latin American BRTs to have pedestrians cross along the median to or from the station, especially if the BRT green phase is relatively long. Some BRTs, such as Macrobús in Guadalajara, have implemented signalized crosswalks along the median. While we do not have evidence of the safety impact of this specific feature, the Macrobús BRT has a good overall safety record. This type of solution can be considered on BRTs, especially when pedestrian signal compliance is low and crossing along the median can be expected, with or without a crosswalk.

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, and should be considered for contexts where driver signal compliance is relatively good.

Figure 50 Pedestrian area filled to capacity at the exit of the Calle 72 station on TransMilenio

7.2 STATION ACCESS ON AN URBAN ARTERIAL

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 recommend is closed stations, regardless of whether the bus system uses offboard or onboard fare collection. The station should have access points situated only at signalized pedestrian crosswalks or pedestrian bridges.

Another important safety feature to include is 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.

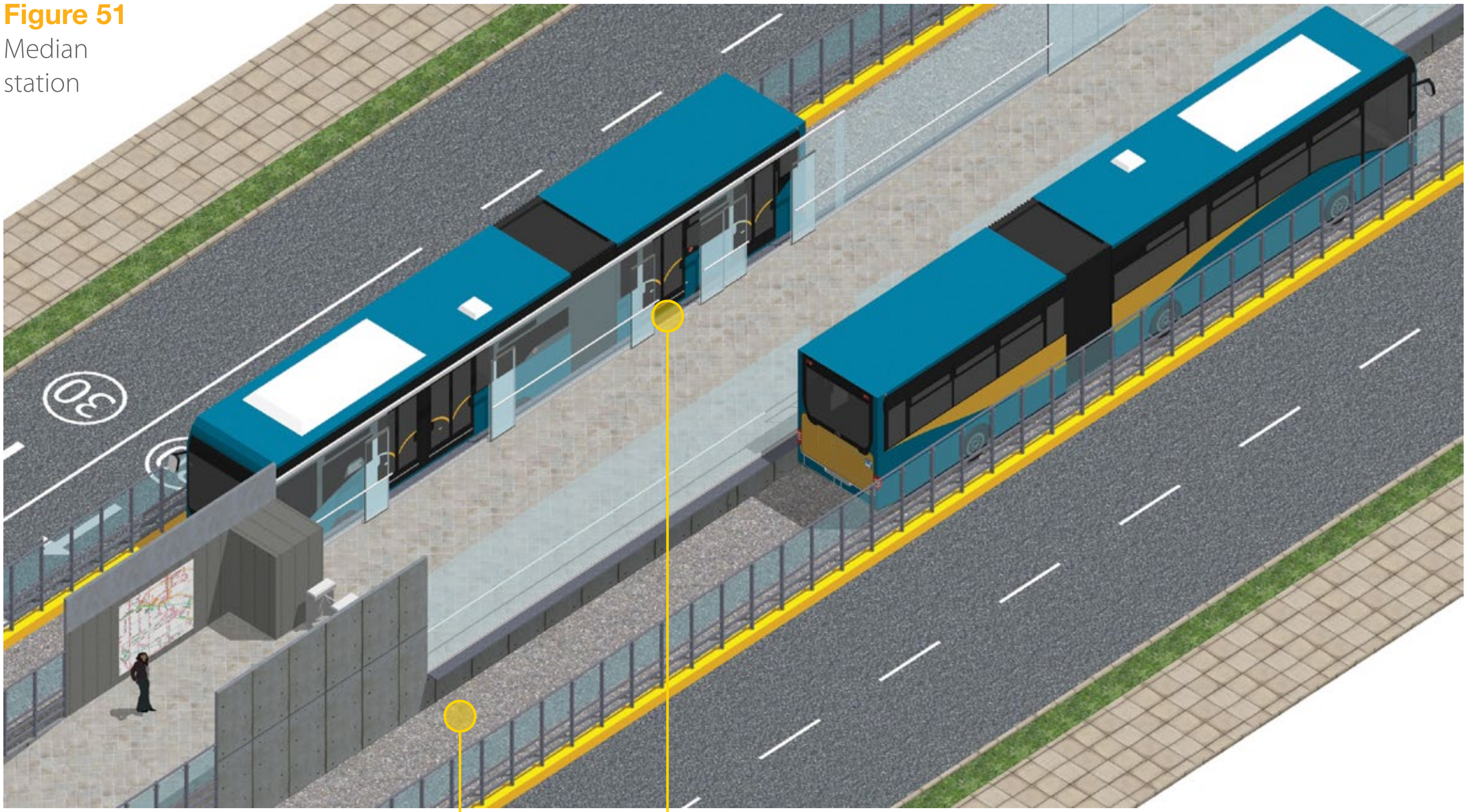
Figure 48 Pedestrians running across the bus lanes to attempt to enter the station without paying the fare, on TransMilenio

A 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 Metrobús in Mexico City will commonly have anywhere between 2,000 to 12,000 daily passengers exiting the station. 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 resulted from the presence of multiple pedestrian signal phases, which often risked leaving large volumes of pedestrians stranded on narrow medians.

Figure 51 Median station



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. The mechanism for opening the doors needs to be carefully designed, however, to ensure that it cannot be accidentally activated by a passing express bus, or by a bus docking at another platform nearby.

Figure 52 Pedestrian crossing the road in front of a station with no barrier between the bus lane and mixed traffic.

Figure 53 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 into the bus lanes.

7.3 CENTER LANE BRT/BUSWAY STATION DESIGN

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 (onboard or offboard) or the type of vehicles.

Figure 54 TransMilenio 2006: A pathway between two substops 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.

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, without any footholds, 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.

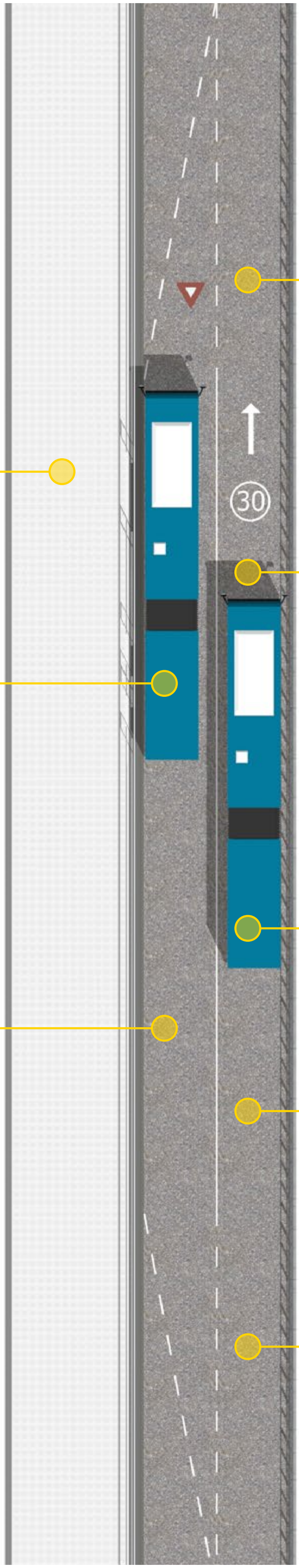
Using platform screens

Platform screens can help prevent jaywalking and ensure that passengers waiting on the platform stay clear of buses maneuvering in the bus lanes. But the screen doors can pose several problems. In addition to accidental opening, there is also the problem of people forcing the doors open. Sometimes, this is an attempt to enter or exit the station illegally and run across the bus lanes. In other cases, passengers have been observed simply preventing the screen doors from closing while waiting for the bus.

Figure 55 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

Figure 56 Passengers forcing the screen doors open at a TransMilenio station

Figure 57 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. 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 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 give 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 no more than 30 km/h, in order to help avoid crashes.

Articulated bus docked at a station platform

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. One 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 23 meters.

Express bus traveling through the station

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).

7.4 STATION DESIGN: EXPRESS LANES

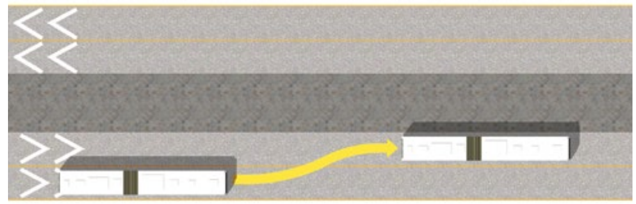
For high-capacity stations with express lanes and multiple stopping bays, there are additional safety risks to consider. The most serious is the danger of collisions between local and express buses, which can be serious and even fatal.

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 risk of collisions between different buses is higher.

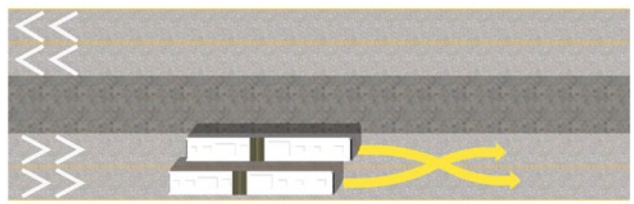
Rear-end collisions are the most frequent type of accidents recorded between buses on TransMilenio and also on the Metropolitano BRT in Lima, which has a similar layout. Most rear-end crashes occur away from stations, but those that happen at stations tend to be more severe, because they usually involve 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 is 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.

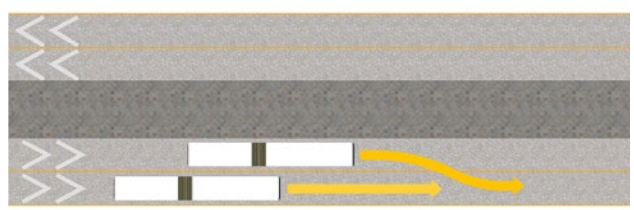
Figure 58



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 traveling 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.

Figure 59 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 midblock. Guardrails should be long—in excess of 10 meters—to be effective.

Figure 60 Station access

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

The image shows a staggered arrangement of station platforms on either side of the intersection. Having a station close to an intersection allows more pedestrians from surrounding areas to safely access the station using the crosswalk. The use of guardrails and walls can direct passengers to the crosswalk and discourage jaywalking. Placing the platform before the intersection on either side also allows buses to queue up at the station or at red lights without blocking the intersection.

The guardrail between the two bus lanes prevents pedestrians from attempting to take shortcuts across the bus lanes from the station platform to the opposite sidewalk and directs them to the signalized crossing.

7.5 STATION ACCESS AND DESIGN

Busways often have open, low platform stations and feature onboard 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 2010). The solution is to design stations 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 allow only those across signalized crossings or pedestrian bridges.

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.

Figure 61 Pedestrians jaywalking from a station on the BRTS corridor in Delhi

Figure 62 Pedestrian jaywalking across the bus lanes to reach the station platform on the BRTS corridor in Delhi

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. It can also eliminate the problem 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.

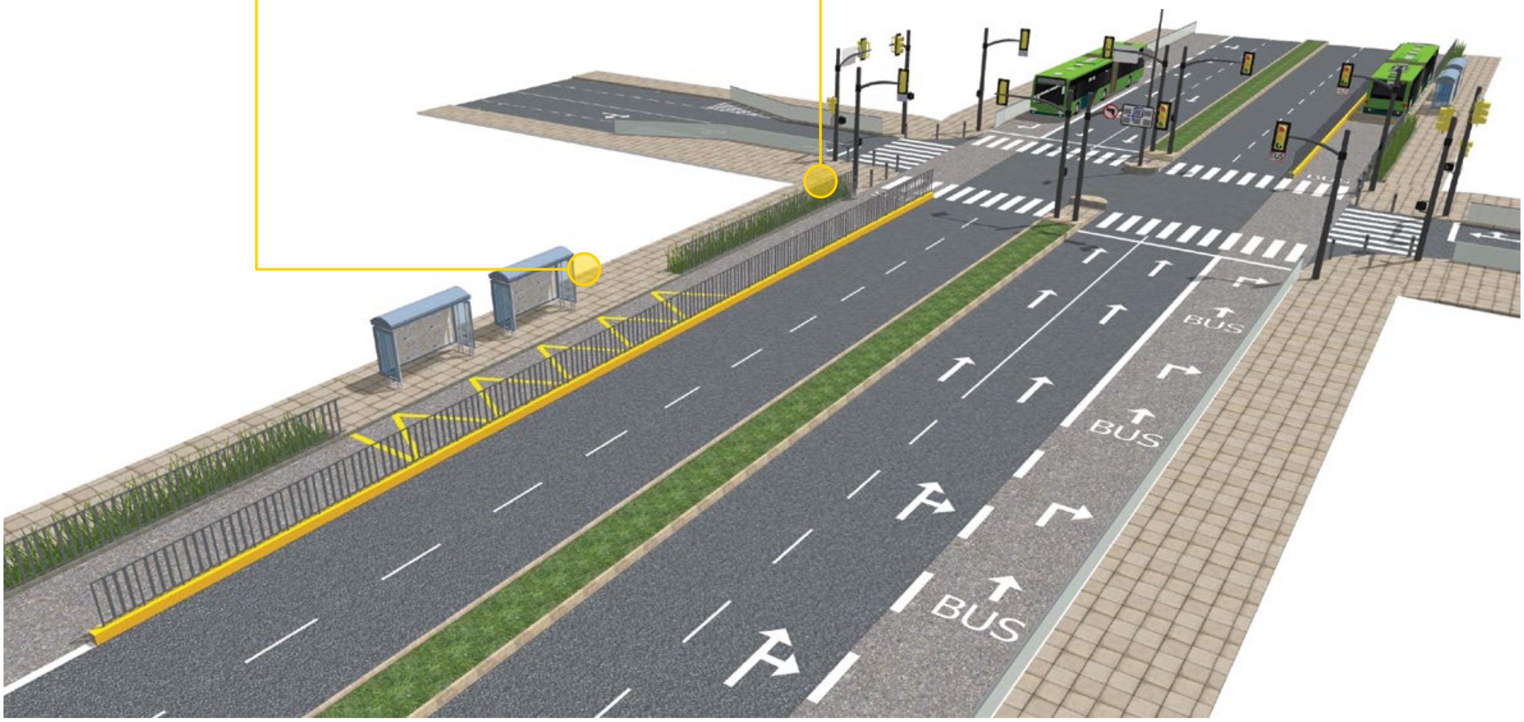


Figure 64 Curbside stations

7.6 CURBSIDE BRT/BUSWAY STATIONS

Pedestrians may attempt to cross in midblock 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.

