



Road Safety Design Guidelines for Bus Rapid Transit in Indian Cities

with consideration for local accessibility and traffic capacity

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1. BACKGROUND TO THE GUIDELINES

Bus Rapid Transit

In the last few decades, Bus Rapid Transit (BRT) has emerged as a cost-effective, flexible and environmentally sustainable form of public transportation. The world's first BRT was developed in Curitiba, Brazil, which was followed by the development of many other BRTs across Latin America, notably the TransMilenio BRT in Bogota, Colombia. Encouraged by the success of these systems, BRTs began to spring up in many cities across the globe. At the time of this writing, there are 146 cities worldwide operating a total number of 3,658 kilometers of BRT, serving just under 24,000,000 passengers per day. These numbers are expected to continue to grow.¹

In India, BRT has received considerable interest, spearheaded by the success of the Ahmedabad BRT. At present, more than 5 Indian cities are developing or augmenting their BRT systems. At the same time, BRT has met with some scepticism, due to the

¹ <http://www.brtdata.org/> accessed on 10.3.2012

perceived shortcomings of such systems in a couple of Indian cities.

The term, Bus Rapid Transit (BRT), has come to represent a wide range of bus-based, public transportation systems. Although these systems have commonalities, they may also have some very different features. Often, it is the decision of which BRT feature to include or exclude, that determines the success or failure of the system.



Picture 1: The TransMilenio BRT in Bogota, Colombia is an example of a system, with all the design features of a full-fledged BRT

For the purpose of these Guidelines, we have considered the most common definition of a

BRT system, which has, at least, all of the following features:

- Segregated bus lanes that are meant exclusively for BRT buses;
- Level-boarding at enclosed bus stations;
- Intelligent transport systems for commuter information and schedule optimisation;
- Centralised authority responsible for the development and operations of the BRT.

BRT and road safety

Road safety is emerging as a major concern, across the developing world, especially in India. India leads the world in the number of road fatalities, with over 130,000 reported each year. Since the country is rapidly urbanising, a growing proportion of these fatalities are beginning to occur in cities. Within cities, the most vulnerable road users are non-motorised transport users, such as pedestrians and bicyclists, who account for about half the share of road fatalities. The greatest perpetrators of road accidents tend to be larger vehicles, such as trucks and buses.

A BRT system typically improves the traffic safety scenario, because it segregates the movement of buses from all other transport modes, and also introduces other changes in the road infrastructure that are associated with safety, such as shorter pedestrian crossings and refuge islands. In particular, a central lane BRT places the buses away from the paths of pedestrians and bicyclists, who are the most vulnerable roads users. Thus, a well executed BRT can significantly reduce road accidents.

However, sometimes poorly designed BRT infrastructure may actually have the reverse impact on road safety, if it does not take into consideration its negative impact on local accessibility and vehicular capacity. These aspects of the BRT are discussed in the next two sections respectively.

BRT and accessibility

A BRT is, generally, built along existing roads with well established mobility and accessibility patterns. The BRT introduces segregated bus lanes, usually fenced off on both sides by guardrails. This segregation tends to impede local accessibility for other transport modes.

For example, the BRT guardrails limit opportunities for pedestrians to cross the road. Turning movements for vehicles also become restricted.

A BRT that does not take into consideration these impediments may actually end up worsening the road safety scenario. In the Indian context, where both traffic discipline and enforcement are minimal, road users may flout traffic rules and thus create a road safety risk, both for themselves and other road users.

For example, pedestrians may resort to jaywalking or jumping the guardrail in order to cross the road. Motor-vehicle drivers, in order to avoid a long detour to take a right turn or u-turn, may resort to driving in the wrong direction, or illegally turning through pedestrian crossings. This is, no doubt, very dangerous for all road users.

Thus, poor local accessibility causes road accidents. A BRT design that neglects the local accessibility needs of the population cannot be a safe system. Thus, while the focus of these Guidelines is on road safety, the problems of local accessibility are also considered, as the two issues are interrelated.

BRT and traffic capacity

A BRT lane generally carries many more times the number of people per lane than the mixed traffic lanes. Yet, the negative impact that BRT has on vehicular capacity is often cited as a criticism against BRT. Critics of BRT argue that the congestion faced by all other traffic completely offsets any benefit of time saved for BRT commuters. This has become a deal breaker for some BRTs in India.

Since a BRT is typically built along existing roads, some impact on mixed traffic capacity is unavoidable. However, if a BRT is designed well, it can minimise the negative impact, or better yet, improve throughput capacity. The development of the BRT results in reengineering the road, which may correct previous impediments that were affecting traffic flow. Further, the BRT restricts cross movement to an extent, which can also help in improving throughput capacity. Finally, the BRT takes slow-moving and frequently-stopping buses out of the traffic mix. This also helps to create a smoother traffic flow.

However, a poorly designed BRT creates unnecessary bottlenecks that reduce traffic capacity. This is especially true at

intersections, where poor traffic signal management further aggravates the situation.

If BRT projects are to find support in India, then it is necessary that the needs of vehicular traffic users are also addressed. Further, if adequate provisions for these roads users are made, then they will be less likely to break traffic rules; such as illegally driving on the BRT lanes. These infringements are also a big cause of road safety problems.

About the Guidelines

On the one hand, BRTs, like the Ahmedabad BRT, have demonstrated successes in providing cost-effective and efficient public transportation systems for emerging cities. On the other hand, BRT detractors have become more vocal about their arguments against BRT, fuelled by the shortcomings of a couple of BRTs in India.

BRT advocates state that it is the most viable public transport system for emerging cities, and the social benefits that accrue from the system far outweigh the negative impact on capacity for private motorised transport. At the same time, there is a growing recognition that for BRT to gain a wider acceptance by all

stakeholders, it needs to address the concerns of road safety, local accessibility and capacity for all road users.

It is this background that provides the context for these Guidelines. Although the focus of these Guidelines are on road safety, the impacts on local accessibility and road traffic capacity are also considered; as the neglect of the same are often the biggest causes of road safety problems along BRT corridors.

These Guidelines are developed out of EMBARQ's experience in conducting road safety audits on a number of BRTs in India and abroad. In India, EMBARQ conducted audits on the BRTs in Ahmedabad, New Delhi and Indore; and the observations from the same have been utilised in developing these Guidelines. Further, EMBARQ has conducted road safety audits on BRTs in North and South American cities, such as Bogota (Colombia), Arequipa (Peru), Mexico City (Mexico) and Rio de Janeiro (Brazil). In addition, in 2012, EMBARQ released draft Guidelines on "Traffic Safety on Bus Corridors", which addressed road safety on all bus corridors, (including BRT), in the international context, which has also been used in the development of the Indian Guidelines.

Structure of the Guidelines

The next chapter of these Guidelines provides our interpretation of the major safety issues for BRT in the Indian context. For instance, we consider the implications of such issues as heterogeneous traffic mix, poor traffic discipline, high pedestrian volume, prevalence of auto-rickshaws, etc. This chapter intends to juxtapose the Indian context against the generic International context, wherein it is argued that international road design best practices may not always be practical in the Indian context.

The subsequent chapter discusses general best practices for BRT design, wherein we consider issues such as: median BRT lanes v/s kerb side BRT lanes; full-fledged BRT v/s bus priority or bus way systems; regular flow v/s counterflow; safe design speed, etc.

We next illustrate our recommended templates for various sections along a BRT corridor. Each chapter is dedicated to one such element. We start with the basic midblock template. Each subsequent chapter introduces an additional feature, such as pedestrian crossings, u-turns, and BRT stations.

This is followed by chapters on BRT intersection design, wherein we cover both minor as well as major intersections. We also cover issues related to commuter transfers between BRT stations on intersecting BRT corridors.

We finally discuss some additional aspects of BRT corridors, such as express lane BRTs and BRT terminals

Each chapter consists of a general introduction to the issue at hand; followed by a 3-D, bird's-eye-view model, demonstrating our recommended design template for this element; followed by supporting information about the operational aspects of the proposed design.

Although the recommended design templates are focused on road safety, they also take into consideration the impacts on local accessibility and road capacity, both for the BRT and for mixed traffic. These impacts, and measures to minimise the same, have been provided for each sub-section, wherever they are applicable.

Unless otherwise stated, all the recommended templates used in these Guidelines, are

demonstrated on a fixed road width of 38 meters. BRTs in India are typically developed on urban arterials, with a width of 40 to 60 meters. By choosing a design width marginally below the lower spectrum, we intend to demonstrate how all the various elements of a BRT can be accommodated, without needing additional road width; and without eliminating or reducing the width of other road elements such as traffic lanes, NMT lane or footpath.

2. BRT IN THE INDIAN CONTEXT

In many ways, the transportation and traffic scenario in India is different from other countries in the world. Even among developing countries, there are some factors that are very unique to the Indian context. As a result, international best-practices for road safety and street design, especially from developed countries, may not always be relevant or practical in the Indian context. Sometimes, these recommendations may not achieve the desired result, or in other cases, they may even have the counter effect of worsening the road safety scenario.

In this chapter, we have documented some of these unique characteristics of transportation and traffic in the Indian scenario. These observations have influenced all the design recommendations that we have proposed in subsequent chapters.

Heterogeneous traffic mix

In India, especially in smaller cities, the passenger car is not the most dominant motor-vehicle. In many cities, motorised 2-wheelers far outnumber cars in the traffic mix.

There also tends to be a high proportion of autorickshaws, used both for passenger and freight transport. Added to this mix, is a wide assortment of buses, trucks and vans of all forms and sizes. Interspersed in between, are non-motorised transport users, as well as, in some cases, animal-powered transport.

Thus, road design standards that use the passenger car as the design unit are irrelevant in the Indian context. A road safety intervention that works perfectly for cars may be ineffective for motorbikes. For example, bollards placed along the ramps of footpaths, to prevent cars from mounting the footpath, are incapable of preventing motorbikes from doing the same.

Even road capacity calculations, based on Passenger Car Units (PCU) are not easily applicable to the Indian context. A heterogeneous traffic mix, with a high proportion of slow vehicles results in a lower capacity. On the other hand, a high proportion of motorised 2-wheelers may increase road capacity, because of the relative ease by which they can squeeze past other vehicles.



Picture 2: In modest Indian cities, cars are not the dominant motor-vehicle, and other vehicles, like motorbikes, tend to have a much larger share in the traffic mix.

Bicycles are not the only NMT mode

In most developed countries, bicycles are, virtually, the only form of non-motorised transport (NMT). In developing countries like India, apart from bicycles, there are a wide range of NMT modes, such as tricycles (for the disabled), cycle-rickshaws, vendor hand carts, push-carts, etc.

NMT infrastructure needs to be designed to be usable by all these modes. For example,

the NMT/bicycle lane needs to be wide enough to accommodate cycle-rickshaws street-vendor pushcarts. Similarly, bollard spacing at pedestrian crossings need to be wide enough to be accessible to larger NMT vehicles.



Picture 3: In most Indian cities, the bicycle is only one of many different NMT vehicles, such as tricycles, vendor push-carts, cycle-rickshaws, etc. NMT infrastructure needs to cater for all such vehicle types.

High pedestrian density

Indian cities are characterised by much higher pedestrian densities than most international cities, outside Asia. This influences the effectiveness of many design standards. For

example, in some western countries, it is acceptable for pedestrian crossings to share a signal phase with left-turning vehicles, because the number of pedestrians is not very high. But In the Indian context, this may not be possible due to the sheer volume of pedestrians, and poor traffic discipline, where motorists are unlikely to yield for crossing pedestrians.



Picture 4: Indian cities are characterised by high pedestrian densities. Adequate provision needs to be made for pedestrian movement; else they will spill onto the traffic lanes.

Poor traffic rules awareness, discipline and enforcement

In most Indian cities, traffic discipline is lacking, both by users of motorised and non-

motorised transport. The general awareness of traffic rules is also quite low. Enforcement is also difficult, given the high volume of vehicles and people, and the limited resources available to the traffic police.

As a result, traffic discipline cannot be taken as a given in the Indian context. As far as possible, roads must be designed so as to encourage and make it easier for people to understand and follow traffic rules. Concurrently, road features should be adopted, which make it difficult or impossible to break traffic rules. As far as possible, road design should dictate user behaviour, rather than relying on signage and information systems. Further, a systematic assessment needs to be made to understand why people flout traffic rules, and what simple measures can be made to encourage them to follow the rules.

Finally, the road should be designed along the principle of “forgiving infrastructure”; that means, in case a traffic rule is flouted, it should, as far as possible, not lead to a serious accident.



Picture 5: In the context of poor traffic discipline and enforcement in most Indian cities, road design should, as far as possible, dictate user behaviour. For example, provisions should be made to discourage or make it impossible for motorists to illegally use a pedestrian crossing to make a turn.

Abundant road edge development

BRTs, in most international cities, are built along major urban arterial roads that are meant to primarily serve thoroughfare traffic. Typically, these arterial roads are very wide, and have long continuous sections without an intersection. Moreover, there tends to be no direct access to properties from these roads. As a result, the demand for vehicles to make right turns or u-turns is quite low. Further, the lack of edge development results in very few

pedestrians using this road; so the required footpath width and required number of crossings are both quite low.

In Indian cities, most urban arterial corridors have abundant edge development along the road. These developments are a mixture of residential, institutional, commercial and retail users. As a result, the demand for right or u-turns, and the demand for pedestrian crossings, are both very high. Also, adequate space needs to be provided for vehicles to wait on the side of the road, to load or unload passengers or freight.

If adequate provisions are not made for these movements, then it encourages people to break traffic rules, posing a risk to themselves and others. For example, if there are not sufficient right or u-turn opportunities along a long section of the road, then motorists may be induced to illegally drive on the wrong side of the road. Since they are doing something illegal, the tendency is to do it very fast; this creates a risk of head-on collisions with oncoming vehicles, or colliding with pedestrians crossing the road.



Picture 6: Urban arterials in most Indian cities are characterised by extensive edge development that have direct access from the main arterial. Such development generates local demand for parking, waiting areas, u-turns, right turns, pedestrian crossings, etc

Street vendors and immovable obstructions along the road

Many roads in India are characterised by a high volume of street vendors. Often, these vendors locate themselves along the footpath, and their activities spill over to adjacent areas, such as the NMT lane or traffic lanes.

Further, there are many immovable, (or very difficult to move), obstacles along the road that impede the smooth flow of traffic and pedestrians. The obstacles could be in the

form of trees, utility boxes, street furniture, religious shrines, encroachments, etc. When faced with an obstacle, the road user leaves his/her path to make his/her way around the obstacle. This puts them into conflict with other vehicles.

These obstacles can also create bottlenecks that impact traffic flow. Traffic flow across a midblock is typically determined by the capacity limit at its most constrained point. This inconsistent width of the carriageway encourages excessive speeding in some sections, and leads to congestion-causing bottlenecks in other sections.



Picture 7: Obstructions on the footpath make them unusable for pedestrians.

Auto-rickshaws as the feeder system

Auto-rickshaws play an important role, as a para-transit vehicle, in most Indian cities. Yet the infrastructure for this sector is often neglected. This results in auto-rickshaws clustering around areas with a potentially high volume of customers. BRT stations, thus, typically tend to attract a high volume of auto-rickshaws. If proper infrastructure is not provided for them, they end up queuing along the carriageway. The carriageway width may already be constrained in order to accommodate the BRT station; thus the additional space taken away from the carriageway by the autorickshaws will only worsen the throughput capacity.

As vehicles and people jostle their way through these stretches, it creates road safety problems for all road users.



Picture 8: Autorickshaws are an important para-transit mode in most Indian cities. If adequate provisions are not made for their needs, they can cause both safety and traffic congestion problems.

3. GENERAL BRT DESIGN GUIDELINES

Overview

From 2010 to 2012, EMBARQ conducted an extensive research project, evaluating how different design options for bus corridors impacted pedestrian and traffic safety.² The findings from this research informed a set of planning and design guidelines for bus corridors, aimed at maximising safety, while considering impacts on passenger capacity, operating speeds, and accessibility. A pilot version of this guidebook, *Traffic Safety on Bus Corridors*, was released by EMBARQ in 2012, with a final version to follow in 2013.

We provide here an overview of the main findings on the safety aspects of BRT that have informed our recommendations. We discuss the safety aspects of various other bus systems, in comparison with the standard segregated central-lane BRT, such as:

- **Bus priority:** Here, buses, for the most part, ply within mixed traffic, but may be provided with some additional priorities, such as bus-only permitted turns, signal priority, etc.
- **Busways:** Here, buses run on exclusive lanes, generally on the kerb side, though not necessarily segregated
- **Counterflow systems:** Here buses ply in the opposite direction of mixed traffic. This is usually done when a busway runs in both directions on a one-way street.

The overall safety impact of a BRT

The overall safety impact of implementing a bus system on a corridor depends on the characteristics of the system and the existing conditions on the street. In developing world cities, implementing BRT systems has generally proven to have a positive impact on safety. Other types of corridors, such as busways or bus priority lanes, have not always had the same positive impact. A BRT usually involves eliminating several mixed traffic lanes on a street, separating bus traffic from other modes, and adding or expanding a median, (in

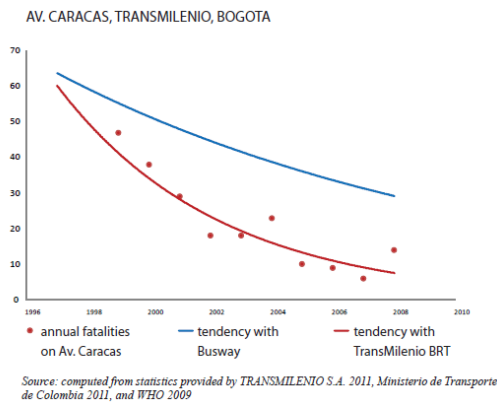
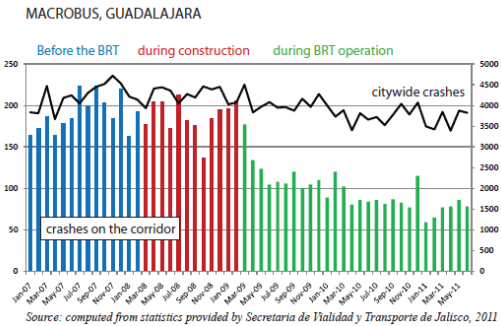
the case of centre-lane BRTs), which reduces the length of pedestrian crossings. Bus operations are better organised, commonly replacing a variety of services with a single operating agency with common standards for driver training, vehicle maintenance, etc.

Macrobus is a full-fledged BRT in Guadalajara, Mexico, which replaced an existing bus priority lane on a street with heavy traffic. TransMilenio in Bogota, Colombia is another full-fledged BRT, which replaced an existing central busway. Both these BRTs contributed to significant reductions in crashes and fatalities on their respective corridors. Crashes went down by 46% on one such corridor in Guadalajara after Macrobus started operations, while fatalities decreased by 60% on a BRT corridor in Bogota after the implementation of the first TransMilenio corridor.

Not all bus systems had the same positive impact on safety. The Cristiano Machado Busway in Belo Horizonte (Brazil), for example, remains the street with the highest crash frequencies citywide, despite the

² Duduta, N. et al. *Understanding the Traffic Safety Impact of High Performance BRT and Busway Design Features*. Transportation Research Record, Journal of the Transportation Research Board, forthcoming 2012.

presence of a central busway.



Safety impacts beyond the corridor

After learning that crashes had reduced, on average, by 46% on the Macrobus BRT corridor in Guadalajara, we checked whether

the safety improvement on the corridor may have been offset by an increase in crashes in the area around the corridor. This was based on the hypothesis that the decrease in crashes simply reflects a reduction in traffic volumes and that the traffic had simply been rerouted and had shifted the risk from the BRT corridor to other streets.

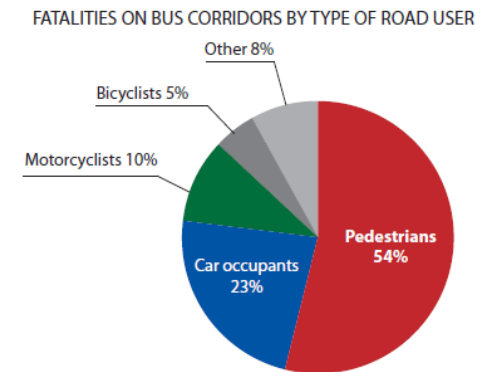
The crash data from Guadalajara suggest this was not the case. We selected a 3-kilometer buffer zone on both sides of the corridor. We chose this width in order to include several major arterials that run parallel to the BRT corridor. Crashes in the buffer zone (excluding the BRT corridor) decreased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

At a smaller scale, however, there were some 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 centre-lane BRT systems, (right turns in the Indian context, as traffic in Latin America drives on the right side of the road). The left turns were replaced with loops, redirecting traffic through the neighbourhood. Some of the better designed loops did not have any impact

on crashes in the neighbourhood 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.

Fatal crashes

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



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

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 BRT stations, as passengers will often attempt to cut across the bus lanes to go in or out of the station, in order to avoid paying the fare, or simply in order to take a shortcut. This suggests that station access design can play a key role in improving safety on bus corridors, along with better provisions for pedestrian mid-block crossings.

Location of crashes

Dedicated bus lanes can significantly reduce the incidence of crashes involving buses. Segregated high capacity bus corridors can carry more passengers, considerably more safely than the mixed traffic lanes.

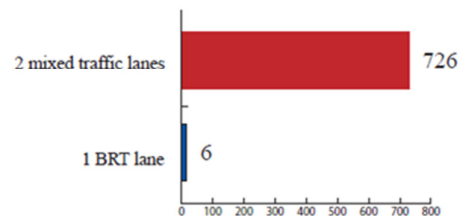
We illustrate this with data from the Macrobus BRT in Guadalajara, Mexico, which features one BRT lane and two mixed traffic lanes per direction. The BRT lane carried over 30% more passengers, while having over 90% fewer crashes than the mixed traffic lanes.

There are two important takeaways from the statistics presented on this page. The first is that while being on a bus is the safest place on

a bus corridor, walking to and from the station is when bus passengers are at the highest risk

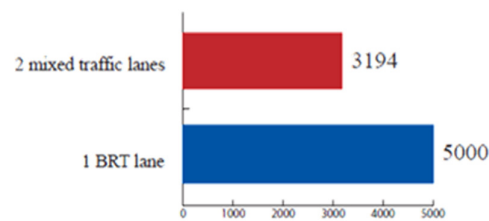
CRASHES

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



PASSENGER THROUGHPUT

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



Ensuring safe station access is therefore the key to improving safety to bus passengers. The second is that on a bus corridor, over 90% of crashes will usually occur outside of the bus facilities (i.e. lanes and stations) and will not involve buses. This was confirmed by similar findings from TransMilenio, and it implies that

the safety of a bus corridor will depend more on the layout of the mixed traffic lanes than on the configuration of the bus system itself.

The impact of street and intersection design on safety

The results from our data analysis indicate that road width as well as the size and complexity of intersections are the most important predictors of crash frequencies on bus corridors.³ This makes sense, since on most of the bus corridors in our sample, only about 9% of all crashes occur in the bus lanes, while the vast majority occur in the general traffic lanes and do not involve buses. The number of approaches per intersection is one of the key issues, along with the number of lanes per approach, and the maximum pedestrian crossing distance. Intersections where traffic from the cross streets is allowed to cross the bus corridor are more dangerous than intersections where only right turns are allowed, (left turns in the Indian context).

³ Duduta et al. 2012, op. cit.

The impact of bus lane configuration on safety

Counterflow bus lanes in Mexico City and Porto Alegre were found to be significantly correlated with higher crash rates for both vehicles and pedestrians. The consistency of the results across the different models suggests that counterflow lanes are the most dangerous configuration for bus systems, of all those included in our study. We also found that kerbside bus lanes in Guadalajara increased both vehicle and pedestrian crash rates, whereas in Mexico City they did not have a statistically significant impact on crash frequencies. While the results are not always significant, they generally tend to indicate that kerbside lanes may be problematic, though not as much as counterflow lanes.

Assessing the safety impact of centre-lane systems is slightly more complex, since the changes introduced by a centre-lane BRT on a street are measured by several variables. Unlike kerbside bus corridors, which usually only replace one traffic (or parking) lane with a bus lane, centre-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 centre of the street, and creating more T intersections and fewer 4-way intersections along the corridor. While the variable accounting for the presence of the centre-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.⁴

General design recommendations

The results from our research have influenced our general design recommendations for BRT systems. We conclude that the safest BRT systems should have the following features:

- Central BRT lanes, as opposed to kerbside bus lanes
- Segregated BRT lanes, as opposed to simple lane marking indicating a busway
- BRT plying in the regular direction as mixed traffic, rather than counterflow
- Restriction on right turns for mixed traffic across the BRT lanes.

⁴ Duduta et al. 2012, op. cit.

- Signalised pedestrian crossings at frequent intervals, and physical measures to prevent jaywalking
- Centralised BRT authority, to regulate BRT driver performance, with respect to speeding and traffic violations.
- Physical speed control measures for mixed traffic lanes.

The design speed

Speed is the single most important causal factor in road accidents that result in a road fatality. Often, road designers incorrectly apply highway standards to urban roads. Urban roads cannot neglect the mobility and accessibility requirements of all road users, including that of pedestrians and NMT. As argued earlier, in the urban Indian context, there is a high volume of pedestrian, NMT and other slow moving traffic.

Furthermore, the abundant edge development that characterises most urban roads in India, creates the need for even motor-vehicles to slow down in order to access these properties. This puts them into conflict with the fast-moving through-vehicles.

We recommend a **maximum design speed of**

40 kmph for any road upon which a BRT is developed. As far as possible, this speed should be induced through road design, rather than relying on signage and/or enforcement. These design features include narrower lanes, speed tables, chicanes, etc. A combination of these features are utilised in various templates in these Guidelines.

It is important to note that in the urban context, achieving a high midblock speed has very little impact on total journey time. This is because of the frequent need to slow down or stop at intersections, which are present at a much more frequent interval than in the context of a regional highway.