Figure 63 A bus maneuvering around a stopped vehicle at a curbside station on Transantiago, Santiago de Chile

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. We also advise providing pedestrian refuge islands in the center of the street.

Figure 65 Bus priority and conventional bus lanes

7.7 STATIONS: BUS PRIORITY LANE OR MIXED TRAFFIC

In the case of bus priority lanes or conventional bus service, improving safety has more to do with general street and intersection design than with the station itself. The goal is the same as for the other stations: preventing jaywalking to and from the station and directing pedestrians toward 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.

Figure 66 The Mecidiyeköy station on the Metrobüs BRT in Istanbul

CASE STUDY

BRT OPERATING ON A FREEWAY: **METROBÜS ISTANBUL**

OVERVIEW OF METROBÜS ISTANBUL

Istanbul's Metrobüs began operations in 2007. As of 2014 the system carried close to 800,000 trips a day along a 52 km corridor connecting the Asian and European sides of Istanbul and is one of the main eastwest transit connections in the city. The BRT line operates along a freeway and is entirely grade-separated, allowing for higher speeds with no at-grade intersections or pedestrian crossings.

By using long platforms (commonly in the range of 120–170 meters) and by operating buses in convoys (Figure 66) Metrobüs is able to achieve a peak headway of close to 20 seconds and a capacity of over 20,000 people per hour per direction (pphpd) at stations, considerably higher than any other single-lane BRT, with no overtaking possibilities. Since it operates on a freeway, Metrobüs benefits from an entirely segregated right-of-way and has no signals or intersections along its route. As a result, commercial speeds on Metrobüs are higher than all other BRTs included in this study and are comparable with those of a typical heavy rail system (Table 13). Another feature of Metrobüs that can be observed in Figure 66 is

Table 13 Typical commercial speeds by mode and type of running way

Type of transit mode	Commercial speed (km/h)	Source
Standard bus	varies with traffic conditions	
BRT on urban arterial and no express service (e.g. Metrobús Mexico City)	20 – 28	Metrobús 2010
BRT on suburban arterial with predominantly express service (e.g. Transoeste, Rio de Janeiro)	28 – 35	Rio Onibus 2012
BRT on expressway (e.g. Metrobüs Istanbul)	40 +	IETT, Istanbul
Light rail	18 – 40	Vuchic 2007
Rapid rail (Metro, subway)	20 – 60	Vuchic 2007
Regional rail (e.g. Tren Suburbano, Mexico City)	30 – 75	Vuchic 2007

that buses operate in counterflow (i.e., while mixed traffic drives on the right side of the road in Turkey and on the Metrobüs corridor, Metrobüs vehicles drive on the left).

In this case, counterflow, in combination with the low platforms at stations, allows IETT operational flexibility, since the same right-door, low-platform buses can be used both on the BRT corridor and on conventional routes throughout the city. While counterflow can be dangerous on an urban arterial, it is considerably less so on a freeway. To the extent that a BRT's right-of-way is fully segregated (i.e., the buses never intersect pedestrian flows or mixed traffic at grade), as is the case for Metrobüs, the problems associated with counterflow are avoided. Note, however, that even if all the flows (BRT, mixed traffic, pedestrians) are separated in theory by the roadway design, there may still be cases where unauthorized vehicles or pedestrians enter the bus lanes, and in those cases, the counterflow configuration may increase the likelihood and the severity of a crash. We discuss this in more detail in the following section.

COMMON CRASH TYPES

Despite operating at considerably higher speeds than a more typical BRT example on an urban arterial, the lack of conflicts means that freeway-operating BRTs will tend to have a much better safety record than arterial-running BRTs.

As Figure 67 shows, bus-pedestrian collisions are the most common type of injury crash involving BRT vehicles operating on a freeway. This statistic includes two crash scenarios. The most frequent involves pedestrians running across the freeway (attempting

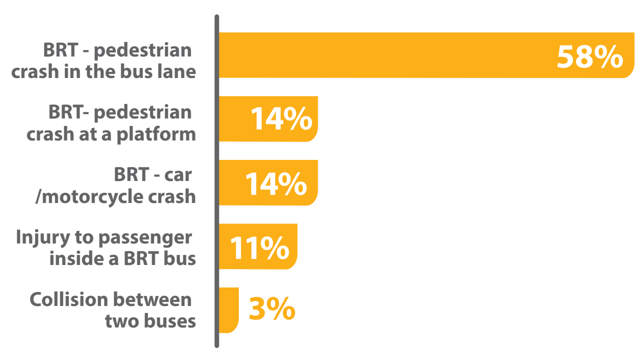


Figure 67 Most common types of injury crashes involving BRT vehicles operating on a freeway.
Source: EMBARQ analysis, based on data provided by IETT

to cross the street or take a shortcut to the station platform) and being run over by buses in the bus lane. The other scenario involves pedestrians walking in the bus lanes (usually to avoid congestion on the platform) and being struck by buses.

Collisions between buses and pedestrians at station platforms may include the latter of the two scenarios mentioned above, as well as passengers being struck by side mirrors or bus doors opening.

Finally, collisions between BRT vehicles and cars or motorcycles are typically a result of vehicles running over the crash barrier into the bus lane. It is important to note here that because of the counterflow configuration on a system such as Metrobüs, any collision between a bus and a vehicle that has accidentally entered the bus lane from the mixed traffic lanes will be a head-on collision at freeway speed—potentially a severe or fatal crash.

DESIGN RECOMMENDATIONS FOR FREEWAY OPERATING BRTS

Guardrails and crash barriers

Most of the crash types described above can be addressed by using a combination of guardrails and crash barriers. In these cases, it is important to use a double-sided crash barrier (Figure 68), since there will be traffic on both sides of the crash barrier, and it needs to be able to absorb impacts from both sides. The crash barrier is considerably more important if the BRT is operating in counterflow, as discussed in the previous sections. Guardrails can help deter pedestrians from attempting to cross the freeway at grade. Crash barriers and guardrails also need to be designed according to local or national standards and guidelines allowing sufficient space to absorb an impact at the speeds allowed in the corridor.

Figure 68 Design concept illustrating a combination of a double-sided crash barrier and a high guardrail, recommended for freeway-running BRTs

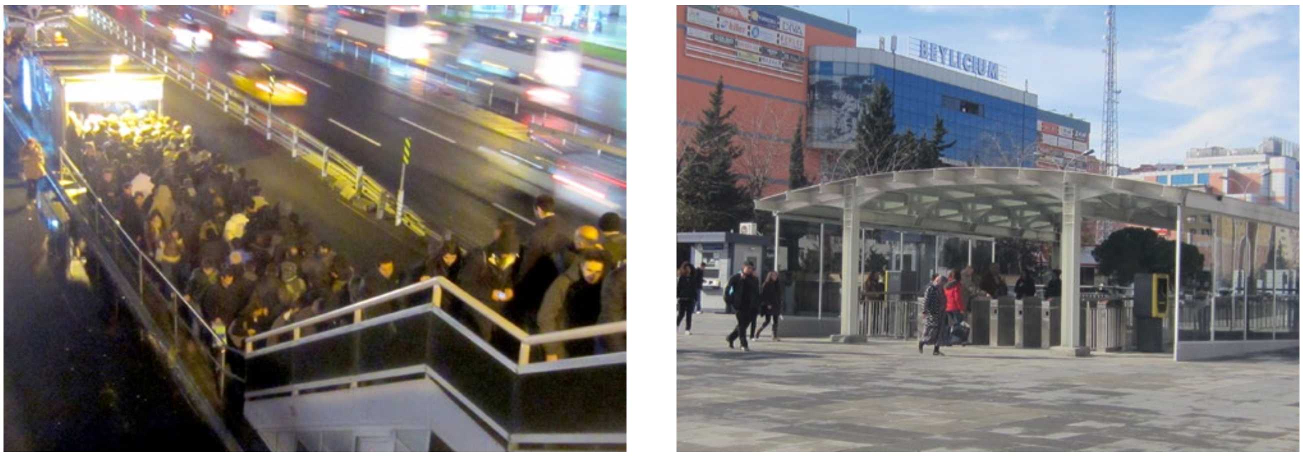


Figure 69 Left: a congested station entrance during the evening rush hour at Cevizlibağ, in an older section of the Metrobüs corridor; right: an improved station access point with turnstiles on a pedestrian plaza above the corridor.

Station access points

Station access points are another critical design element of a freeway-running BRT. The most common problem encountered here is overcrowding, which can lead some passengers trying to avoid congestion to walk in the bus lanes—a potential contributing factor to bus-pedestrian crashes (e.g., the left image in Figure 69).

When a transit system is placed in the center of a freeway, there are important space constraints to consider. In the case of Metrobüs in Istanbul, the transit right-of-way is restricted to the two bus lanes and the width of the central median, which accommodates the station's platform. Access to the station is commonly via a pedestrian overpass. Station designs that place the entrance and the turnstiles at the bottom of the stairway that connects to the bridge have a capacity limit imposed by the width of the central median. This type of layout only allows four turnstiles at a station entrance, which limits capacity to just under 5,300 passengers per hour.[5]

Metrobüs ridership has increased by over 450% between 2008 and mid-2011, and more recent data suggests that this trend continued through 2013. This considerable increase has left some of the initial station layouts unable to handle the new passenger demand. At Cevizlibağ in 2012, for example (Figure 69, left image), an average of 6,300 passengers attempted to enter the station during the peak evening rush hour, almost 20% more than the station's capacity.

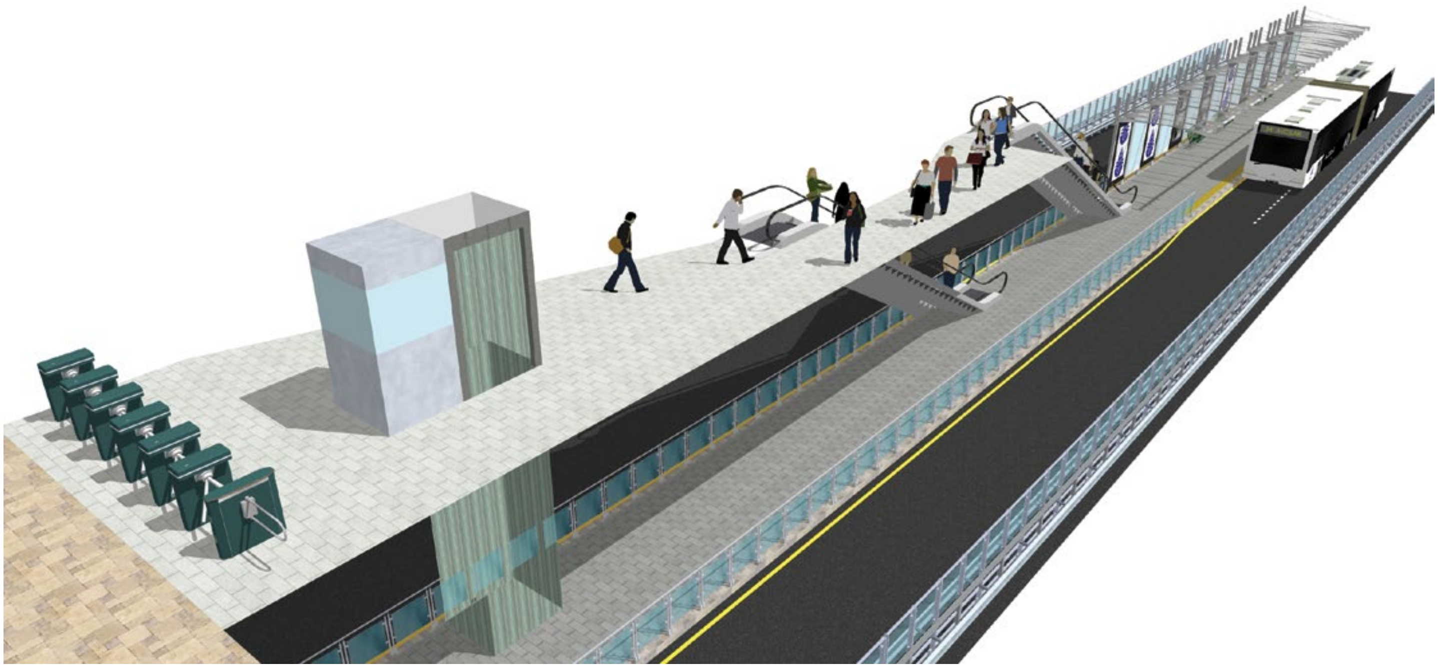


Figure 70 Design concept aimed at increasing passenger capacity and reducing overcrowding at a BRT station on the median of a freeway (note that this is a conceptual drawing of passenger access and does not show all the recommended guardrails)

To address this issue, IETT has rethought station entrances, moving turnstiles to the pedestrian overpasses connecting to the station, where there is more space to accommodate additional turnstiles (Figure 69, right image). We discuss here some design options for addressing overcrowding at station access points and illustrate them in Figure 70.