Further, a slower and more consistent speed, may also improve the capacity of the road. This is because the safe gap or headway needed to be maintained between vehicles is less for slower moving traffic. Thus, the space requirement for slower moving traffic is less, and this allows a higher density of vehicles on the road. Up to a certain point, this higher density is associated with a higher throughput volume on the road, beyond which congestion sets it.

4. THE BRT MIDBLOCK ELEMENTS

BRTs are generally constructed along urban arterials. A BRT corridor contains all the elements that are typical of an urban arterial, such as footpaths, traffic lanes, dividers, etc. Additionally, there need to be elements that are associated with the BRT, such as dedicated bus infrastructure and NMT lanes.

As argued earlier, in order to achieve a high level of road safety, additional elements, that address the local accessibility demands, are also necessary. For the purpose of these Guidelines, we have used the following two categories, namely continuous elements (i.e. footpaths, NMT lanes) and discontinuous elements, such as crossings and U turns.

Continuous elements

They are the elements that continue across the length of the corridor, without breaks, such as the footpath, NMT lanes, mixed traffic lanes, BRT lanes, etc. These elements must typically maintain a constant width across the length of the corridor.

Discontinuous elements

These are the elements that need to be provided at varying intervals along the corridor. This includes elements that aid the mobility and accessibility functions of the corridor, such as pedestrian crossings, u-turn lanes, turning lanes, property accesses, auto-rickshaw pick-up/drop-off areas, etc.

Additionally, there are space requirements for elements that contribute to the non-transport uses of the road, such as utility boxes, street vendor areas, trees, street furniture, etc.

Often, road designers tend to neglect the space requirements for these discontinuous elements. These elements then tend to be, either under-provided, or provided in an ad-hoc manner. For example, utility boxes are placed on the footpath, forcing pedestrians to walk on the NMT lane. This discourages NMT traffic from using the NMT lane, which forces them onto the mixed traffic lane.

Furthermore, in order to accommodate these discontinuous elements, road designers may

reduce the width of some of the continuous street elements, such as the footpath or traffic lanes. This creates bottlenecks which cause both safety as well as capacity problems.

Introducing a multi-utility (MU) strip

In order to provide adequate space for all road uses, it is, thus, necessary, to provide an additional strip of continuous area on either side of the road that can be used to accommodate all these discontinuous road elements. In these Guidelines, we call this the multi-utility strip, or MU strip. This MU strip will be used in different places for different purposes, but its continuous presence ensures that there is adequate space to accommodate for these uses, without infringing upon the other continuous elements of the road.

The MU strip can also be used to provide adequate space for vehicles to pull-over, or for auto-rickshaws to queue. If such space is not provided at frequent intervals, then vehicles will be forced to stop on the traffic lanes, thus reducing the capacity of the road. This problem is further aggravated in the

Indian context, where there is abundant edge development along the urban corridors.

The MU strip has one additional advantage; it can adjust to the varying width of the road. Generally, a well-design road is one where the continuous elements of the road maintain a constant width irrespective of the varying road width, in order to avoid the associated capacity and safety issues created by bottlenecks. The MU strip width can be adjusted to accommodate for such variations, such that the widths of the other continuous elements of the road are not compromised.

The model on the following page shows our recommended design template for a standard midblock BRT corridor. Here, we demonstrate how the MU strip can be used to contain all the discontinuous elements essential for an arterial corridor in the Indian context, such as autorickshaw stand, street vendor area, property accesses, vehicular pullover area, etc.

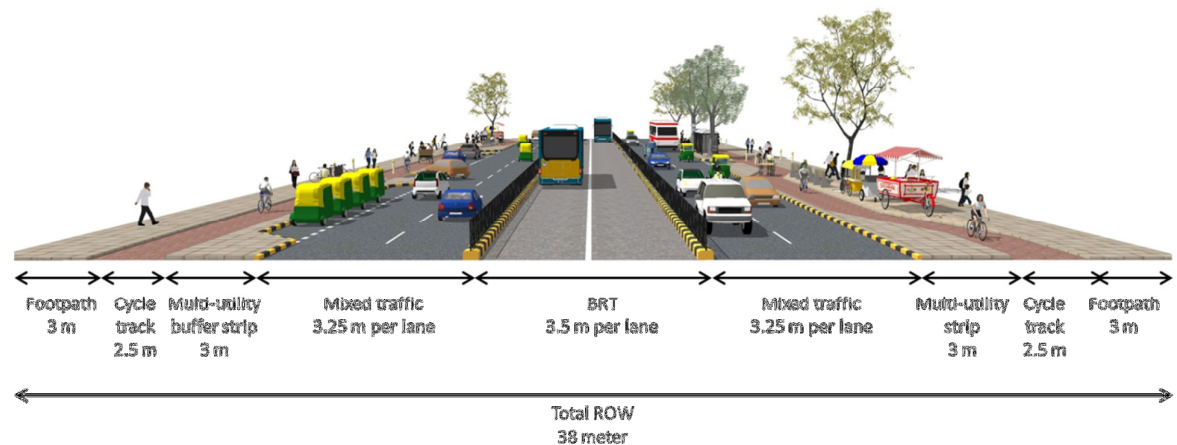
As stated earlier, unless otherwise stated, all the recommended templates used in these Guidelines, are shown on a fixed road width of 38 meters, in order to demonstrate how all the various elements of a BRT can be

accommodated, without needing additional road width; and without eliminating or reducing the width of other road elements such as traffic lanes, NMT lane or footpath.

The section that follows the model provides explanation about each continuous element in the model, including the space standards assumed or recommended for each element.

The widths (and heights) that we have used for the various continuous elements of the corridor are as follows:

Element	Width (meters)	Height (meters)
Footpath	3.0	0.10
NMT lane	2.5	0.00
MU strip	3.0	0 to 0.15
Mixed traffic lanes	6.5	0.00
Divider	0.5	0.15
BRT lanes	3.5	0.00
SUM - width of half the road	19.0	
TOTAL width of the road (19 x 2)	38.0	

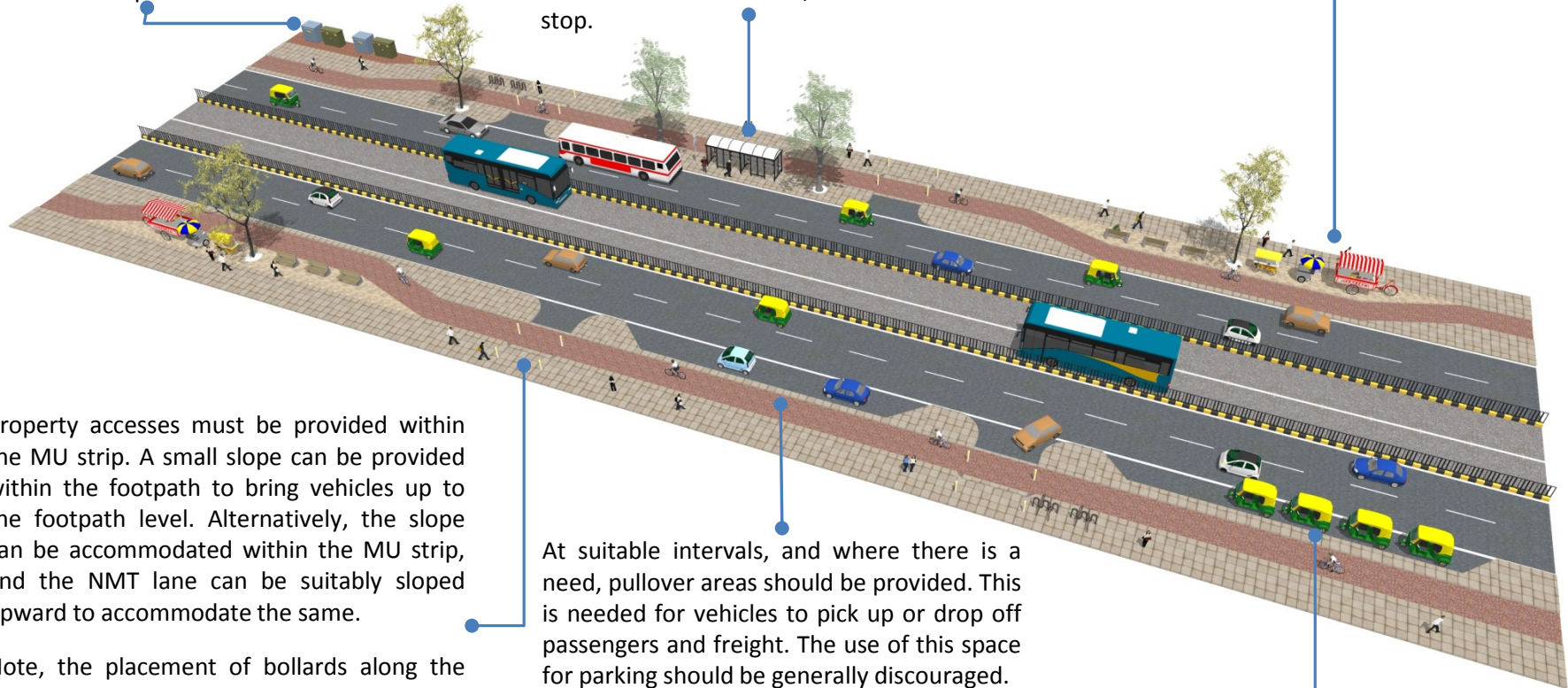


Recommended Design Template 1: Basic Midblock

The footpath and NMT lane is gently meandered around any immovable obstacles in their natural path, such as trees and utility boxes, by utilising the additional space of the MU strip. This should be done with a gradual curve so as to not impede the natural movement of pedestrians and NMT.

Sometimes, regular bus services will run parallel to the BRT corridor for short distances, such as the case with feeder bus systems. In this case, the bus-stop can be accommodated in the MU strip, right next to the traffic lanes. The NMT and footpath continues unobstructed, behind the bus-stop.

Street vending is most viable when located close to pedestrians, without obstructing their path. In order to create street vendor space, the NMT lane can gently meandered into the MU strip.



Property accesses must be provided within the MU strip. A small slope can be provided within the footpath to bring vehicles up to the footpath level. Alternatively, the slope can be accommodated within the MU strip, and the NMT lane can be suitably sloped upward to accommodate the same.

Note, the placement of bollards along the NMT lane and footpath, in order to prevent larger vehicles from entering these spaces. The bollards must have at least 1.2 meters space on either side, to allow larger NMT vehicles, like cycle rickshaws, to pass.

At suitable intervals, and where there is a need, pullover areas should be provided. This is needed for vehicles to pick up or drop off passengers and freight. The use of this space for parking should be generally discouraged.

At least 0.3 meters buffer kerb width must be provided next to the NMT lane, so that the left doors of cars can be opened without colliding with oncoming NMT vehicles.

Auto-rickshaws can also be accommodated in the MU strip. At least 0.5 meters buffer space should be provided next to the NMT lane to accommodate waiting people

Footpath

We recommend a minimum footpath width of 3 meters for an urban corridor with extensive edge development. This includes the dead space along the edge of the footpath, abutting the property line. This does not include space for utility boxes, street vendors, etc, where we recommend that these elements be provided within the MU strip.

The recommended footpath kerb height is 0.10 meters. In these Guidelines, the footpath is never placed along the traffic lanes, and instead is placed along the NMT lane. Thus, a lower kerb height is desirable so that the bicycle pedals do not clip the kerb when they are in their lowest position.

NMT lane

We recommend an NMT lane width of minimum 2.5 meters. International standards may permit a minimum width of 2 meters for a bicycle track. But, as argued earlier, the NMT mix in the Indian context consists of a number of wider vehicle types, such as tricycles, cycle rickshaws, and street vendor hand-carts. The widest of these vehicles, the cycle rickshaw, has a width of approximately 1.2 meters.

Thus, the width of 2.5 meters was chosen, so as to accommodate 2 such vehicles passing side-by-side.

One has to keep in mind that given the varying speed among different NMT vehicles, and the more frequent need for stopping, the overtaking demand is very high. Unless adequate width is provided, NMT users will not use the NMT lane, and prefer to use the mixed traffic lanes.

MU strip

The MU strip width was chosen as 3 meters. This was done to accommodate the widest space requirement of the MU strip, which is to provide the additional space required to create a turning lane. As explained earlier, the width of the MU strip can vary in conjunction with the varying width of the road, so as to maintain a constant width of the other road elements.

The MU strip height varies between 0 and 0.15 meters. When functioning as a traffic lane kerb edge, the height of the MU strip will be 0.15 meters, which is consistent with the recommended height for kerbs adjacent to the traffic lanes. This is to prevent vehicles

from deliberately or accidentally mounting the kerb. When the MU strip is utilised to accommodate pullover or turning lanes, then, naturally, these lanes will be at the same height as the traffic lanes.

Mixed traffic lanes

We recommend 6.5 meters width for the mixed traffic lanes. This accommodates 2 lanes of 3.25 meters each. Highway manuals recommend a lane width of 3.5 meters. However, an urban arterial should not be designed with the specifications used for highways. The main function of the highway is throughput capacity for motor-vehicles driving at a very high speed, say above 80 kmph. Typically, pedestrians and NMT traffic are banned from such highways.