Some of the key features of the design concept in Figure 70 include:

- Expanding the station on both sides of the pedestrian overpass and using one side of the station for each direction of travel (e.g., westbound buses would stop on one side of the bridge and eastbound buses on the opposite side)
- Moving the turnstiles to the overpass, which allows the placement of more turnstiles, since the width of the access point to the station is no longer constrained by the width of the median
- Using the placement of escalators to separate the two directions of passenger flow inside the station to avoid friction between opposing flows

Aerial view of the Indios Verdes transfer station, Mexico City

CHAPTER 9

RECOMMENDATIONS FOR **MAJOR TRANSFER STATIONS**

9.1 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 10 locations with the highest number of crashes on Avenida Caracas, on TransMilenio, three—including the top one—are either terminals or major transfer stations (Avenida Jimenez, Portal de Usme, and Santa Lucia). On the South Line in Curitiba, the three locations with the highest number of crashes are all terminals (Pinheirinho, Raso, and Portão).

This does not necessarily mean that transfer stations and terminals are more dangerous, but it does indicate 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, as well as on the urban context. Large, integrated transfer

Figure 71 Aerial view of Indios Verdes, Mexico City, a transfer point between the Metrobús BRT, the Metro, and minibuses connecting north to Estado de Mexico.

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.

The **safest types of transfers** between two main routes are those where **the passengers do not have to leave the station platform**

LIST OF DESIGN CONCEPTS

On the following pages, we present several design concepts for transfer stations and terminals that address the key safety issues discussed above according to the type of transfer. We start with transfers between BRT or busway trunk lines, 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.

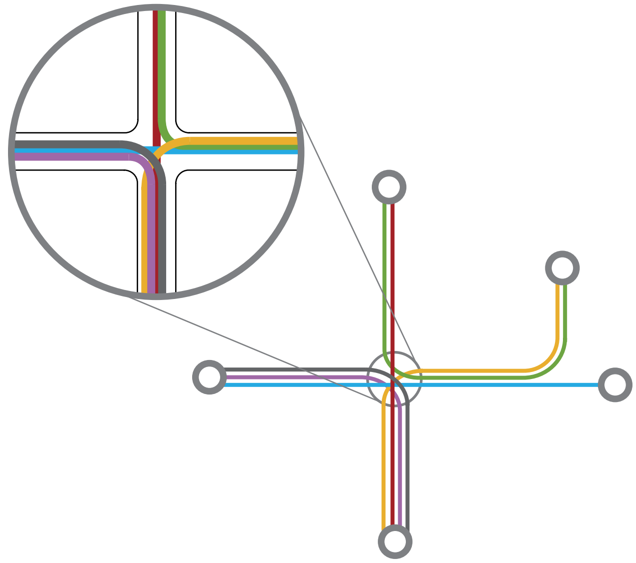
The second aspect to consider is the overall safety of the location where the transfer occurs—for not just transfer passengers but all road users. From this point of view, the recommendations are the same as for intersections and stations in general: narrow junction areas, turn restrictions, short pedestrian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

9.2 TRANSFERS BETWEEN TRUNK LINES: DIRECT ROUTES TO ALL DESTINATIONS

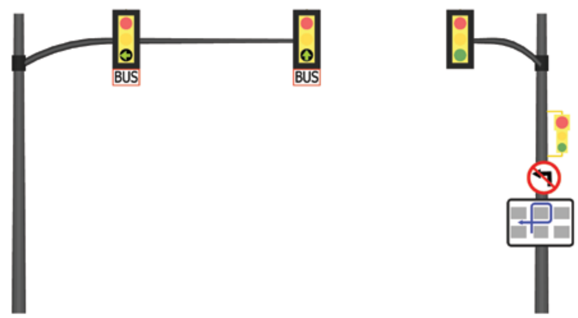
EXAMPLE: TRANSMILENIO

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.



Allowing buses to make all possible turns at an intersection is quite difficult in practice, 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 they can 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.



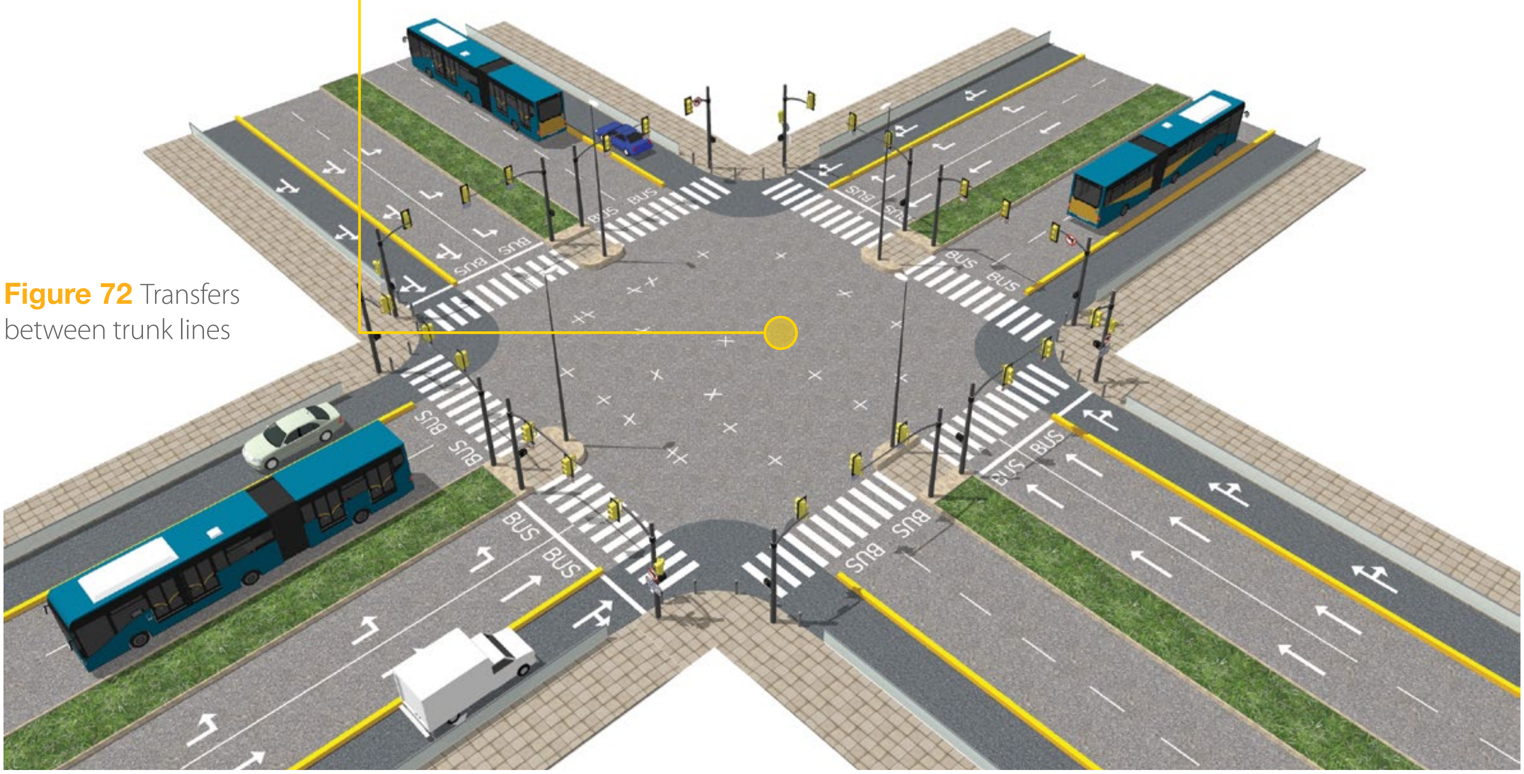


Figure 72 Transfers between trunk lines

For transfer passengers, this is the safest option, since the there is no actual transfer involved, and passengers simply choose the bus that takes them to their destination. Because of the need to accommodate multiple bus turns, 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.

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 attract more riders to the BRT system. The downside is that the location where two BRT corridors intersect can become a major bottleneck. A multilane 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, increasing the amount of green time available for that movement and decreasing it for others. If both corridors have high passenger demand, an overpass or underpass could be created to connect the corridors, as in the case of the junction between NQS, Avenida Suba, and Calle 80 on TransMilenio.

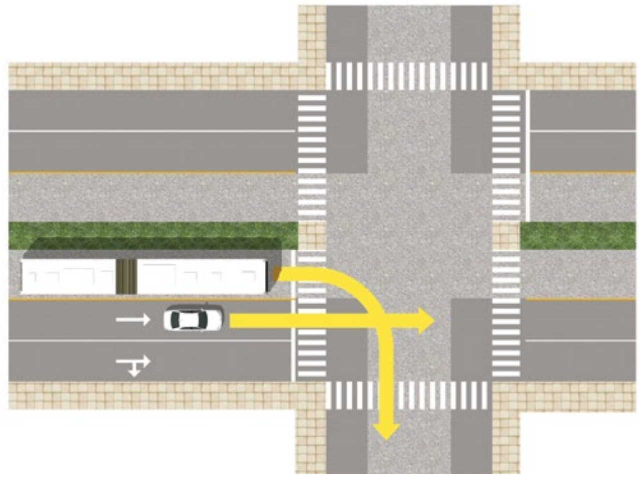


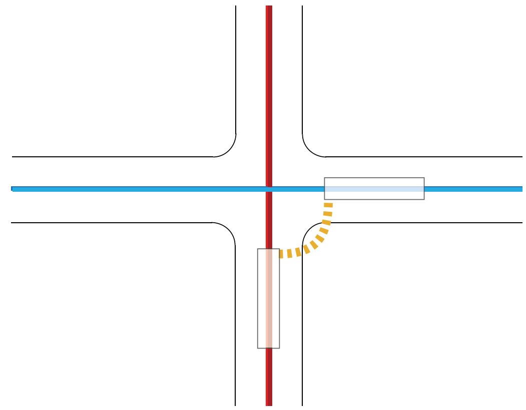
Figure 73 Crash diagram illustrating a potential conflict between right-turning buses and vehicles continuing straight. This type of crash has been reported on TransMilenio.

Figure 74 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 minimizes potential conflicts between buses.

9.3 TRANSFERS BETWEEN TRUNK LINES: TRANSFER ACROSS AN INTERSECTION

EXAMPLE: MEXICO CITY METROBÚS

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 can be avoided by connecting the two stations via a bridge or overpass.



It is also possible to use a combination of transfers across the intersection and bus turns. This is the design in the case of the Avenida Jiménez 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 reduce the number of signal phases required for the intersection.

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.

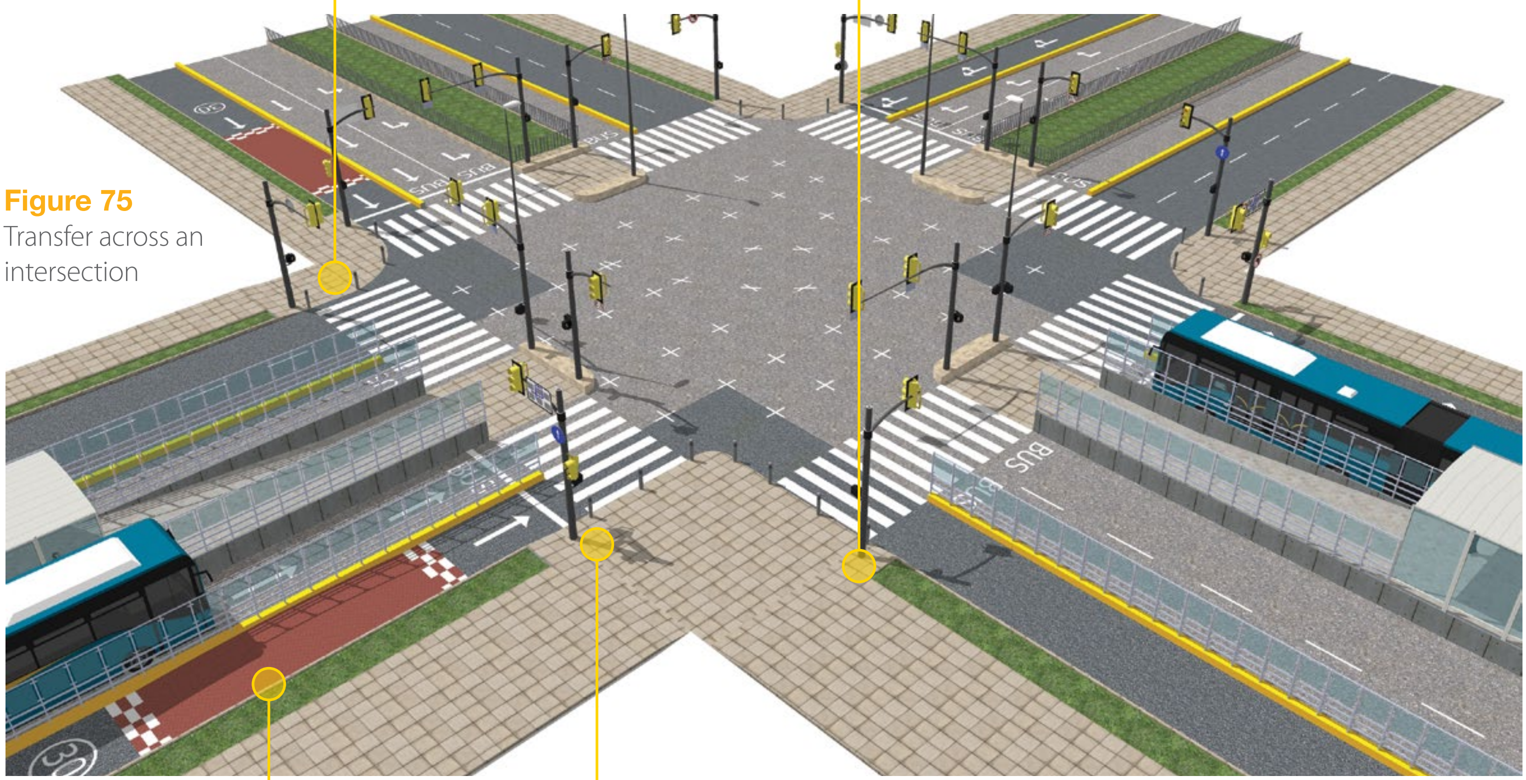


Figure 75
Transfer across an intersection

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.

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 illustration here. 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 prohibiting any turning movement that might conflict with pedestrians' transfer between the two stations. If there are high volumes of transfer passengers, a pedestrian-only signal phase could be included 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 Jiménez 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 walk, 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.

Without an overpass or underpass, this type of transfer would require passengers to exit at one station and reenter at the next one. This would require a decision about its impact on the fare that transfer passengers pay for their trip. While posing some problems in terms of collecting fares from transfer passengers and increasing the risk 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, it would not constitute a bottleneck, as the capacity of the intersection would be higher than that of the two stations. The two corridors in this configuration can handle higher volumes of passengers per lane than the scenario in which transfers are made by direct routes intersecting at grade.

9.4 TRANSFERS BETWEEN TRUNK LINES: HYBRID OPTION: DETOUR ON ONE LINE TO ALLOW CROSS-PLATFORM TRANSFERS

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. The downside is that this option would increase travel times for 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 to bring all buses to the same station.

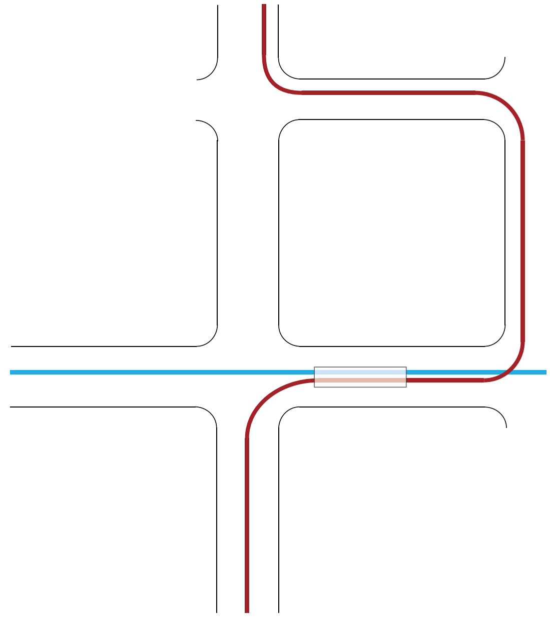


Figure 76 Transfers between trunk lines

This option would allow cross-platform transfers between two corridors, even though only one line operates 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 arises in 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, and so on. The risk is that if the intersections are poorly designed, this would offset the safety benefits of the cross-platform transfers.

In this type of transfer, capacity is likely to be limited by the intersection rather than the station. To improve operations in this design, dedicated lanes should be provided 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 prohibiting left turns for mixed traffic, as such turns would increase the number of signal phases required and lower the capacity for both BRT corridors.

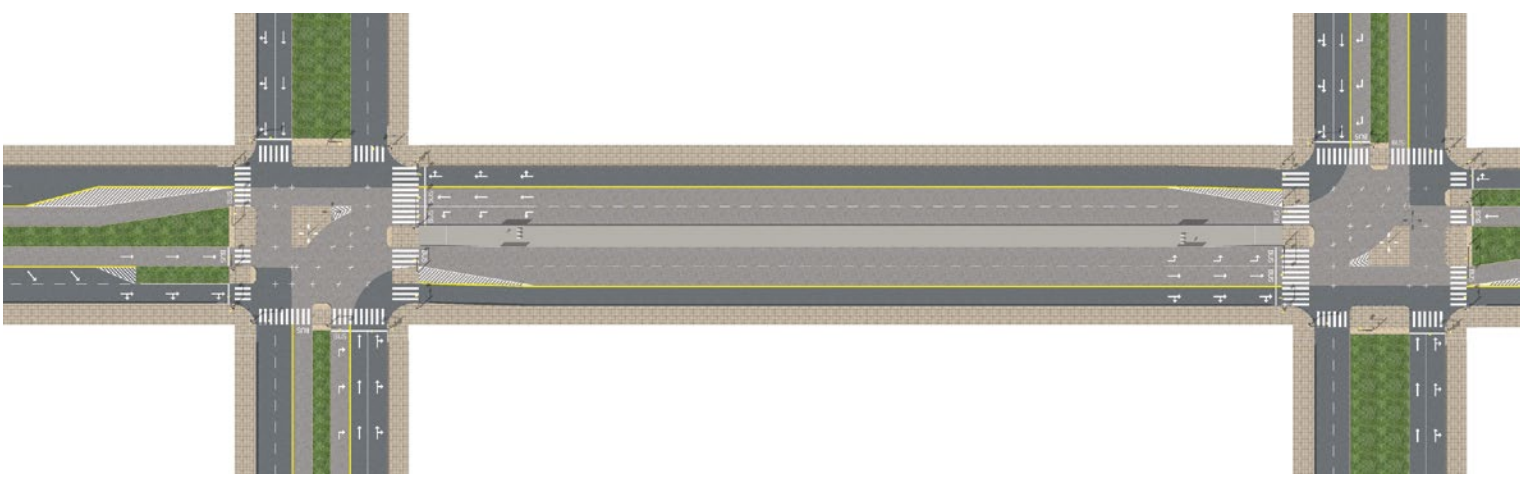
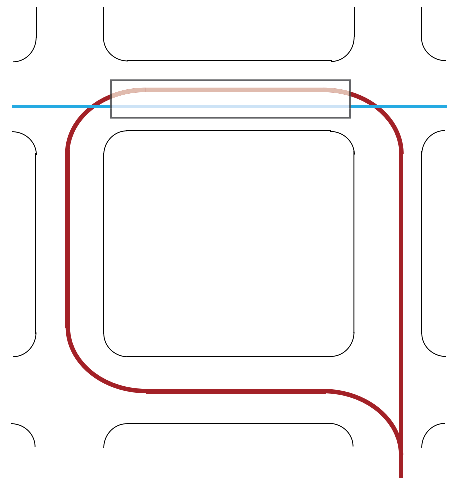


Figure 76 Transfers between trunk lines

9.5 TRANSFERS TO OTHER SERVICES: INTEGRATED TERMINALS

EXAMPLES:
TRANSMILENIO TERMINALS, SAN JERÓNIMO TERMINAL ON THE OPTIBÚS BRT, LEÓN



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 offboard fare collection, while the other side can be open. The transfer itself is quite safe, but there is a risk of collisions between buses at access points to the terminal.

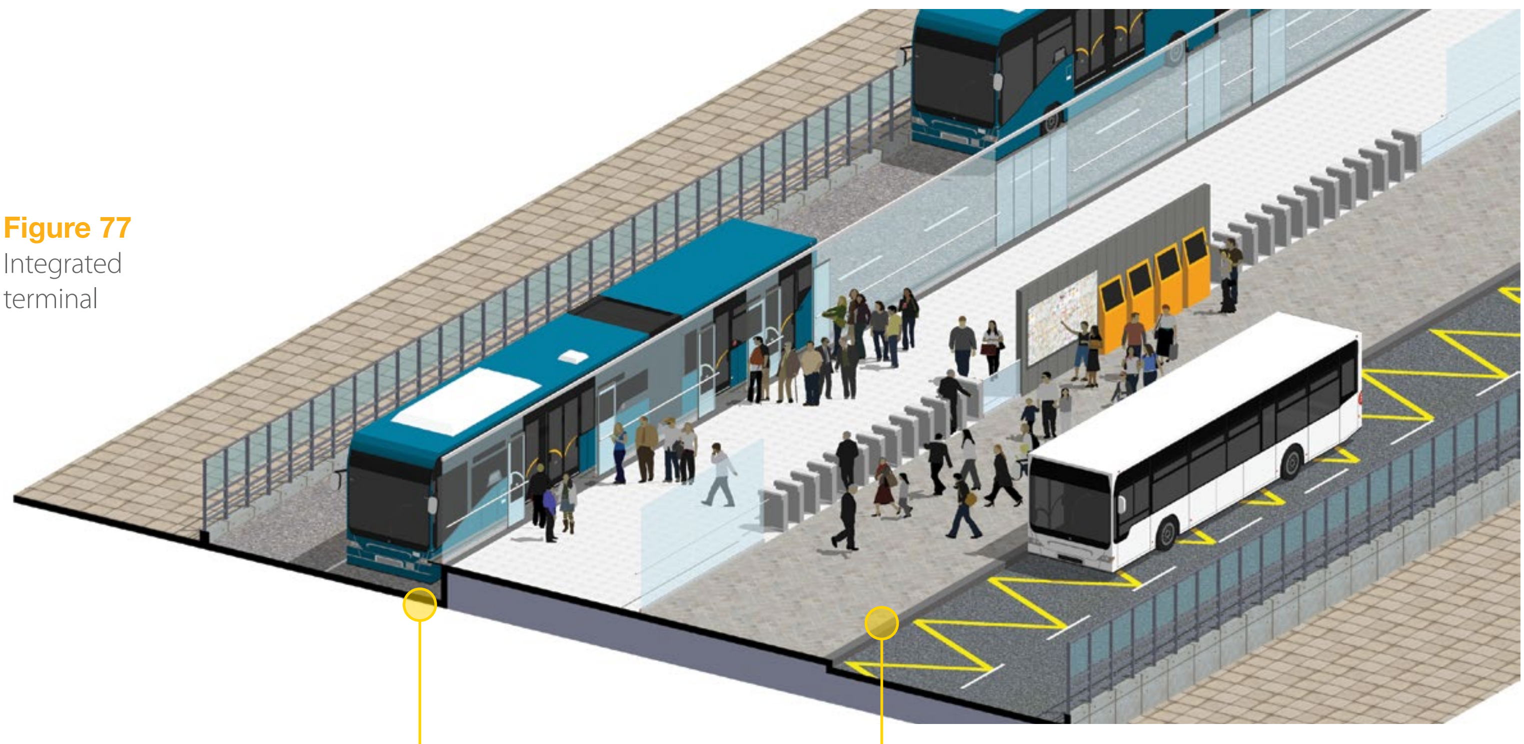


Figure 77
Integrated terminal

Platform height: Same as bus floor height

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 offboard 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 onboard 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.

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 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 need is sufficient width to accommodate the expected volumes of passengers. If the platforms become overcrowded, passengers may walk in the bus lanes—particularly on the side of the terminal with low platforms.

Figure 78 Images showing a typical layout for a TransMilenio terminal.
Left: the green feeder buses stop on the left side of the platform.
Right: the articulated red trunk line buses stop on the right side of the same platform

Access points for integrated terminals

The design of the access points to the terminal should aim to minimize conflicts between different buses and ensure safe pedestrian access. Figure 79 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. Pedestrian access to the terminal via an underpass or overpass is essential to eliminate conflicts between pedestrians and buses.