The urban arterial, on the other hand, should be designed for the dual function of throughput mobility and local accessibility. Moreover, the traffic mix is far more heterogeneous, with a higher volume of smaller vehicles, NMT and pedestrians. In this context, a much lower design speed is essential in order to ensure the safety of all road users.

As argued earlier, as far as possible, road design, rather than signage, must dictate road behaviour. Thus, if one intends to ensure that vehicles drive at a lower speed, then one has to design the road for lower speeds.

International experience has shown that reduced lane width is one of the most effective measures to control vehicular speeds. It has the psychological effect of encouraging motorists to sub-consciously drive at a lower speed, without them realising that they are doing so. A width of 3.25 meters is still sufficient to accommodate the movement of the largest of motor-vehicles, without being a safety risk to other vehicles. The width of a bus or truck is about 2.6 meters. The width of a car is much lower, typically between 1.5 to 1.8 meters.

Finally, as explained earlier, traffic discipline in most Indian cities is poor. Wider lanes encourage smaller vehicles, such as motorbikes or autorickshaws, to squeeze between adjacent vehicles. This is a major safety risk, as it leads to collisions when vehicles change lanes.

These Guidelines are demonstrated on a road with two mixed traffic lanes in each direction.

The recommendations can be extended to roads with three or more traffic lanes as well. However, it is important to state that when a road has 4 or more traffic lanes in each direction, it cannot safely function as an urban arterial, especially for pedestrians and NMT users.

Divider

A divider of minimum 0.5 meters width is recommended to be placed between the mixed traffic lanes and the BRT lane. This is to accommodate a guardrail, and sufficient vacant space on both sides of the guardrail. The vacant space is needed so as to ensure the full utilisation of the adjacent traffic lanes. This is because vehicles tend not to drive very close to a visible vertical obstruction, and thus sufficient space is needed on both sides, so that both the BRT bus and the mixed traffic make full use of their respective traffic lanes.

The divider height is recommended to be 0.15 meters, which is consistent with the recommended height for kerbs adjacent to the traffic lanes.

BRT lane

The width selected for the BRT lane is recommended to be 3.5 meters. This is consistent with the recommended width for BRT lanes across the world. It is to ensure that the BRT bus can drive safely at a speed of 40-60 kmph, without running the risk of colliding with the guardrails or a bus approaching from the opposite direction.

5. MIDBLOCK PEDESTRIAN CROSSINGS

As explained earlier, in many cases, there is extensive edge development of residential, commercial and institutional uses along a typical urban arterial road in India. These developments have accesses provided directly from the urban arterial. These developments generate a high volume of pedestrian movement.

An arterial road, in its strictest definition, is not allowed to have direct property access. In this way, midblock pedestrian movement is virtually eliminated. However, for most Indian roads, this is not the case, and there exists a high demand for midblock crossings. When a BRT is developed along such a road, it adds significantly to the total pedestrian volume, creating a greater need for more frequent pedestrian crossings.

A BRT is typically constructed in an existing urban development, with already established crossing patterns. The BRT infrastructure, by virtue of the guardrails along its length, creates a barrier for pedestrians to cross at ease. If the crossing requirements of pedestrians are not significantly addressed,

then it encourages them to jaywalk by climbing over the BRT guardrail. This is extremely dangerous, as the pedestrian can trip and fall directly onto the path of speeding traffic or BRT buses. Thus, the presence of the guardrail can actually worsen the safety scenario if there are not adequate provisions for pedestrian crossings.



Picture 9: If adequate opportunities are not provided for pedestrians to cross the road, then they may resort to jumping the guardrail. Signage, as seen in the picture, does not serve the purpose.

We recommend that, before the development of a BRT corridor, a systemic study should be conducted to evaluate the high crossing

zones. As much importance must be given to analysing pedestrian movements as is given to analysing traffic movement.

As a general principle, for a road with extensive edge development, a pedestrian crossing must be provided **every 100-150 meters**. The exact location of the crossing should be determined by the local demand and space considerations.

The number of lanes that a pedestrian has to cross at one go is a significant determinant in the risk of an accident. We recommend that the pedestrian **should never be made to cross more than two lanes of traffic without a pedestrian refuge in between**. This is to accommodate for slow-moving pedestrians, and NMT vehicles, which may not be able to cross the full length of the road in one go. We recommend that the pedestrian refuge be wide enough to accommodate the larger NMT vehicles, such as cycle rickshaws and street vendor carts.

We recommend that all pedestrian crossings be signal controlled. We further recommend

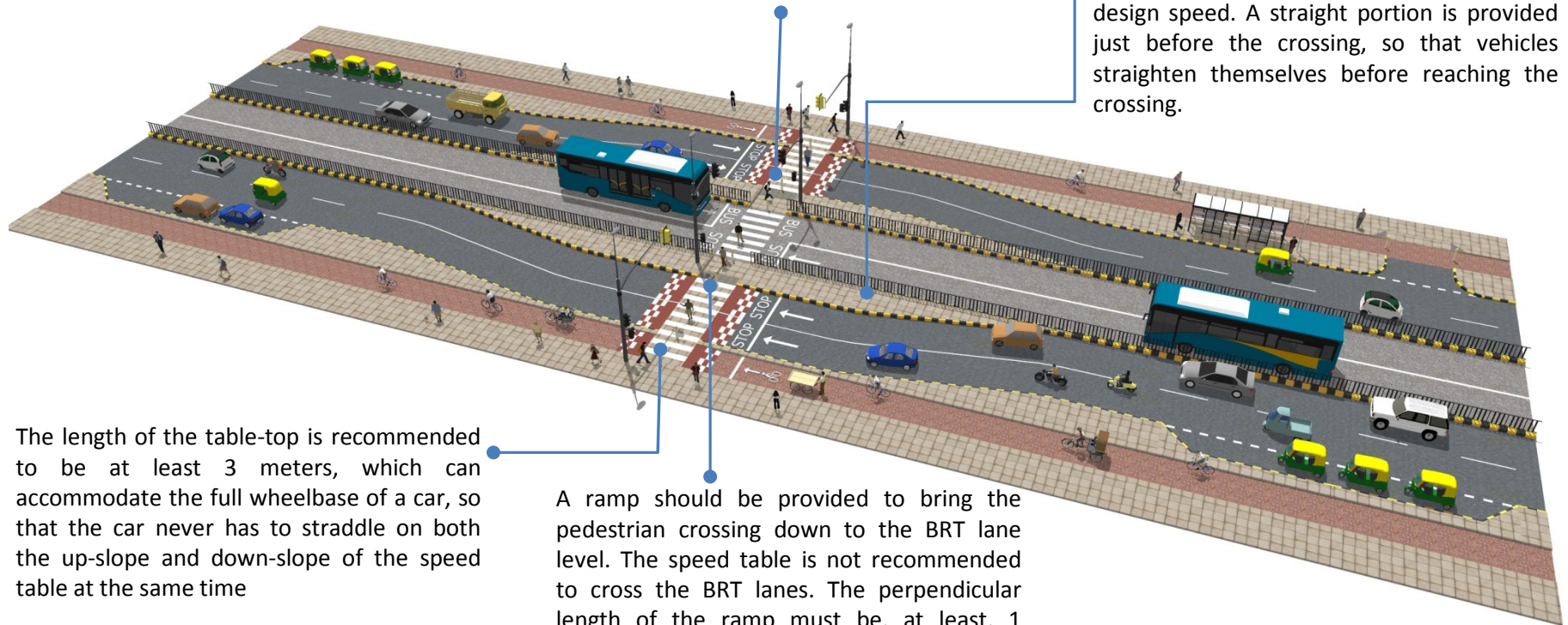
that the crossings be supplement with speed tables, in order to induce motorists to drive at the design speed.

The model on the following page shows our recommended design template for a pedestrian crossing. This design is demonstrated with the same road width of 38 meters as shown in the previous model. By utilising the width of the MU strip, and moving the same to the centre of the road, we have demonstrated how pedestrian refuge areas can be created without the need to compromise on the width of any of the other elements of the road.

Recommended Design Template 2: Midblock pedestrian crossing

Bollards should be provided along the centre line of the pedestrian crossings, where appropriate, to prevent vehicles from illegally using the pedestrian crossing to make a u-turn. The spacing between the bollards must be at least 1.2 meters, so that the larger NMT vehicles can pass through.

A pedestrian refuge is created by meandering the traffic lanes into the MU strip. This bend in the traffic lanes further induces vehicles to slow down on approaching the crossing. A taper of 15 meters is used to create the pedestrian refuge, which is consistent with a 40 kmph design speed. A straight portion is provided just before the crossing, so that vehicles straighten themselves before reaching the crossing.



The length of the table-top is recommended to be at least 3 meters, which can accommodate the full wheelbase of a car, so that the car never has to straddle on both the up-slope and down-slope of the speed table at the same time

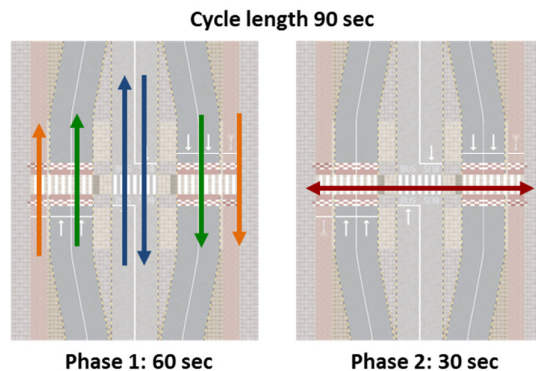
The perpendicular length of the slopes of the speed table should be 1.8 meters each, given the height of the speed table at 0.1 meters. This is consistent with a 40 kmph design speed. The height of the speed table should be the same as the height of the footpath.

A ramp should be provided to bring the pedestrian crossing down to the BRT lane level. The speed table is not recommended to cross the BRT lanes. The perpendicular length of the ramp must be, at least, 1 meter, so as to be convenient for wheelchairs.

The width of flat portion of the pedestrian refuge must be at least 2 meters to accommodate an NMT vehicle.

Pedestrian crossing signals

As stated earlier, we recommend that all pedestrian crossings be signalised. It is observed that in most Indian cities, traffic rarely yields for pedestrians at un-signalised pedestrian crossings. Further, we recommend the pedestrian delay to be not more than 30 seconds on average. We have demonstrated here a possible signal phasing plan that can be utilised for the peak demand scenario.



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	Mixed Traffic
	Pedestrian
	Bicycle
	Bus

We have assumed a walking speed of 1.2 meters per second, which will allow a pedestrian to cross the 32 meters of the pedestrian crossing length in about 27 seconds. An addition 3 seconds is added in order to account for the pedestrian reaction time, and for slower moving pedestrians.

We strongly recommend that the phases of successive pedestrian crossing signals be synchronised, so as to reduce the probability that vehicles will have to wait at more than one signal in the same midblock. We do not recommend pedestrian actuated signals in the Indian context, as such signals are only useful when there is a low and infrequent crossing demand.

As explained earlier, if adequate measures are taken to address vehicular capacity, then motorists are less likely to flout traffic rules that create safety problems. Thus, issues like signal management are of prime importance, as they have an indirect influence on safety.

Speed tables

Since traffic discipline in most Indian cities is poor, motorists may not always respect pedestrian signals. This can be extremely

dangerous, especially if the vehicle in the lane closer to the footpath stops at the signal, while the vehicle away from the footpath doesn't stop. Here, the stopped vehicle in the leftmost lane creates a sense of security for the crossing pedestrian, and also blocks his/her view of the oncoming vehicle in the other lane. This can lead to a fatal collision.

We thus recommend that all signalised pedestrian crossings be placed on top of **speed tables**. This is an added safety feature to slow down vehicles at the pedestrian crossing, and to induce them to drive at a safe speed. For our design, we have used a gentle speed table of the following dimensions:

Length of up-slope ramp	1 meter
Length of table-top (pedestrian crossing width)	3 meters
Length of down-slope ramp	1 meter
Height of table-top	0.1 meters

The dimensions of the speed tables are consistent with our design speed of 40 kmph. This means that a typical motor-vehicle can safely and comfortably cross the speed table if it is driving at a speed of 40 kmph.

The length of the table-top is recommended to be at least 3 meters, which can accommodate the full wheelbase of a car, so that the car never has to straddle on both up-slope and down-slope of the speed table at the same time. This permits a 3 meter wide pedestrian crossing, which is also equal to our recommended footpath width. In general, the pedestrian crossing must be as wide as the footpath.

We do not recommend that the speed table be continued across the BRT lanes, because the speed table length that achieves a 40 kmph design speed for a bus is much longer, since the wheelbase of a bus is longer. It is advisable to regulate BRT bus speeds through driver training and monitoring by the central BRT authority. This is made very easy with recent technology advancements in vehicle performance tracking.

We do not recommend abrupt speed bumps on any urban arterial. Speed bumps force vehicles to come to a complete stop. This is unnecessary and significantly reduces road capacity. Furthermore, speed bumps can be dangerous for motorbikes, as they may cause the rider to lose his/her balance.

Pedestrian refuge

We recommend the provision of pedestrian refuges between the mixed traffic and BRT lanes in order to accommodate slow-moving pedestrians that may get stranded at the end of a pedestrian green phase. The pedestrian refuge must be wide enough to accommodate waiting NMT vehicles, such as street vendor push-carts.