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 to increase the likelihood that pedestrians will cross on red. This could be addressed by ensuring pedestrian access via an underpass or overpass.

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.

Figure 79 Access points to integrated terminals

Figure 80 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. Trunks and feeders stop on both sides of two parallel platforms. Access points for buses to the terminal are not signalized, relying on drivers to yield to each other.

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.

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 in the two configurations shown above.

9.6 TRANSFERS TO OTHER SERVICES: TRANSFER TO LOCAL BUS SERVICES ACROSS AN INTERSECTION

EXAMPLE: MACROBÚS, 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 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 goal 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 prohibiting turns at this intersection that may conflict with the path of transfer passengers.

Figure 81 Transfer to local bus services

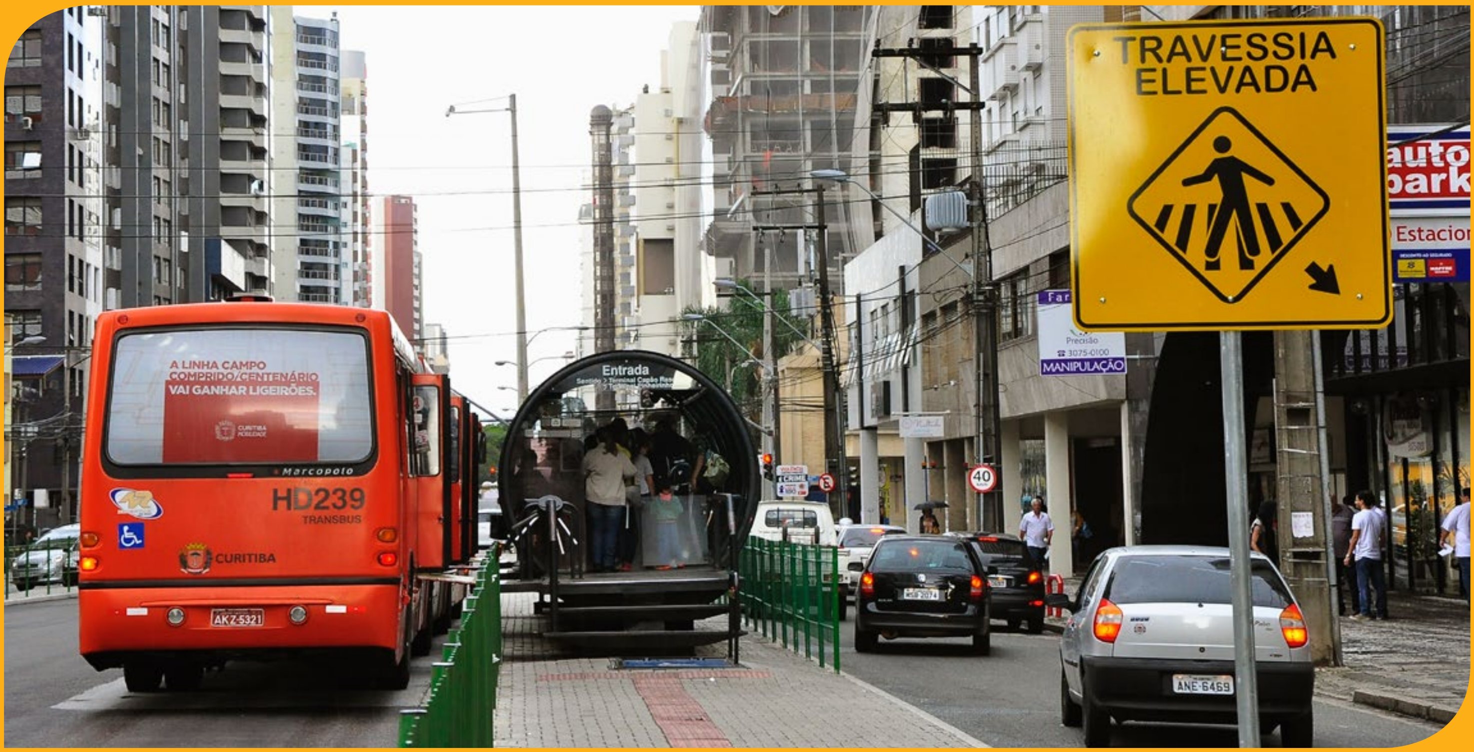
9.7 TRANSFERS TO OTHER SERVICES: INTEGRATING BRT WITH A CYCLE NETWORK

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.

Figure 82 Integrating a cycle network



Median BRT station in Curitiba, Brazil

RESEARCH **AND ANALYSIS**

In this section we explain the data and methodology used to assess the safety impact of different types of bus systems and transit-priority features as well as the economic value of safety impacts.

Conventional bus service and infrastructure in Brasilia

10.1 SAFETY PERFORMANCE OF DIFFERENT BUS SYSTEM TYPES

Understanding the overall safety impact of different transit priority features can be particularly important in the early phases of planning of such systems. It is common for transit projects to receive national government funding, with decisions often based on cost-benefit analyses. Several national transit funding programs currently mention safety among the potential benefits that can be included in the analysis. However, there are few estimates available in the literature on the expected safety impacts from implementing transit priority, and the majority of the research available is on bus priority lanes from the United States and Norway (Elvik and Vaa 2008).

The ability to quantify the expected safety impacts for a given type of transit priority scheme in a city of the developing world can help in estimating context-specific project benefits. This is relevant in the early phases of planning, and it can contribute to a better understanding of the magnitude of safety impacts that can be expected from implementing transit priority features. Having estimates based on local data would also be more valuable than applying estimates based on studies in the United States or Europe. We therefore begin our analysis with an overview of the overall safety impact from implementing different types of transit priority schemes. We discuss different methodologies for assessing the economic value of safety impacts and how this could be factored into cost-benefit analyses and transit funding decisions.

We present here evidence of the safety impact and the associated economic benefits of several bus systems around the world, drawing from the existing literature and our own data analysis. In all cases, we show the impact of implementing some form of transit priority compared to the existing conditions on the corridor. In most cases, the transit priority schemes were implemented on streets that featured either conventional bus service or

Evidence indicates that implementing more advanced transit priority features on urban streets tends to improve safety

informal transit service. But this was not always the case. The TransMilenio BRT in Bogotá, for instance, replaces an existing busway on Avenida Caracas, while the Macrobús BRT in Guadalajara replaces a previous bus priority lane.

The main challenge in evaluating the safety impact of a transit priority scheme is determining to what extent the change in crashes is attributable to the intervention. It is important to distinguish the impact of the intervention from the general randomness of crash data (particularly the regression to the mean, or RTM effect) and from the impact of various other policies or trends at the citywide and national level. RTM refers to situations in which a location that experiences a particularly high or low crash volume in 1 year will tend to experience a crash volume closer to the mean the following year (Barnett, van der Pols, and Dobson 2004). Simple comparisons of crash counts cannot take into account RTM and can lead to inaccurate results. For this reason, the preferred technique for evaluating the safety impacts of interventions such as BRT is the Empirical Bayes (EB) method.

Our estimates of transit priority safety impacts are based not on a before-and-after analysis but rather on the comparison between a baseline scenario (assuming that transit priority had not been implemented) and the actual postimplementation conditions. This is an important step in isolating the change in crashes that could be attributed to the BRT itself, versus the existing citywide trends.

Another challenge to estimating safety impacts is that countries in the developing world tend to underreport traffic injuries and fatalities. In part this results from different definitions of what constitutes a traffic fatality or a traffic injury, but reporting errors are also to blame (Híjar et al. 2011). The World Health Organization (WHO) has developed adjustment factors to standardize the data across the different countries (WHO 2013), and we apply these factors in our analysis.

Table 14 shows evidence of safety impacts from different bus systems around the world. The results in Table 14 represent actual impacts measured using local data and adjusted for underreporting using WHO-recommended adjustment factors. In general, the results show that implementing more advanced transit priority features (i.e., going from a busway to a full-fledged BRT or from conventional service to priority lanes and signal priority) tends to improve safety.

Chapter 5.3 will explore in more detail the reasons behind the positive safety impacts noted in Table 14. In general, the reduction in injuries and fatalities is not dependent on the type of transit priority system being implemented. Rather, these reductions can be attributed to two main factors.

First of all, transit priority features tend to improve the road geometry in ways that also make the infrastructure safer (e.g., segregating buses from mixed traffic, prohibiting certain turning movements, or shortening pedestrian crosswalks). Second, transit priority typically also makes transit a more attractive option. Especially in the Latin American context, BRT implementation also results in increasing the operational productivity of transit (measured in boardings per bus-kilometer). These impacts are discussed in detail and quantified in chapter 5.3.

Using the data from Table 14, we developed estimates for the expected safety effect of transit priority features using the log-odds method of data analysis. The methodology for developing the estimates is presented in detail in chapter 5.3. Table 1 shows the weighted mean safety effect and 95% confidence interval for several types of transit priority features around the world. One of the reasons that BRT projects in the developing world show a much greater impact on safety compared to some HOV lane conversions in the developed world is the improvements to street geometry and accessibility that accompany such projects.

Table 14 Safety impact of different types of bus systems

City	Before	After	Corridor and length (km)	Safety impacts, per year, per km (percent change in parenthesis)		
				Crashes	Injuries	Fatalities
			INFORMAL TRANSIT TO BRT			
Ahmedabad[a]	Informal transit	Single lane BRT	Janmarg system (49 km)	-2.8 (-32%)	-1.5 (-28%)	-1.3 (-55%)
Mexico City[b]	Informal transit	Single lane BRT	Metrobús Line 3 (17 km)	+7.5 (+11%)	-6.7 (-38%)	- 0.3 (-38%)
			EXISTING BUS PRIORITY TO BRT			
Guadalajara[c]	Bus priority lane	BRT with overtaking lane	Macrobus (16 km)	-83.19 (-56%)	-4.1 (-69%)	-0.2 (-68%)
Bogota[d]	Busway	Multi-lane BRT	Av. Caracas (28 km)	n/a	-12.1 (-39%)	-0.9 (-48%)
			IMPROVEMENTS TO CONVENTIONAL BUS SERVICE			
Melbourne[e]	Conventional bus	Queue jumpers, signal priority	SmartBus Routes 900, 903 (88.5 km)	-0.09 (-11%)	-0.1 (-25%)	-0.03 (-100%)

Notes: [a] EMBARQ analysis, based on data provided by the Center for Environmental Planning and Technology (CEPT), Ahmedabad. [b] EMBARQ analysis, based on data provided by the Government of the Federal District of Mexico; [c] EMBARQ analysis, based on data provided by the Jalisco State Secretariat for Roadways and Transport and the Department of Public Health at the University of Guadalajara; [d] EMBARQ analysis, based on data provided by TRANSMILENIO S.A. and based on data from Bocarejo et al. 2012; [e] Source: Goh et al. 2013

The values for both the best estimate and the 95% confidence interval in Table 1 should be interpreted as the percent reduction in crashes by severity that can be attributed to a particular type of transit priority feature.

The estimates are based on data from the Metrobús BRT in Mexico City, the Macrobús BRT in Guadalajara, the TransMilenio BRT in Bogotá, and the Janmarg BRT in Ahmedabad. The extent to which these estimates are applicable to new projects depends on how similar these projects are to the examples cited above.

10.1.1 Evaluating the economic impact of safety effects

There is no single methodology available in the literature for determining the cost of a traffic crash. There are several methods available, which can yield very different estimates. In addition, most of the literature on the cost of crashes comes from the developed world (e.g., Blincoe et al. 2002; BITRE 2009), and there is a gap in knowledge regarding the cost of crashes in low- and middle-income countries. In the absence of local estimates, the cost of crashes in emerging economies is typically estimated through benefits transfer (i.e., using a reference value from a study in the developed world and finding an appropriate way to adapt the value to the context of a developing country). In this section

Table 15 VSL values and ranges from the developed world

VSL estimate (in 2012 USD)	Country or region to which VSL applies	VSL source
(1,200,000 – 4,130,000)	European Union	Harmonized European Approaches for Transport Costing and Project Assessment (HEATCO)
2,620,000	Australia	Australian Bureau of Infrastructure, Transport, and Regional Economics (BITRE)
2,740,000	United Kingdom	UK Department for Transport (DfT), Transport Analysis Guidance (TAG)
7,060,000	United States	US Department of Transportation (DOT)
8,430,000	United States	US Environmental Protection Agency (EPA)

we discuss methodologies for benefits transfer and present different possible sources for reference values, focusing on fatal and injury crashes.

Multiple components make up the cost of a traffic crash. In a study for the US National Highway Traffic Safety Administration (NHTSA), Blincoe et al. (2002) identify the following components of crash costs: lost income for crash victims, lost income for other household members, medical expenses, property damage, insurance costs, workplace costs, and legal fees. In addition, Cropper and Sahin (2009) highlight the importance of also valuing the loss of life and the loss of quality of life, which is typically done using concepts such as the value of a statistical life (VSL), or quality adjusted life years (QALY).