Pedestrian crossing width and bollard spacing

We recommend that the pedestrian crossing width must be at least as wide as the footpath, which in our case is 3 meters. This, as explained earlier, is also the minimum recommended width of the table-top.

Further, we recommend placing bollards along the centre line of the pedestrian crossing, where appropriate, that is on the dividers that separate the NMT lane from the mixed traffic lanes, and the mixed traffic lanes from the BRT lane. The bollard should be placed, such that there is at least 1.2 meters gap on either side of the bollard. This is to allow larger NMT vehicles, such as cycle rickshaws and vendor

pushcarts to be able to use the pedestrian crossings.

As mentioned earlier, urban arterials in the Indian context are characterised by a high volume of street vending activity. If adequate provisions are not made for the mobility of street vendors across the BRT corridor, it will create major safety concerns. The street vendors will be forced to make very dangerous manoeuvres in order to cross the BRT corridor.



Picture 10: Since the gap between the bollards at the pedestrian crossing is not wide enough, the street vendor is forced to enter the BRT lane from the intersection, and then make a dangerous detour around the median, in order to cross the road.

6. MIDBLOCK U-TURNS

A BRT in India will, typically, be implemented on an urban arterial with extensive edge development of commercial, residential and institutional uses. These properties will have direct access from the arterial road.

Hence, there tends to exist a high and scattered demand for vehicles to make right turns across the median of such roads in order to access these properties. If these roads have a divider running across the median then there needs to be adequate provisions for vehicles to make u-turns in order to access properties on the opposite side of the road.

The non-provision of u-turn opportunities along a BRT corridor induces motorists to flout traffic rules, such as driving in the wrong traffic direction, so as to avoid the long detour associated with finding a u-turn opportunity. This is extremely dangerous, as these motorists tend to drive very fast in order to quickly finish the activity before they are caught by a traffic policeperson. This puts them at risk of head-on collisions with oncoming vehicles. Moreover, these vehicles may also crash into pedestrians caught

unaware while crossing the road, as the pedestrians will not be looking in their direction.



Picture 11: The white car is driving on the wrong side of the road, in order to avoid the long detour to find a u-turn opportunity. This could lead to a head-on collision with crossing pedestrians or oncoming vehicles.

Furthermore, if adequate u-turn opportunities are not provided, motorists may resort to using the pedestrian crossings to make u-turns. This is possible for smaller vehicles, like motorbikes, that can squeeze through the gap between the bollards in the pedestrian crossing. This gap cannot be reduced to prevent motorbikes from doing this, because

it will also end up preventing larger NMT vehicles from using the pedestrian crossing.



Picture 12: If adequate u-turn provisions are not made, smaller vehicles, like motorbikes, may resort to illegally using the pedestrian crossing to make u-turns.

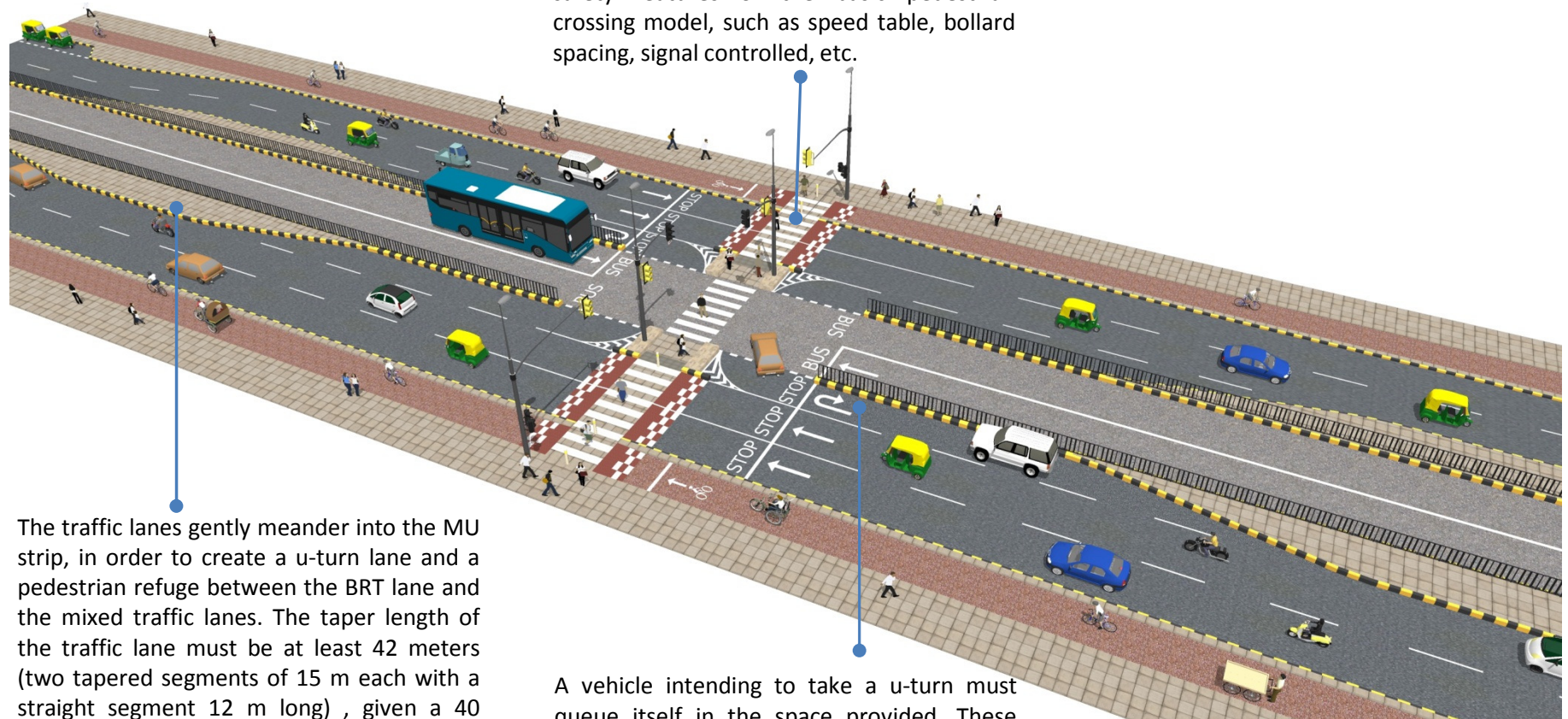
We recommend that formalised u-turn opportunities be provided every **400-600 meters**. In our design template, we have demonstrated how u-turn opportunities can be safely clubbed with a pedestrian crossing. We recommend that every fourth pedestrian crossing should utilise this design, in order to meet the u-turn requirements of the corridor.

Our recommended design for the u-turn, combined with the pedestrian crossing is shown on the following page. It can be observed that this u-turn model is an extension of the previous pedestrian crossing model, with u-turn lanes provided on each side of the crossing.

Like with the previous model, this model too is demonstrated on a road width of 38 meters. The intention is to show how safe u-turns can be provided at the midblock, without compromising on the width of any of the continuous elements of the corridor. This is made possible by gently meandering the traffic lanes into the MU strip, in order to create a u-turn lane and a pedestrian refuge between the BRT lane and the mixed traffic lanes. The taper of the traffic lanes is consistent with a design speed of 40 kmph.

Recommended Design Template 3: Midblock U-turn + pedestrian crossing

The u-turn opportunity is provided on either side of the pedestrian crossing. This pedestrian crossing incorporates all the road safety features of the basic pedestrian crossing model, such as speed table, bollard spacing, signal controlled, etc.



The traffic lanes gently meander into the MU strip, in order to create a u-turn lane and a pedestrian refuge between the BRT lane and the mixed traffic lanes. The taper length of the traffic lane must be at least 42 meters (two tapered segments of 15 m each with a straight segment 12 m long) , given a 40 kmph design speed.

A vehicle intending to take a u-turn must queue itself in the space provided. These vehicles have to leave the straight lanes in order to enter the u-turn lane. This is a safer design than one where the rightmost lane, itself, becomes the u-turn lane.

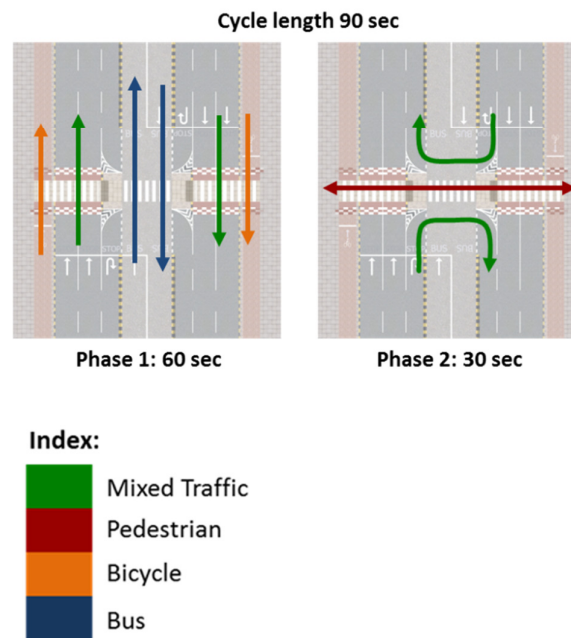
The recommended design for the u-turn combined with the pedestrian crossing, incorporates all the safety features from the previous pedestrian crossing template. This includes the same design standards for features of speed tables, ramps, tapers, etc. The additional features of this model include the creation of u-turning lanes on either side of the pedestrian crossing. This u-turn lane is carved out of the additional space obtained by ending the MU strip.

This design requires vehicles wanting to make a u-turn to leave the rightmost traffic lane, and move into the adjacent u-turn lane. This is a safer solution than the rightmost lane, itself, becoming the u-turn lane. This is because vehicles that do not wish to take a u-turn will have to abruptly change their lane, putting them at risk of a side-on collision with vehicles in the left-adjacent lane.

Signal plan

We recommend that all u-turns be signalised. Our studies have shown that un-signalised right turn movements across the BRT lanes, are very dangerous. All lateral movement across the BRT lanes must be signalised.

In this design, u-turns happen at the same time as pedestrians crossing; that is, they share the same signal phase. This further improves the capacity of the corridor. We thus recommend the following signal phase plan:



7. MIDBLOCK BRT STATIONS

The following chapter provides our recommendations for safe design for a midblock BRT stations, especially from the point of view of pedestrian accessibility to the station. If designed improperly, the area around the BRT station can become a hotspot for road accidents. This is because of the high volume of pedestrians that need to cross the road to access the station. In order to reduce the risk of these accidents, adequate priority and infrastructure needs to be provided for pedestrian crossing, in the form of pedestrian refuge areas, signal crossing time, etc.

In general, pedestrians are at risk when they cross the corridor away from designated crossings. The risk is particularly high near BRT stations, as passengers will often attempt to cut across the bus lanes to go in or out of the station, in order to avoid paying the fare, or to take a shortcut. This suggests that station access design can play a key role in improving safety on bus corridors, along with better provisions for pedestrian mid-block crossings.

Due to the presence of the BRT station in the centre of the road, the available cross-

sectional width of the road is already compromised. This makes it difficult to also provide additional crossing facilities, like pedestrian refuge areas. Hence, pedestrians may have to cross both the BRT lane and the mixed traffic lanes at one go. This is not necessarily dangerous, if the crossing is signalised. However, in the absence of working pedestrian signals, this can lead to a high number of pedestrian fatalities.



Picture 13: A pedestrian crossings that does not have a refuge area between the mixed traffic lanes and the BRT lane can be dangerous, if there are no pedestrian signals.

If designed improperly, the presence of the BRT station may also require reduction of the width of some, or all, the other continuous elements of the road, such as the footpath, NMT lane and traffic lanes. This discourages their use and forces pedestrians and NMT users onto the traffic lanes, which can be quite dangerous. If the width or number of the traffic lanes is reduced, then it will create a bottleneck, which may cause congestions and/or accidents.

In the following model, we have put forth our recommended template for the design of midblock BRT stations. We have achieved the provision of the additional width required for the station, by eliminating the MU strip in this section, and moving the additional space to the centre of the road. In this way, the widths of the other continuous elements of the road are not compromised. Similar to the previous models, this design is also demonstrated on the same road width of 38 meters.

As explained earlier, if adequate u-turn opportunities are not provided at the midblock, then smaller vehicles like

motorbikes may resort to illegally using the pedestrian crossing to make u-turns. This is a dangerous situation at any place, but even more so at the station, given the higher volume of pedestrians that are expected at the station. We thus recommend that u-turns be provided just before the pedestrian crossing at stations, similar to the design shown in the previous model. We have demonstrated this in the following model.