The value of a statistical life (VSL) is typically defined as the sum of what individuals across a population would be willing to pay for reductions in risk, which, together, would result in one fatality avoided for the entire population (Cropper and Sahin 2009). VSL should be interpreted not as the value assigned to the life of an individual but rather as the value of risk reductions that can result in one less fatality over a given population. There are multiple ways of estimating VSL, ranging from willingness to pay to foregone earnings, or to estimates based on gross domestic product (GDP) per capita. The wide range of methodologies available is also reflected in the wide range of VSL values available in the literature. Table 15 shows different estimates of VSL from some of the leading agencies providing transport and environmental analysis guidance in the developed world.

VSL estimates vary widely between different countries or agencies within the same country. Moreover, agencies are constantly revising their VSL estimates, a fact that contributes to the difficulty of selecting an appropriate value, especially when considering transferring the value to the developing world. We offer two recommendations for addressing the issue of the “correct” VSL to use. First, it is important to use the same VSL in all components of a cost-benefit analysis for the same project (i.e., safety, air quality, physical activity impacts). But it would also be useful to conduct a sensitivity analysis to check the extent to which variations in the VSL used impact a project’s net present value of benefit-cost ratio.

When transferring a VSL estimate to another country, the most common methodology is to assume that since VSL is typically conceptualized as willingness to pay for risk reductions, differences in VSL among countries should be proportional to gross national income (GNI). A common formula for transferring VSL from a reference country to country *i* is shown in the equation below, adapted from Esperato, Bishai, and Hyder 2012; and Cropper and Sahin 2009:

$$VSL_i = VSL_{reference} \times \frac{GNIi}{GNI_{reference}} \times \varepsilon$$

Where

VSL_i = the value of a statistical life in country ***i***

$VSL_{reference}$ = the value of a statistical life in the reference country

GNI_i *and* $GNI_{reference}$ = the gross national income in country ***i*** and in the reference country, respectively

ε = coefficient taking values in the range of 1 to 1.5, to offer a range of possible VSL estimates that better account for the uncertainty involved in benefits transfer

The gap in knowledge about the cost of traffic fatalities in the developing world also extends to traffic injuries. The issue is further complicated by the poor quality of injury data available. Injury costs vary significantly with the severity of the injury, which is why it is important to have a clear, standardized scale of injury severity in order to be able to estimate costs.

One such system is the Abbreviated Injury Scale (AIS), an anatomical scoring system that ranks injuries on a scale of 1 to 6, where 1 represents a minor injury and 6 a fatality. Research in the United States assigns average costs to different AIS ranks, both in absolute value and as a fraction of the cost of a fatality (e.g., Blincoe et al. 2002).

However, most of disaggregate crash data available, usually from traffic police reports, do not use the AIS system for ranking injury severity. Most often, the reports distinguish between fatalities, injuries, and property damage only (PDO) crashes, with no mention of injury severity. This is an important limitation in developing robust estimates of injury costs in the developing world, and it illustrates a clear need both for more research in this area and for improvements in crash data collection systems. A possible source to use for the average cost of a traffic injury is provided in the UK Department for Transport's (DfT) Transport Analysis Guidance, shown in Table 16.

Table 16 Cost of traffic injuries, based on DfT's Transport Analysis Guidance (TAG)

Type of injury	**Injury cost**	
	Total cost (2012 USD)	Cost as fraction of the cost of a fatality
Average across all injury types	84,835	0.03
Slight injury	24,402	0.008
Serious injury	316,681	0.112

10.1.2 Safety impacts compared to other benefits of transit priority schemes

Based on our experience conducting cost-benefit analyses for transit priority projects in Latin America, we estimate that, on average, safety improvements account for around 8% to 16% of the economic benefits of a bus rapid transit system (Figure 83).

The variation between the two scenarios results from the large difference between the various possible values that can be used for VSL. However, the use of different VSLs does not change the fact that safety improvements are typically the third-highest benefit, after travel time savings for transit users and reduced transit operating costs. This highlights the importance of including safety impacts as part of cost-benefit analyses for BRT projects, since this is one of the main impacts in terms of magnitude, and the omission of the safety component can significantly reduce the benefit to cost ratio for a given project. We do not currently have similar estimates for other types of transit priority schemes, and this is an area that will require further research, especially in terms of developing local estimates for cities in the developing world.

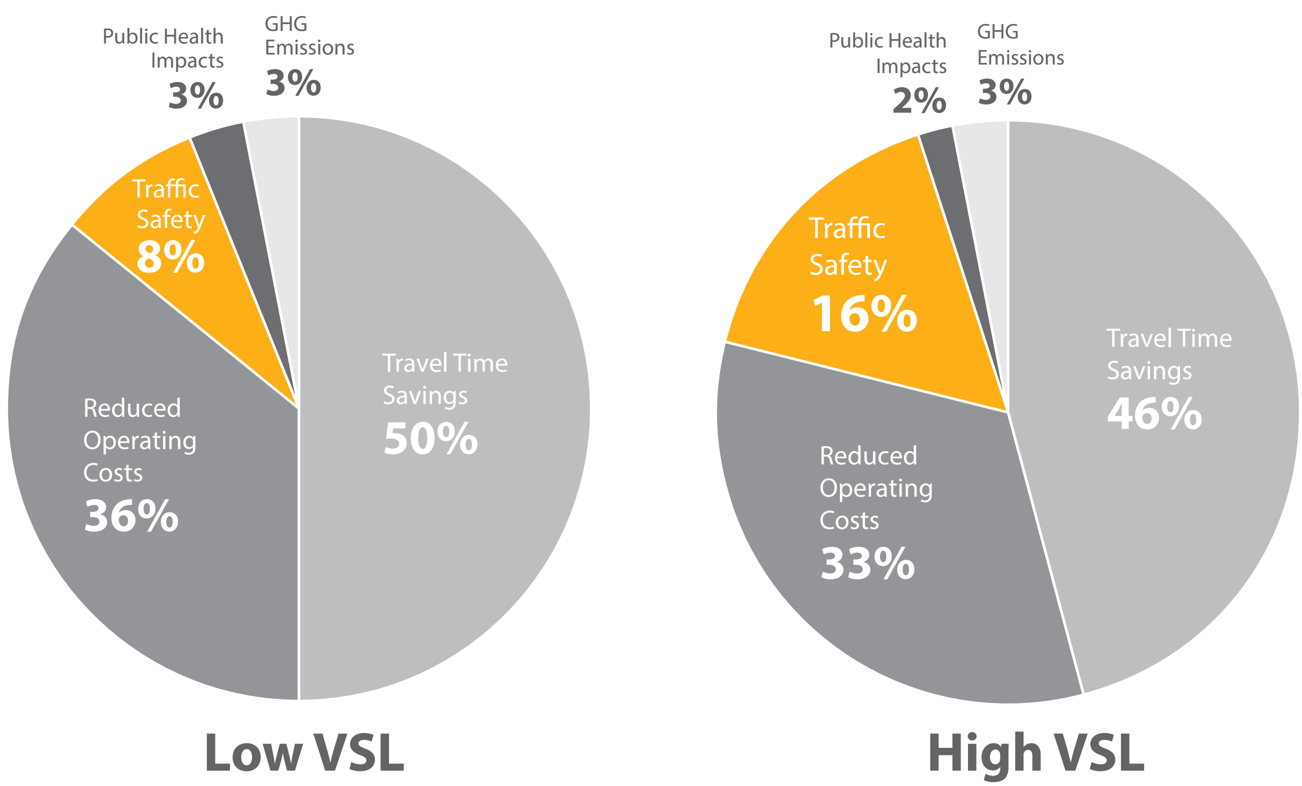


Figure 83 Safety benefits as a percentage of the total economic benefits of a bus rapid transit system

Source: EMBARQ analysis, based on estimates of benefits for BRT systems including Metrobús (Mexico City) and TransMilenio (Bogotá) (Carrigan et al. 2013). The "low-VSL" scenario estimates safety benefits using a reference VSL of USD 3.81 million, based on Esperato, Bishai, and Hyder 2012; whereas the "high-VSL" scenario uses a reference VSL of USD 8.4 million, based on the value used by the US EPA.

10.2 UNDERSTANDING THE FACTORS THAT CONTRIBUTE TO SAFETY IMPACTS

In general, more advanced transit priority, such as BRT and the combination of queue jumpers and signal priority, appears to have a better safety impact than the examples from the United States, which generally include shared lanes for buses and other vehicles. The results from Table 1 show a wide range of possible safety impacts from these different transit priority schemes. Our research shows that 90% of the crashes on bus corridors did not involve buses and occurred outside of the bus lanes. This shows that other factors involving the design of the general traffic lanes may be contributing to crashes. We sought to better understand the factors that contribute to the different safety records of various transit priority schemes, with a focus on developing world cities. We therefore collected and analyzed crash data from cities with transit priority schemes in Latin America and Asia. We present the detailed results of this analysis in this chapter.

10.2.1 Data sources

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., 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 relatively minor events 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 3 to 7 years, depending on the city.

On streets with dedicated median bus lanes, the **vast majority of crashes occur outside of the bus lanes** and do not involve buses

10.2.2 Study methodology

The key component of our evaluation was crash data analysis. Because of 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 permitted at each intersection, the results were not as consistent.

We selected crash frequency modeling as the appropriate statistical technique. This 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, after controlling for exposure—that is, the number of vehicles or pedestrians.

Crash data are count variables, which are usually best represented by a Poisson distribution (Ladrón de Guevara, Washington, and Oh 2004). However, previous studies have noted that crash data are also overdispersed (i.e., the variance is much larger than the mean) and therefore are better represented by a negative binomial distribution (also known as Poisson-Gamma), which, unlike Poisson, allows the variance to differ from the mean (Dumbaugh and Rae 2009). For this reason the negative binomial (NB) is the preferred probability distribution for modeling crash frequencies in most cases. 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 overdispersed. In this case we used a Poisson regression instead.

The scale at which to develop the models was an important decision. Previous studies have developed crash frequency models at very different scales, ranging from intersection models to neighborhood models, and even zip code–level crash models. 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 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 midblock 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 unable to separate intersection and midblock crashes, we decided to create separate variables for intersection and street design characteristics, to separate their impact on crashes. Therefore, variables such as the number of legs, the number of left turns, or lane imbalance characterize intersection geometry, whereas the number of lanes or the presence of a central median refer to the street layout. We also created a dummy variable for a counterflow configuration for bus lanes.

Only four of the cities had sufficient data to develop statistical models: Mexico City, Guadalajara, Bogotá, and Porto Alegre. The location reporting system is much better in some Brazilian cities and includes geographical coordinates as well as a clear distinction between intersection and midblock crashes. In order to remain as consistent as possible in the analysis across the different case studies, we decided to develop intersection models for Porto Alegre.

The same variables can have different safety impacts on different types of crashes and different injury severity levels. For this reason, we developed crash frequency models by crash type (e.g., motor vehicle collisions, pedestrian crashes) and crashes causing either fatalities or injuries to isolate severe crashes.

10.2.3 Findings from crash frequency models

Poisson and NB models predict the natural log of the dependent variable. To estimate safety impacts we used the incidence-rate ratio (IRR) interpretation of the coefficients, obtained by exponentiation of the coefficients. The IRR can be directly interpreted as a percent change in crashes corresponding to a unit change in the independent variable. We then estimated the weighted mean safety impact of each of the variables across the four cities (Mexico City, Guadalajara, Bogotá, and Porto Alegre) using the log-odds method of meta-analysis (see Elvik and Vaa 2008 for more details). The weights corresponded to the standard error of the IRR from each study. This provides an estimate for a mean impact on safety for each design and traffic variable we considered as shown in the table below, as well as the 95% confidence interval. A positive sign for a coefficient indicates a higher crash rate, whereas a negative sign indicates a feature associated with a lower crash rate.

10.2.4 The impact of bus system configuration on safety

Counterflow bus lanes in all cases were significantly correlated with higher crash rates for both vehicles and pedestrians (Table 17). The consistency of the results across the different models suggests that for the cities in this study, counterflow lanes are a dangerous configuration for bus systems. This conclusion was further substantiated by data analysis

Table 17 Weighted mean impact based on coefficients from negative binomial and Poisson crash frequency models from Mexico City, Porto Alegre, Guadalajara, and Bogotá

	Weighted mean impact	% change in crashes	95% Confidence Interval
Each additional approach	Fatal or injury crashes	+78%	(+56%, +103%)
	Vehicle collisions	+65%	(+46%, +87%)
Converting a 4-way intersection into two T-junctions	Fatal or injury crashes	-66%	(-88%, -1%)
	All crashes	-57%	(-70%, -37%)
Each additional lane	Fatal or injury crashes	+17%	(+12%, +21%)
	Vehicle collisions	+14%	(+10%, + 18%)
Crosswalk length (each additional meter)	Fatal or injury crashes	+2%	(+0.04%, + 4%)
	Pedestrian crashes	+6%	(+2%, +9%)
Each additional left turn movement allowed	Fatal or injury crashes	+28%	(+14%, +48%)
	Vehicle collisions	+35%	(+11%, +75%)
Presence of a central median	Fatal or injury crashes	-35%	(-55%, -8%)
	Vehicle collisions	-43%	(-56%, -26%)
Market area	Pedestrian crashes	+94%	Not available*
Counterflow bus lane	Fatal or injury crashes	+83%	(+23%, +171%)
	Vehicle collisions	+35%	(+0.02%, +86%)
	Pedestrian crashes	+146%	(+59%, +296%)
Major T junction	Vehicle collisions	+112%	(+27%, +253%)
Block length (every 10 meter increase)	Fatal or injury crashes	+3%	(+1%, +5%)
	All crashes	-2%	(-4%, -0.03%)
	Pedestrian crashes	+5%	(+1%, +8%)
Pedestrian bridge on expressway	Pedestrian crashes	-84%	(-94%, -55%)
Pedestrian bridge on arterial road	Pedestrian crashes	+67%**	(-23%, +262%)

*from Duduta et al. 2012 ** not statistically significant at the 95% confidence level

in cities for which statistical models could not be developed. For example, a section of the South Line in Curitiba, Brazil, that features a counterflow lane had four times the number of crashes per lane kilometer as the rest of the South Line, which has a center-lane configuration. The next section gives more details about counterflow lanes.