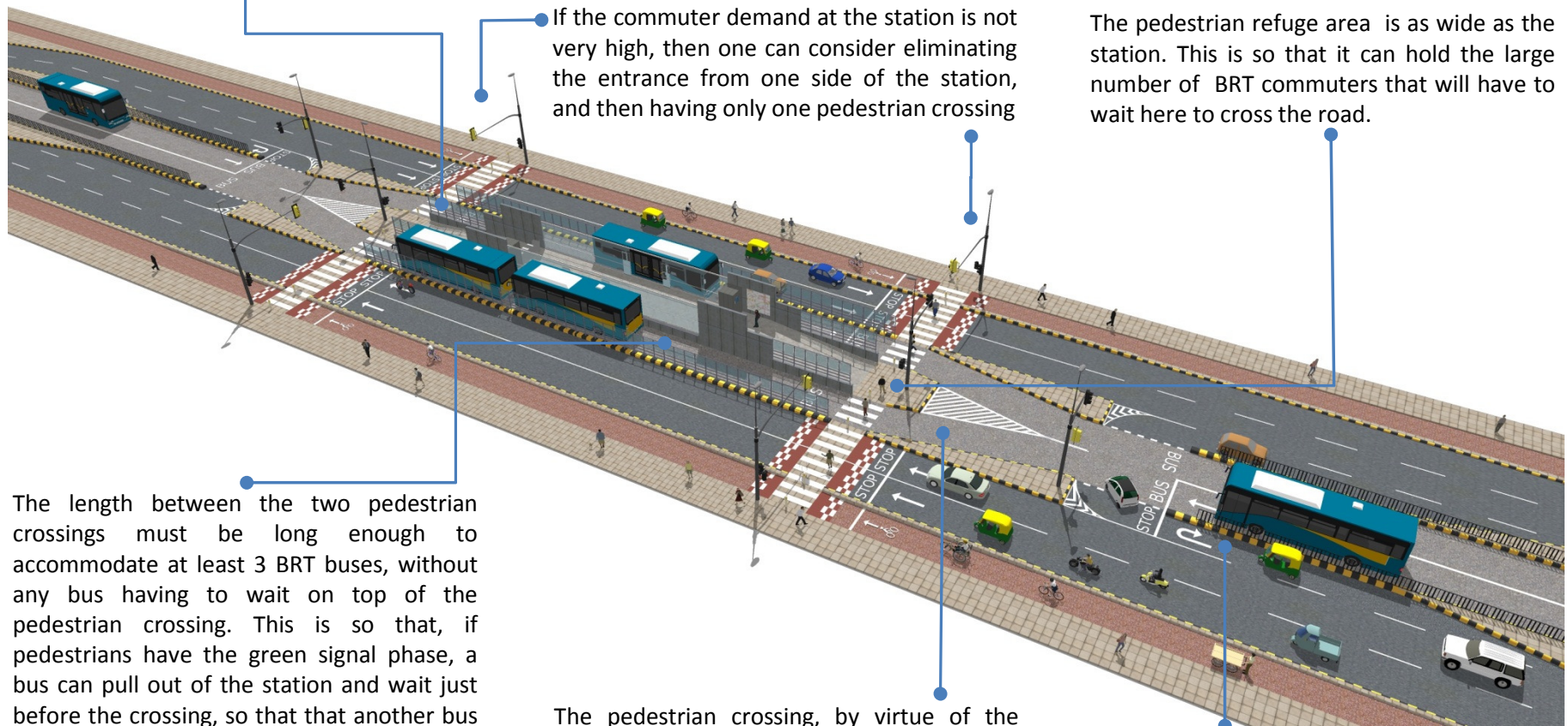
Recommended Design Template 4: Midblock BRT station with pedestrian crossing + U-turn

The barrier segregating the station ramp from the BRT lane should be transparent, so as not to block the visibility of the crossing pedestrian and the BRT bus of each other.

The signals of both pedestrian crossings should be synchronised, so that vehicles do not get caught in the red phase of both signals.

If the commuter demand at the station is not very high, then one can consider eliminating the entrance from one side of the station, and then having only one pedestrian crossing

The pedestrian refuge area is as wide as the station. This is so that it can hold the large number of BRT commuters that will have to wait here to cross the road.



The length between the two pedestrian crossings must be long enough to accommodate at least 3 BRT buses, without any bus having to wait on top of the pedestrian crossing. This is so that, if pedestrians have the green signal phase, a bus can pull out of the station and wait just before the crossing, so that another bus can pull into the station. Similarly, if the BRT has the green phase, then the bus can cross the pedestrian crossing and wait just behind another bus that is already waiting at the station.

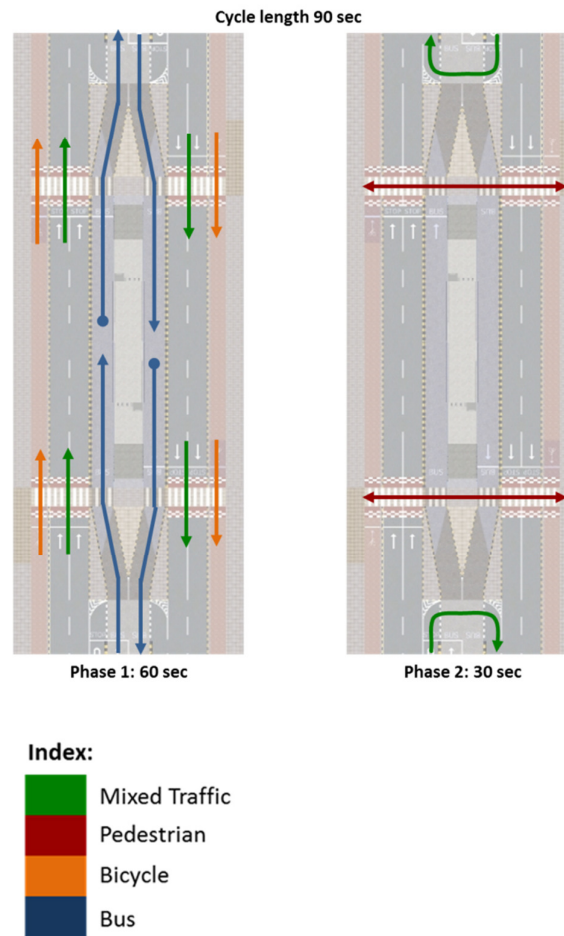
The pedestrian crossing, by virtue of the speed table on the mixed traffic lanes, is 0.10 meters above the bus lane level. Thus, this section of the BRT lane is used to gently ramp-up 0.10 meters. The slope will be 1:150, which will be unperceivable to buses.

U-turns should be provided before the pedestrian crossings, so that motorists are not induced to use the crossing to make u-turns. The u-turn should share the green signal phase with the pedestrian crossing

As can be seen, this BRT station model is similar to the u-turn plus pedestrian crossing model shown in the previous chapter, wherein the pedestrian crossing has been split into two, and a BRT station has been positioned between the two crossings. As such, the same safety design principles from the previous models will apply here.

Signal plan

This design will not be a safe solution, without the presence of functional pedestrian crossing signals. It is imperative that the signals of both pedestrian crossings be synchronised, so that vehicles do not get caught in the red phase of both signals, which would encourage them to run a red light. We recommend the following phasing plan for these signals.



If the commuter demand at the station is not very high, then one can consider eliminating the entrance from one side of the station, and then having only one pedestrian crossing

8. T-INTERSECTION WITH A MINOR STREET

A BRT corridor is likely to intersect with a number of minor streets along its course. These intersections, if not designed correctly, may pose a safety hazard, especially for pedestrians and NMT users.

As a general principle, minor streets must not be allowed to cut across the BRT corridor; that is, it is better to terminate the minor street into a T-intersection, rather than introducing a 4-arm intersection. T-intersections are generally safer than 4-arm intersection, because of lesser number of conflict points.

In order to not unduly impact local accessibility for motorists, it is imperative that this principle be applied only to minor streets. A minor street is typically one of narrow width and limited length. Often the minor street will terminate in a cul-de-sac, or loop back into the BRT corridor. Typically, a minor street will not carry through-traffic, and as such, the volume of traffic on this street will be very low.

If a BRT corridor has many minor streets that meet or cross it, then not only is it a safety risk if designed improperly, but also, it will reduce

operating speeds of the main corridor, if the minor roads are allowed to cut across the main corridor. The safety implications are also quite serious. It is very dangerous for a vehicle to take a right turn across a BRT corridor. If there is a large number of intersecting minor streets, then the provision of signals for each of these intersections becomes unviable, as it will significantly impact travel times for mixed traffic and BRT lanes.



Picture 14: It can be very unsafe if the intersection of a minor street with the BRT is un-signalised, especially if vehicles are allowed to make a right turn across the BRT lanes.

We, therefore, recommend eliminating the possibility of right turns, either from the minor street into the BRT corridor, or from the BRT corridor into the minor street. We recommend, instead, facilitating a combination of a u-turn and a left turn to complete this manoeuvre.

Eliminating right turns, not only improves the safety aspects of the intersection, but also improves traffic flows of the main corridor, both for the BRT and mixed traffic. This is because, there will be no need to have right turn phases in the signal cycle, which means more green time for through traffic on the main corridor. Thus, the minor impact to a relatively small volume of vehicles, that need to take a right turn, is completely offset by the benefit of time saved for the much larger volume of through traffic on the major corridor.

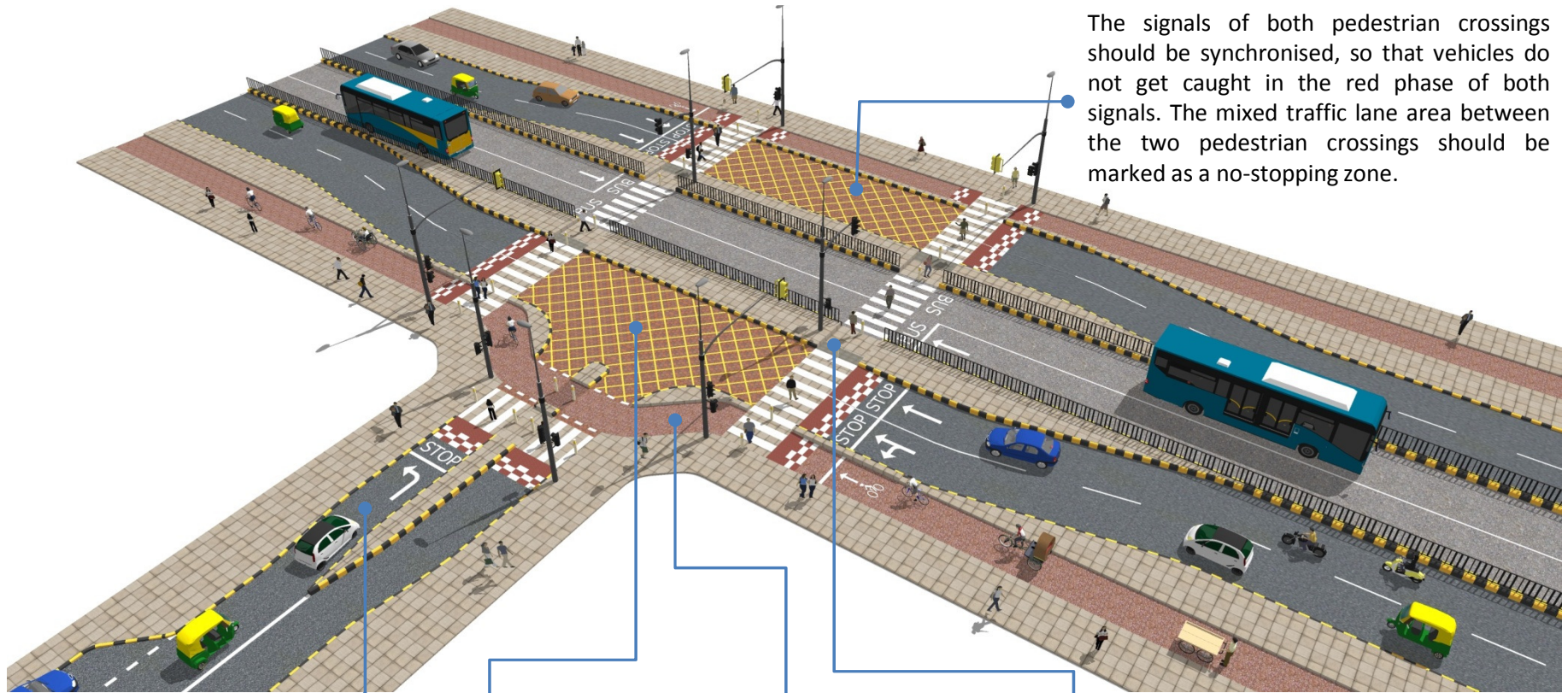
Our recommended design for an intersection of a minor street with the BRT corridor is shown in the following model. Here, we have demonstrated the recommendation on a minor street that terminates into the BRT

corridor. However, the same design can be extended to a minor street that continues across the BRT corridor, since we have recommended that right turns and through movements to and from the minor street should not be permitted.

As usual, we have demonstrated this design on a road width of 38 meters.

Recommended Design Template 5: T-intersection with a minor street

The signals of both pedestrian crossings should be synchronised, so that vehicles do not get caught in the red phase of both signals. The mixed traffic lane area between the two pedestrian crossings should be marked as a no-stopping zone.



We do not recommend that right turns be made possible into and out of the minor street. This not only improves safety, but also improves through capacity of the main corridor, both for the BRT and mixed traffic.

We recommend providing a table top intersection here, so that traffic on the main corridor will not have to cross two speed tables spaced so close together.

A slight bend is introduced in the NMT lane at the intersection. This is done in order to move the NMT user away from the mixed-traffic lane, so that the motorist has better visibility of the NMT user when making a left turn. The bend also makes the NMT users more aware of their approach to the intersection, and thus encourages them to slow down. This is important as NMT shares the signal phase with vehicular traffic

The mixed traffic lanes meander into the MU strip near the intersection, in order to create pedestrian refuge areas at the pedestrian crossing, between the BRT lane and the mixed traffic lane. This is to accommodate, slow moving pedestrians, who may get stranded halfway, at the end of the pedestrian green phase.

Raised tabletop intersection

We recommend creating a raised tabletop intersection for all minor streets. The tabletop will be 0.10 meters in height, the same height as the pedestrian crossing and the footpath. The kerbs along the tabletop should also be raised so that they are 0.10 meters higher than the tabletop. A tabletop is preferred to a combination of raised pedestrian crossings / speed tables, because of the proximity of the two pedestrian crossings from each other. The raised tabletop has the same advantages as the speed table; that is, firstly, it induces motorists to drive at the design speed of 40 kmph; and secondly, it allows wheelchair users to cross the mixed traffic lanes without the need of a ramp.

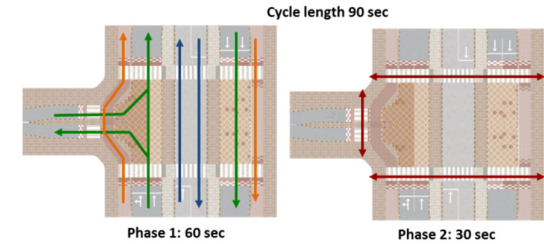
Traffic signal plan

As explained earlier, providing right turns for minor streets becomes unviable if there are many minor streets intersection the BRT corridor. In the absence of right turning movement, it is relatively safe for mixed traffic to share a common signal phase, provided that there is sufficient traffic calming elements. In our design, the table top

intersection acts as the traffic calming device that induces motorists to drive at the design speed. The slope to the tabletop from the minor street is much steeper than the slope on the main corridor, in order to induce motorists from the minor to come to a virtual stop before taking a left turn that merges with traffic from the main corridor.

Since speeds are reduced on account of the tabletop, it is relatively safe for NMT users to share the signal phase with left-turning motor-vehicles. The sharp kerb curvature ensures that motorists cannot make this turn at a high speed. It is to be noted that this is a minor street, and hence it can be assumed that there will not be many vehicles entering or exiting this street. As discussed in the next section, the additional design element, of the slight bend in the NMT lane, makes it further safe for NMT to share the signal phase with left-turning vehicles.

The proposed signal phase for such an intersection is shown as follows:



Index:

- Mixed Traffic
- Pedestrian
- Bicycle
- Bus

Bend in the NMT lane

As shown in the model, there is a small bend provided in the NMT lane at the intersection. This is done in order to move the NMT user away from the mixed-traffic lane, so that the motorist has better visibility of the NMT user when making a left turn. The bend also makes the NMT users more aware of their approach to the intersection, and thus encourages them to slow down. This is important as NMT shares the signal phase with vehicular traffic. This design feature has been successfully used for the design of bicycle tracks at intersections in The Netherlands.

9. FOUR ARM INTERSECTION WITH MAJOR ROAD

In the previous chapter, we discussed the intersection of minor streets with the BRT corridor, wherein we recommended that right turns and through movement to and from the minor street should not be made possible. However, the same principle cannot be extended to an intersection of a major road with a BRT corridor.

A major road will typically have the same level of significance in the traffic hierarchy as the BRT corridor. Like the BRT corridor, it may be a major urban arterial that connects distant and important nodes of the city. Such a road tends to be wide and long. Like the BRT corridor, this road's main function is to serve thoroughfare traffic, although it, too, may have extensive edge development with direct property access.

As thoroughfare movement of the major road is its main function, through movement across the intersection cannot be restricted. In order that these movements take place safely, and at grade, this intersection needs to be signalised.

The safety implication of right turns

Right turns, for mixed traffic on a BRT corridor, have huge safety implications, if designed incorrectly. This is due to the positioning of the BRT lanes along the central lanes of the road. As a result, traffic on the BRT corridor that needs to make a right turn, must do so by cutting across the BRT lanes. This can be dangerous, because the BRT bus will, typically, need to move straight, through the intersection. Thus, there is a risk that the right-turning vehicle may collide with the straight-moving BRT bus.

BRTs in different cities have adopted various measures to counter this safety risk. One alternative is to terminate the segregation of the BRT lane a few meters before the intersection, and allow right-turning vehicles to merge into the BRT lane, so that they make the right turn from the same lane that the BRT bus continues straight. This can be a safe solution if the merging of the right-turning traffic into the BRT lane is signalised, or if there is adequate merging length and sight distance. However, if neither of these features

is present, then it may simply result in moving the collision risk from the intersection to the point before the intersection, where the merging happens.



Picture 15: Here, the right turning traffic is allowed to merge with the BRT lane. This can be a safe solution, if this merging movement is signalised.

Another design alternative is to continue the segregation of the BRT lane till the intersection, but have separate signal phases for mixed traffic right turns, and BRT straight movement. This may be a safe solution, but the additional signal phases may significantly reduce the capacity of the intersection, and result in extremely long queues on the traffic

lanes. This encourages motorists to break traffic rules, such as driving on the NMT lanes or BRT lanes. As explained earlier, the BRT design may indirectly cause safety problems, by not adequately addressing the capacity needs for mixed traffic.



Picture 16: Poor intersection design, coupled with poor signal management, results in long queues on the mixed traffic lanes. This induced motorists to flout traffic rules, like waiting on the footpath, as shown in this picture.

We recommend that right turns be not permitted at the intersection. By permitting right turns, one either creates safety concerns or capacity issues. One has to keep in mind that in most cases, the straight-moving traffic on such urban arterial roads will far outnumber the right-turning traffic. By not

permitting right turns, one can have a longer signal phase for straight movements, thus increasing the through capacity of the intersection. This creates a benefit for a larger volume of people and vehicles.

However, vehicles still need to make right turns. If right turns are not being permitted at the intersection, then an adequate alternative needs to be provided in order to complete this manoeuvre. We recommend that all right turns be replaced by a combination of u-turns and left turns. This recommendation is demonstrated in the template model for this chapter.

Safety implications for NMT at intersections

Like mixed-traffic right turns, NMT movement across the intersection can also be potentially problematic. This is because the NMT lane is placed on the left side of the mixed traffic lanes. Hence, NMT vehicles that need to make a right turn at the intersection have to cross the mixed traffic lanes. Given the speed difference between motorised traffic and NMT vehicles, this can be unsafe, if un-signalised.

Similarly, left-turning motorised traffic needs to cross the NMT lane, and, hence, could potentially collide with straight-moving NMT vehicles.

Internationally, there have been various measures adopted to counter these two potential conflicts. One such measure is the advanced stop line. Here, the NMT lane is terminated some distance before the intersection, and NMT traffic is made to merge with mixed traffic. The stop line for motorised traffic is then pulled back a few meters from the intersection, in order to create an NMT waiting area after this stop line. This waiting area is suitably marked to indicate that this is as an NMT-only zone. During a red signal phase, NMT vehicles wait in this zone, positioning themselves in the waiting area depending upon the direction they want to take once they get the green light. Then, when the signal turns green, they start to move. Since they are positioned in the correct lane, and in front of all motor-vehicles, they are less likely to collide with motor-vehicles.



Picture 17: The green box marked on the road is meant exclusively for NMT, and the motor-vehicle stop line is advanced to just before the box. However, as is evident, given the poor level of traffic awareness and discipline, most motor-vehicles do not respect this design feature.

This can be a safe design solution, if there is sufficient awareness of this design feature by users of both motorised and non-motorised transport. Motorists must respect the NMT-only zone, and not end up waiting on top of this zone during the red signal phase. Further, if the point of merger, between the NMT lane and the mixed traffic lane, is not designed with appropriate traffic calming measures, then there will be a high risk of side-on collisions.

In the Indian context, where both traffic rules

awareness and discipline is lacking, this design may not be safe. We, thus, do not recommend that this design feature be used in Indian cities.

Another measure to handle NMT turns at the intersection is known as the Copenhagen Left. Here, we have put this measure in the Indian context, since traffic drives in the opposite direction in Copenhagen. Here, an NMT vehicle that wants to make a right turn, continues straight into the intersection, and then turns and positions itself in the front of the stopped traffic of the intersecting road. Then, when the other road gets the green signal phase, it continues straight, thus completing the right turn.

This is a very safe solution in developed countries, where there is both an awareness of this design feature, coupled with traffic discipline. Here, NMT straight-movement shares the signal phase with left-turning motorised traffic. As such, this can only be a safe solution if motorists yield to NMT. Further, this design is only viable when there is a low volume of NMT traffic, so that a motor-vehicle, yielding for NMT movement, does not end-up holding back traffic behind it.



Picture 18: The Copenhagen turn is demonstrated here. NMT vehicles that want to make a right, continue straight into the intersection, and then position themselves in the green box in front of the intersecting road'

In most Indian cities, traffic discipline is not of the same standard as developed countries. Further, there may be a much larger volume of NMT traffic, making it unviable for motorists to yield for them. Thus, we do not recommend using this feature in Indian cities.

We recommend that NMT movement be separated from motorised traffic movement, through a separate signal phase, called the scramble phase. This feature is demonstrated in the design template for this chapter.

Safety implications for pedestrians crossings

Like NMT movement, pedestrian crossings can also be a cause for conflict, if their movements are not suitably signalised. In cities in some developed countries, it is acceptable for a pedestrian crossing to share the signal phase with left-turning motorised traffic. This is because, by law, motorised traffic has to yield for crossing pedestrians.

This a safe solution for these cities, because of the high level of traffic rules awareness by pedestrians and motorists alike, as well as the high level of traffic discipline and enforcement. However, this may not be the case in most Indian cities.

Moreover, this feature is only viable if the pedestrian volume is low, so that a motor-vehicle, yielding for the crossing pedestrians, does not end-up holding back traffic behind it. As explained earlier, in most Indian cities, the pedestrian volumes are very high. As such, it may not be viable for left-turning traffic to yield for pedestrians.

We, thus, do not recommend that pedestrian crossings share the signal phase with left-

turning traffic. We, instead recommend that pedestrians share the scramble signal phase with NMT. This feature is also demonstrated in the following template.

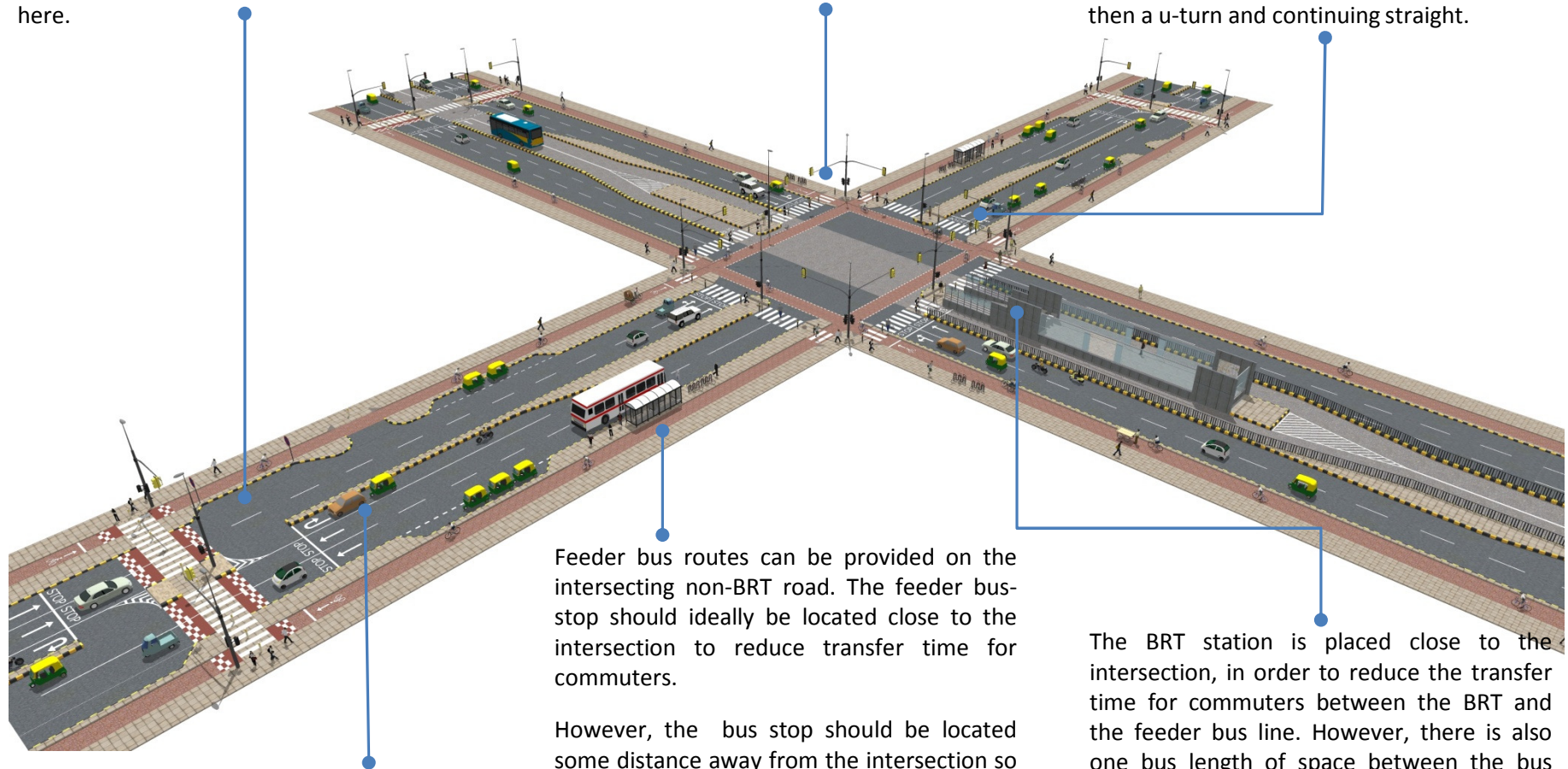
As with all previous templates, the width of the BRT corridor is fixed at 38 meters, and the width of all the continuous elements of the corridor remain the same.