In Table 1 we showed that the implementation of BRTs in several cities around the world resulted in a statistically significant reduction in the number of crashes at all severity levels. However, in the crash frequency models, a dummy variable associated with the presence of a BRT did not have a statistically significant impact on crashes and was therefore not

included in the model. A similar dummy variable for curbside bus lanes showed a correlation with increased crash rates, indicating that they may pose safety risks.

The results suggest that safety has been improved not by the presence of the BRT itself but by the changes to street geometry necessary to accommodate the BRT. Indeed, accommodating a BRT on a street involves creating or widening a central median, thus shortening pedestrian crosswalks and transforming some four-way intersections into T-junctions. It also involves eliminating at least two, and often up to four, mixed traffic lanes in order to accommodate the transit infrastructure (lanes and stations). The variables for the changes described above (fewer approaches per intersection, fewer lanes, shorter crosswalks, a central median) were all associated with lower crash frequencies and statistically significant across all the models (Table 17).

10.2.5 Counterflow lanes

Counterflow bus lanes (Figure 84) are typically built in situations where a transport agency seeks to implement two-way bus service on a street that previously had a one-way configuration for mixed traffic. A common solution in Latin American cities has been to keep the one-way configuration for mixed traffic and add two-way bus lanes, either in the center of the street (e.g., Eje 4 Sur, Mexico City) or on the curbside (e.g., Eje Central, Mexico City). Accommodating left turns more conveniently is another common reason for using counterflow. Indeed, vehicles can usually turn left from a counterflow lane without requiring a protected signal phase.

Various street configurations can be categorized as counterflow (Figure 84). They all have in common the fact that vehicle and pedestrian traffic crossing a street with counterflow will have difficulty understanding the traffic pattern.

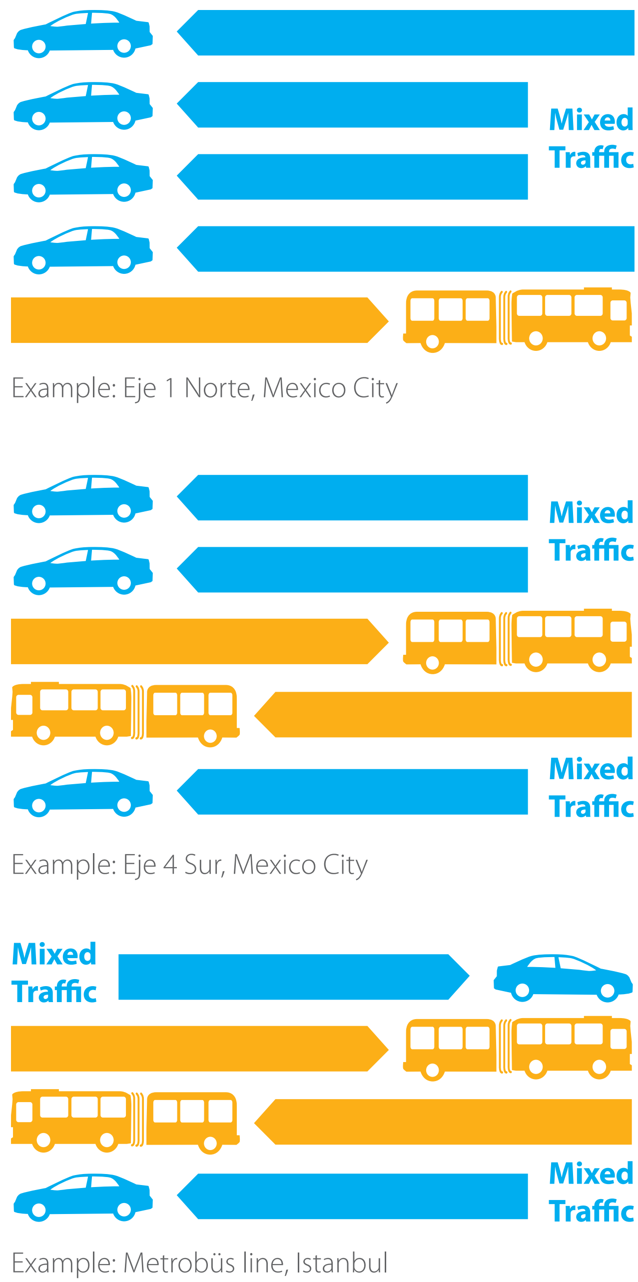


Figure 84 Examples of counterflow configurations with bus lanes

Our research indicates that counterflow lanes are associated with an increase in crashes at all severity levels (+83% fatal or injury crashes, +146% pedestrian crashes, +35% vehicle collisions). Observations from road safety audits and inspections carried out on urban roads across Latin America also suggest that counterflow lanes compromise road safety. The main risk lies in the fact that counterflow is an unexpected configuration, and many road users may not anticipate vehicles arriving from a counterflow direction.

We recommend avoiding counterflow configurations whenever possible and using instead a typical one-way or two-way lane arrangement for streets with bus priority systems. If two-way bus lanes are to be accommodated on a one-way street, the best solution is to make the entire street two-way, including the mixed traffic lanes. Issues with left turns should be solved by increasing the length of the protected left-turn phase or by replacing left turns with a loop. Counterflow should not be considered as an option for better accommodating left turns.

Mexico City has recently taken steps to replace existing counterflow lanes. One of the best examples is on Eje 3 Oriente Eduardo Molina, where the city recently implemented Line 5 of the Metrobús BRT system. The street featured a complex counterflow lane arrangement, with counterflow in the center lanes and normal flow in the curbside lanes (Figure 85). When Metrobús Line 5 was implemented, the lanes were shifted to a typical two-way configuration (Figure 86) and left turns were eliminated and replaced with loops. Our research suggests that this change should improve safety significantly.

Figure 85 Eje 3 Oriente Eduardo Molina before intervention, showing counterflow configuration and a switch in driving direction

Figure 86 Eje 3 Oriente after intervention, showing BRT lanes for Metrobús Line 5 and improved pedestrian infrastructure

10.2.6 Impact of street geometry on safety

As expected, the model results indicate that the size and complexity of intersections along a bus corridor are better predictors of crash frequencies than the configuration of the bus system. Only about 9% of all crashes occurred in the bus lanes; the vast majority occurred in the general traffic lanes and did not involve buses.

Key issues include the number of approaches per intersection, 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. In other words, turning a standard four-way intersection into two T-junctions by continuing the median on the main street should improve safety. This is only the case, however, if the intersection remains signalized. Often on BRT corridors, traffic signals are eliminated at the intersection if the cross street is blocked, and so are the crosswalks. This can allow buses to continue through the intersection with no delays, but it puts pedestrians at higher risk.

10.2.7 The impact of block size and speed

Speed is recognized as one of the key risk factors in traffic safety. Our crash frequency models could not account directly for speed as an independent variable, since no speed measurements were available for the street sections included in our sample. However, we were able to test the impact of speed by using a proxy: distance between signalized intersections. Indeed, the spacing of traffic signals is a key predictor of travel speeds. Table 17 shows the results of crash frequency models for different levels of crash severity. The findings from Guadalajara indicate that sections with longer distances between signalized intersections (and therefore higher speeds) have a lower incidence of crashes overall. This is explained by the fact that fewer intersections along the sections result in fewer conflict points. However, while there were fewer crashes overall, those crashes that did happen were more severe and more likely to involve pedestrians. In fact, the model results suggest that for each 10 additional meters between signalized intersections, there is a 2% decrease in total crashes but a 3% increase in severe crashes and 5% increase in pedestrian crashes.

10.2.8 The impact of land uses around the corridor on safety

Similar streets in different land use contexts can have very different safety records. Our model for Mexico City confirmed this by indicating that land uses are significant predictors of crash frequencies. The presence of a major market near the corridor was one of the strongest predictors of pedestrian crashes in Mexico City and was related to a 94% increase in pedestrian crashes in the area near Merced market (details in Duduta et al. 2012). Increases in pedestrian crashes in these areas result not only from higher pedestrian volumes but also from additional risks related to the configuration of the market. Near 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, forcing some pedestrians to walk in the traffic lanes and reducing visibility for drivers. This example underlines the importance of considering the urban context of a street in its design, a key factor in our design recommendations.

Definitions

The term **bus rapid transit (BRT)** has been applied to transit systems with very different characteristics, and the terms **BRT** and **busway** are sometimes used interchangeably in the literature. In this section, we clarify the definitions for these and other common terms related to bus transit that we use throughout the report.

We use the term **conventional bus service** to refer to buses operating in mixed traffic conditions without any dedicated lanes or signal priority and featuring onboard fare collection. This is the most common type of bus service around the world. From an institutional point of view, this typically refers to public buses operated by a municipal transit agency (a situation common in European and North American cities). We distinguish this from **informal transit service**, which is a more common arrangement in some cities in Africa or Latin America. This usually involves privately owned vehicles (commonly vans or minibuses) operating under various levels of regulatory oversight from the municipal government.

Institutional differences between conventional and informal transit play a significant role in safety. Informal transit providers often compete with one another for passengers without any direct oversight for operational safety. They often do not use fixed bus stops or stations, further increasing risks. Conventional bus services, on the other hand, have no incentive to compete for passengers, and benefit from having a single operating agency, which can oversee safety issues, maintenance, and driver training.

The term **transit priority** refers not to a specific type of infrastructure but to a category of infrastructure improvements aimed at prioritizing buses over the rest of traffic and which includes features such as bus priority lanes, dedicated bus lanes, peak-hour bus lanes, queue jumpers, signal priority, and busways.

We use the term **bus priority lane** to refer to lanes set aside for buses that can also be used by other vehicles under certain conditions. The most common type of bus priority lane is a curbside lane that can be used by buses and also by vehicles making right turns.[6]

A **dedicated bus lane** is set aside for the exclusive use of buses, and no other nonemergency vehicles are allowed to use it at any time. A **peak-hour bus lane** is only set aside as a priority or dedicated bus lane during the peak hour. Typically, a street may feature a peak-hour bus lane in one direction for the morning rush hour and in the opposite direction for the afternoon rush hour.

A **counterflow bus lane** refers to any type of bus lane (i.e., priority, peak-hour, dedicated) that operates in a counterflow situation. There are three types of layouts that we classify as counterflow in this study:

- A multilane one-way street for mixed traffic that also features a single curbside bus lane traveling in the direction opposite to mixed traffic (e.g., Eje Central, Mexico City)
- A layout involving bidirectional mixed traffic lanes on one side of the street and bidirectional bus lanes on the opposite side of the street (e.g., the Brisbane Busway, some of the BRT routes in Curitiba)
- A bidirectional BRT in the center of a one-way mixed traffic street (e.g., Metrobús Line 2 on Eje 4 Sur, Mexico City)

A **queue jumper** is a geometrical design feature that allows buses to bypass mixed traffic at a signalized intersection. The most typical arrangement involves adding a dedicated bus lane on the approach to an intersection, which the bus can use to move to the front of the queue and minimize delay. It can be associated with **signal priority**. We use the term here to refer to active priority features such as actuated signals (i.e., signals able to detect an approaching bus and switch its signal to green).

We use **busway** to refer to situations where a street features dedicated bus infrastructure (lanes and stations) in the center of the roadway or on its own right-of-way. Some typical examples include the busway in Delhi or the busways on Avenida Protásio Alves or Avenida Bento Gonçalves in Porto Alegre. The main difference between a busway and **bus rapid transit (BRT)** is that the latter features several other improvements to quality of service, most commonly including offboard fare collection, level boarding, and centralized operations control. Typical BRT examples include TransMilenio in Bogotá, Metrobús in Mexico City, or Janmarg in Ahmedabad.

We further distinguish between different types of BRTs and busways. A **single-lane** BRT or busway features one dedicated bus lane per direction (e.g., Metrobús, Mexico City). A BRT or busway with **overtaking lanes** typically features a single lane between stations and an additional lane at stations to allow for express services that bypass some stations (e.g., TransOeste, Rio de Janeiro; Macrobús, Guadalajara). Finally, a **multilane** BRT or busway features at least two dedicated bus lanes per direction for most or all the length of a corridor (e.g., TransMilenio, Bogotá).

Acknowledgments

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, the road test process, 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. Qianqian Zhang of the Massachusetts Institute of Technology contributed to the research on pedestrian behavior at signalized intersections. Paula Manoela dos Santos da Rocha of EMBARQ Brazil contributed to the analysis of impacts of safety countermeasures on operational performance, using the EMBARQ BRT Simulator.

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

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 regarding the Metrobús system.

Mario Alberto Valbuena Gutiérrez, Director of Operations, along with Safety Director Carlos Gutiérrez, as well as Martín Salamanca and Jaison Lucumí of TRANSMILENIO S.A. shared their crash database for the TransMilenio BRT system in Bogotá and accompanied EMBARQ staff on an inspection of a TransMilenio corridor. Myriam Haidee Carvajal López and Beatriz Elena Jurado Flóres from the Colombian Ministry of Transport provided 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 Brazil coordinated data collection in Brazilian cities and participated in audits and inspections of Brazilian BRT systems that provided valuable input to this guidebook. Empresa Pública de Transporte e Circulação (EPTC) and Matricial Engenharia Consultiva Ltda. provided 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 São 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.

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

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

Alexandre Castro, Operations Manager for Rio Ônibus, shared his experience regarding operations and safety on Rio de Janeiro's TransOeste BRT corridor as part of a road safety inspection.

Luis Rizzi and Diego Pinto from the Pontificia Universidad Católica de Chile provided access to a crash dataset for the Transantiago bus system in Santiago de Chile and also provided valuable comments for this guidebook.

Ali Doğan Şalva, Elif Can Yüce, and Serdar Oncel from EMBARQ Turkey coordinated data collection for Istanbul and participated in road safety inspections of the Metrobüs BRT in Istanbul. Mümin Kahveci and his staff at Istanbul Elektrik Tramvay ve Tünel (IETT, Istanbul's transit agency) shared crash data as well as their experience regarding safety and operations on the Metrobüs BRT, and also supported a Turkish translation of the pilot version of this document.

The authors would like to thank Tawia Addo Ashong of the World Bank's Global Road Safety Facility (GRSF) and Karla Gonzalez Carvajal of the World Bank for hosting workshops and training sessions around this guidebook in Washington, DC, and in Addis Ababa, which provided the opportunity to receive valuable feedback on this guidebook from experts and local stakeholders.

The authors would also like to acknowledge valuable comments by Fred Wegman, Jacques Commandeur, and Atze Dijkstra (SWOV—the Dutch National Institute for Road Safety Research), Steve Lawson (iRAP), Tony Bliss, Said Dahdah, Sam Zimmerman, O. P. Agarwal (World Bank), Subu Kamal, Sanjay Vadgama (Transport Research Laboratory), Lilia Blades (UN Habitat), César Durán Arróspide (Municipality of Arequipa, Peru), Juan Carlos Muñoz (Pontificia Universidad Católica de Chile), Alexandra Rojas and Claudia Puentes (Fondo de Prevención Vial, Colombia), Janet Ranganathan, Holger Dalkmann, Clayton Lane, David Tomberlin, Benjamin Welle, Aileen Carrigan, Aaron Minnick, Benoit Colin, Heshuang Zeng, Katherine Filardo (World Resources Institute), Paulo Custodio, and Gerhard Menckhoff.

References

Barnett, A. G., J. C. van der Pols, and A. J. Dobson. 2004. "Regression to the Mean: What It Is and How to Deal with It." *International Journal of Epidemiology* 34, no. 1: 215–20.

BITRE (Bureau of Infrastructure, Transport, and Regional Economics). 2009. *Road Crash Costs in Australia, 2006*. Report 118. Canberra: BITRE, November.

Blincoe, L. J., A. G. Seay, E. Zaloshnja, T. R. Miller, E. O. Romano, S. Luchter, and R. S. Spicer. 2002. *The Economic Impact of Motor Vehicle Crashes, 2000*. Report DOT HS 809 446. Washington, DC: U.S. Department of Transportation, National Highway Traffic Safety Administration.

Bocarejo, J. P., J. M. Velasquez, C. A. Diaz, and L. E. Tafur. 2012. "Impact of BRT Systems on Road Safety: Lessons from Bogota." Paper presented at Transportation Research Board Annual Meeting, Washington DC.

Carrigan, A., R. King, J. M. Velasquez, M. Raifman, and N. Duduta. 2013. *The Social, Environmental, and Economic Impacts of BRT Systems*. Washington, DC: EMBARQ.

Cooper, J., R. J. Schneider, S. Ryan, and S. Co. 2012. "Documenting Targeted Behaviors Associated with Pedestrian Safety." Paper presented at the 91st Transportation Research Board Annual Meeting, Washington, DC, January.

Cropper, M., and S. Sahin. 2012. "Valuing Mortality and Morbidity in the Context of Disaster Risks." Background paper for the joint World Bank–UN Assessment on Disaster Risk Reduction, Washington, DC.

Diogenes, M. C., and L. A. Lindau. 2010. "Evaluating Pedestrian Safety at Midblock Crossings in Porto Alegre, Brazil." *Transportation Research Record: Journal of the Transportation Research Board*, no. 2193: 37–43.

Duduta, N., C. Adriazola-Steil, D. Hidalgo, L. A. Lindau, and R. Jaffe. 2012. "Understanding the Road Safety Impact of High Performance BRT and Busway Design Characteristics." *Transportation Research Record* 2317: 8–16.

Duduta, N., C. Adriazola-Steil, D. Hidalgo, L. A. Lindau, and P. dos Santos da Rocha. 2013. "The Relationship between Safety, Capacity, and Operating Speed on Bus Rapid Transit." Paper presented at the 13th World Conference on Transport Research (WCTR), Rio de Janeiro.

Duduta, N., L. A. Lindau, and C. Adriazola-Steil. 2013. "Using Empirical Bayes to Estimate the Safety Impacts of Transit Improvements in Latin America." Paper presented at the International Conference in Road Safety and Simulation, RSS 2013, Rome.

Duduta, N., Q. Zhang, and M. Kroneberger. Forthoming 2014. "The Impact of Intersection Design on Pedestrians' Decision to Cross on Red." Transportation Research Record.

Dumbaugh, Eric, and R. Rae. 2009. "Safe Urban Form: Revisiting the Relationship between Community Design and Traffic Safety." *Journal of the American Planning Association* 75, no. 3: 309–29.

Elvik, R., and T. Vaa. 2008. *The Handbook of Road Safety Measures*. Bingley, UK: Emerald Group.

Esperato, A., D. Bishai, and A. Hyder. 2012. "Projecting the Health and Economic Impact of Road Safety Initiatives: A Case Study of a Multi-country Project." *Traffic injury Prevention*, 13, suppl. 1: 82–89.

Goh, K. C. K., G. Currie, M. Sarvi, and D. Logan. 2013. "Investigating the Road Safety Impacts of Bus Rapid Transit Priority Measures." Paper presented at the Transportation Research Board 92nd Annual Meeting, Washington DC.

Hidalgo, D., and A. Carrigan. 2010. *Modernizing Public Transportation: Lessons Learned from Major Bus Improvements in Latin America and Asia*. Washington, DC: World Resources Institute.

Híjar, M., A. Chandran, R. Pérez-Núñez, J. C. Lunnen, J. M. Rodríguez-Hernández, and A. Hyder. 2011. "Quantifying the Underestimated Burden of Road Traffic Mortality in Mexico: A Comparison of Three Approaches." *Traffic Injury Prevention* 13, suppl. 1: 5–10.

Klaver Pecheux, K., and H. Saporta. 2009. "Light Rail Vehicle Collisions with Vehicles at Signalized Intersections: A Synthesis of Transit Practice." TCRP Synthesis 79. Washington, DC: Transportation Research Board.

Ladrón de Guevara, F., S. P. Washington, and J. Oh. 2004. "Forecasting Crashes at the Planning Level: Simultaneous Negative Binomial Crash Model Applied in Tucson, Arizona." *Transportation Research Record: Journal of the Transportation Research Board* 1897: 191–99.

Moreno González, E. G., M. G. Romana, and O. M. Alvaro. 2013. "Effectiveness of Reserved Bus Lanes in Arterials." Paper presented at the 92nd Transportation Research Board Annual Meeting, Washington, DC, January.

NACTO. 2011. *Urban Bikeway Design Guide*. Washington, DC.

Pereira, B. M., L. A. Lindau, and R. A. Castilho. 2010. "A importância de simular sistemas Bus Rapid Transit." In *Proceedings of XVI CLATPU*. Mexico City.

Rickert, T. 2007. *Bus Rapid Transit Accessibility Guidelines*. Washington, DC: World Bank.

Rosén, E., and U. Sander. 2009. "Pedestrian Fatality Risk as a Function of Car Impact Speed." *Accident Analysis & Prevention* 41, no. 3: 536–42.

Transportation Research Board (TRB). 2010. "Signalized Intersections. Pedestrian Mode." In *Highway Capacity Manual (HCM)*. Transportation Research Board, Washington, DC.

Vuchic, V. 2007. *Urban Transit: Systems and Technology*. Hoboken, NJ: Wiley and Sons.

WHO. 2013. *Global Status Report on Road Safety*. Geneva: World Health Organization.

Wright, L., and W. Hook, eds. 2007. *Bus Rapid Transit Planning Guide*, 3rd ed. New York: Institute for Transportation and Development Policy.

Yazıcı, M.A., H. Levinson, M. Ilıcalı, N. Camkesen, and C. Kamga. 2013. A Bus Rapid Transit Line Case Study: Istanbul's Metrobüs System. *Journal of Public Transportation* 16, no. 1,153-177

Zhou, Z., G. Ren, W. Wang, Z. Yong, and W. Wang. 2011. "Pedestrian Crossing Behaviors at Signalized Intersections: Observational Study and Survey in China." Paper presented at the 90th Transportation Research Board Annual Meeting, Washington, DC, January.

Endnotes

1 See brtdata.org for information on the current state of BRT projects worldwide.

2 Estimated using the value of a statistical life (VSL; see chapter 10.1, for definition and details) based on cost-benefit analysis carried out for BRT systems in Mexico City and Bogotá (see Carrigan et al. 2013).

3 Sources: EMBARQ analysis; Duduta, Lindau, Adriazola-Steil 2013; Goh et al. 2013. Methods used include Empirical Bayes (Guadalajara and Melbourne), comparison of crash counts while controlling for citywide trends (Mexico City, Bogotá), and a simple before-after comparison of crash counts (Ahmedabad).

4 The description, calibration, and previous applications of the EMBARQ BRT Simulator can be found in Pereira, Lindau, and Castilho 2010.

5 EMBARQ estimate, based on the types of turnstiles and payment method used on the Istanbul Metrobüs BRT.

6 This refers to a situation in which traffic drives on the right-hand side of the road. Unless we specifically note otherwise, we always refer to situations in which traffic drives on the right in this report.

List of Figures

List of Tables

Photo Credits:

EMBARQ/ EMBARQ Mexico / EMBARQ Brazil
Cover, Inside cover, Figures: 8, 10, 13, 14, 16, 18, 19, 32, 43, 45, 46, 47, 48, 50, 52, 53, 54, 55, 56, 59, 61, 62, 63, 66, 69, 71, 78, 85, 86
Pages: 10, 16, 17, 18, 22, 34, 58, 92, 93

Guadalajara BRT: Bernardo Baranda Sepúlveda/ ITDP 2009 Flickr Image
Figure: 2

Lucho Molina- Flickr Image
Figure: 56

Map data: Google, DigitalGlobe, INEGI
Page: 76

Map data: Google, DigitalGlobe
Figure: 74, 80

ISBN: 978-1-56973-830-6

EMBARQ, part of the WRI Ross Center for Sustainable Cities, is a global network that helps cities make sustainable transport a reality.

EMBARQ catalyzes and helps implement environmentally, socially and financially sustainable urban mobility and urban planning solutions to improve people's quality of life in cities. Founded in 2002 as a program of the World Resources Institute (WRI), EMBARQ operates through a global network based in Brazil, China, India, Mexico, and Turkey.

The EMBARQ network collaborates with local and national authorities, businesses, academics and civil society to reduce pollution, improve public health, and create safe, accessible and attractive urban public spaces and integrated transport systems. EMBARQ has built its global recognition on its local experience, and addressing national and international policies and finance. More information at www.embarq.org

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

Brasil
EMBARQ BRASIL
Av. Independência,
1299/ 401, Porto Alegre, RS,
Brasil 90035-077
+55 (51) 33126324

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

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

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

Türkiye
EMBARQ TÜRKIYE
Sürdürülebilir Ulaşım Derneği
Gümüşsuyu Mah. İnönü Cad.
No:29 Saadet Apt. Kat:6 D:7
Taksim, Beyoğlu, İstanbul
Tel: 0 (212) 243 53 05

A program of the
WORLD RESOURCES INSTITUTE

www.embarq.org