Recommended Design Template 6: BRT Intersection with a major road

A portion of the MU strip is scooped out, so that larger vehicles can complete the u-turn in one go. No-stopping signs are placed along the side, to discourage vehicles from waiting here.

The NMT lane segregation continues right till the intersection. NMT and pedestrians have a shared all-green scramble signal phase., during which all other traffic is stopped.

Right turns are not permitted from any arm of the intersection. Instead this turn can be done by continuing straight, then taking a u-turn followed by a left turn; or taking a left, then a u-turn and continuing straight.



U-turns are provided a short distance after the intersection on all 4 arms. Sufficient queuing space is provided, to hold the vehicles intending to take a right turn

Feeder bus routes can be provided on the intersecting non-BRT road. The feeder bus-stop should ideally be located close to the intersection to reduce transfer time for commuters.

However, the bus stop should be located some distance away from the intersection so that it does not interfere with the clearing of the intersection. As far as possible, the bus stop should be located on the arm after the intersection.

The BRT station is placed close to the intersection, in order to reduce the transfer time for commuters between the BRT and the feeder bus line. However, there is also one bus length of space between the bus docking area and the pedestrian crossing, so that a bus can wait for a red light, without blocking another bus from loading/unloading passengers at the station.

Replacement of right turns with u-turns

As explained earlier in the chapter, we do not recommend that right turns be permitted at the intersection for a BRT corridor. We, instead recommend that right turns be replaced with a combination of a u-turn and a left-turn. This is explained as follows.

A vehicle that needs to make a right turn queues itself in the rightmost mixed traffic lane, next to the BRT lane. When it gets the green light, it continues straight across the intersection, and then queues itself at the u-turn, which is provided a short distance after the intersection. It then takes the u-turn during the u-turn signal phase, after which it can take a left, thus completing the right turn manoeuvre that it originally intended to make. If the sequencing of signal phases is done correctly, then this manoeuvre can be made possible in a maximum of two signal phases.

In most cases, the straight-moving traffic on such urban arterial roads will far outnumber the right-turning traffic. By not permitting right turns, one can have a longer signal phase for straight movements, thus increasing the through capacity of the intersection. This

creates a benefit for a larger volume of people and vehicles.

Scramble signal

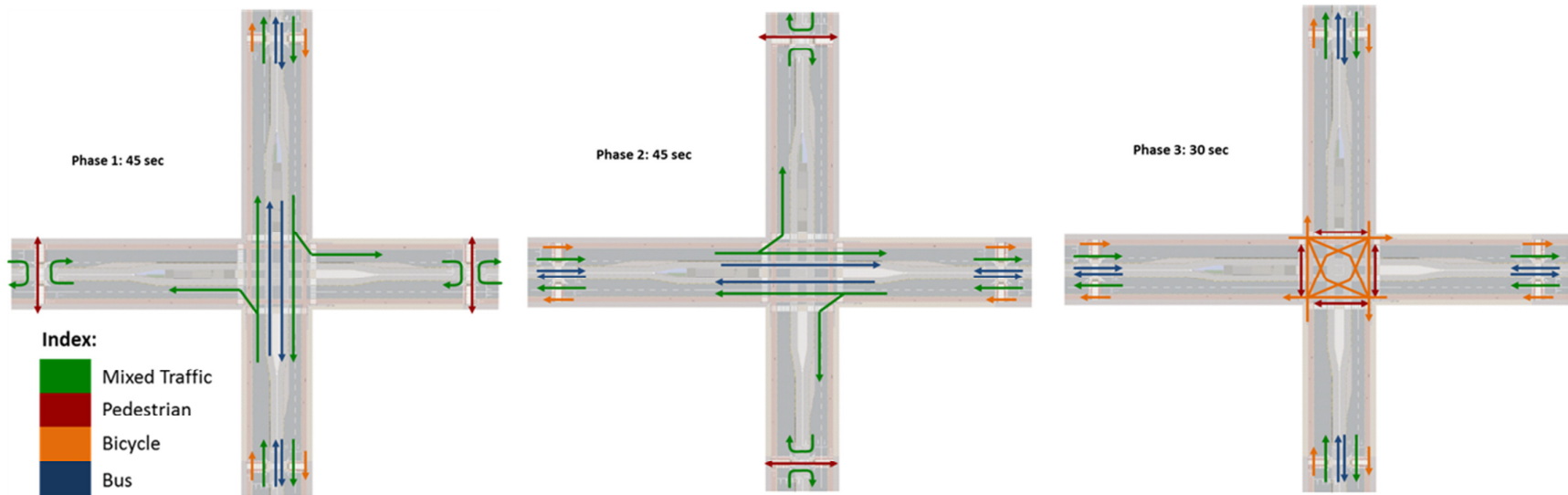
As explained earlier in the chapter, we do not recommend that either NMT or pedestrians share movement with motorised traffic. We, recommend providing an exclusive signal phase for all possible movements for NMT and pedestrians. This is known as the scramble phase. Here, NMT and pedestrians share the same signal phase, from all arms of the intersection to any direction.

Since, there is very less speed differential between NMT and pedestrians, it is not unsafe for them to share a signal phase. The positioning of the pedestrian crossings behind the NMT crossing lane also ensures that the conflict points are kept minimal. One can even provide a few seconds head-start for pedestrians during the scramble phase, so that they will clear the NMT lane when crossing the road.

Signalisation plan

The signalisation plan for this design is an

integral feature of the design. It is important the signal plan for the intersection be synchronised with the signal plan for the adjacent u-turns and pedestrian crossings, in order to minimise the traffic delay, and to ensure that right-turning traffic does not need to wait at more than 2 signal phases in order to make a right turn. We recommend the following signal plan for this intersection.



10. REGULAR INTERSECTION OF TWO BRT CORRIDORS

A comprehensive BRT system is likely to have a number of BRT corridors that intersect each other at various points. An operationally efficient BRT is one, where there is not much overlap between routes; that is, two or more routes do not run a significant distance on the same corridor, and ideally only pass each other at intersections.

The point, where two or more BRT routes meet/pass each other is called the transfer point. This, typically, happens at major intersections. Here, commuters have the option of transferring from one BRT route to the other. Understandably, transfer points, generate a much high volume of commuter traffic that other points along the corridor.

The safe way to design for commuter transfers between two intersecting BRT corridors is the focal point of discussion in the following two chapters. In this chapter, we demonstrate how transfers can be provided for a regular signal-controlled intersection, where space is constrained; that is, the intersection is only as wide as the intersecting roads. In the subsequent chapter, we

demonstrate how transfers can be managed more efficiently, where there is a wider intersection, by placing the BRT transfer station in the centre of the intersection itself.

The template provided in the chapter shows our recommend design for the intersection of two BRT corridors. This template uses all the safety design features discussed in the previous chapter, such as no right turns for motorised traffic, and the scrambled signal phase for pedestrian plus NMT movement.

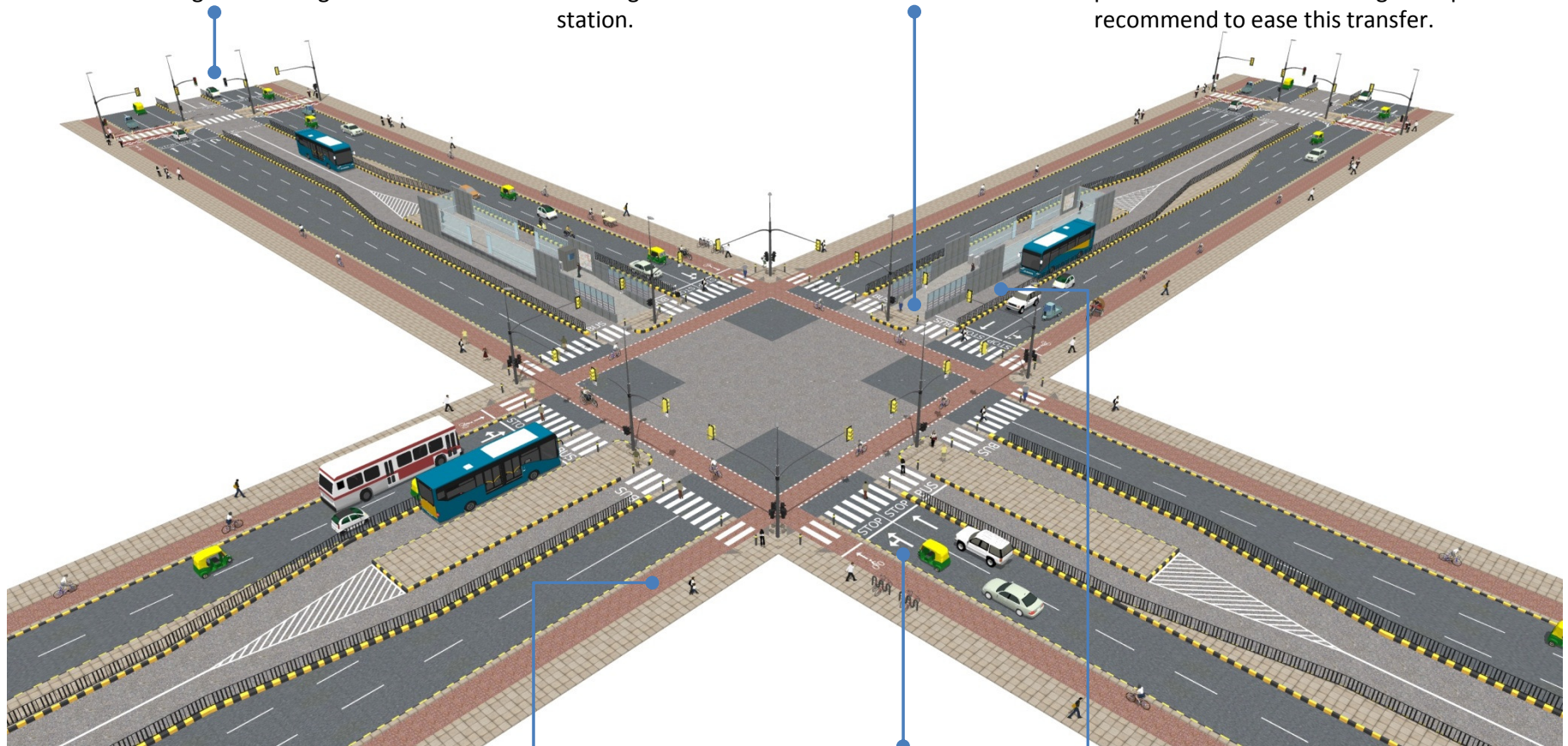
As stated, this template is demonstrated on a road with of 38 meters, where the intersection is also, only 38 meters wide.

Recommended Design Template 7: Regular intersection of two BRT corridors

U-turns are provided a short distance after the intersection on all 4 arms. Sufficient queuing space is provided, to hold the vehicles intending to take a right turn

The BRT station ramp comes out right at the intersection pedestrian crossing. This eliminates the need for having different crossings to serve the intersection and the station.

The BRT stations are placed close to each other at the intersection, to reduce the transfer time for commuters. A all green pedestrian + NMT signal phase is recommend to ease this transfer.



The NMT lane is segregated right till the intersection. This is a safer solution than merging the NMT lane with the mixed traffic lane before the intersection.

Right turns are not permitted from any arm of the intersection. Instead this turn can be done by continuing straight, then taking a u-turn followed by a left turn; or taking a left, then a u-turn and then continuing straight.

There is 1 bus length of space between the bus docking area and the pedestrian crossing, so that a bus can wait for a red light, without blocking another bus from loading/unloading passengers at the station.

11. ROUNDABOUT INTERSECTION OF TWO BRT CORRIDORS

In the previous chapter, we demonstrated our recommended design for the intersection of two BRT corridors, where the intersection was only as wide as the intersecting roads. However, in many cases, the intersection is often significantly wider than the intersecting roads. This will be the case for a roundabout intersection.

This provides the opportunity of locating the BRT transfer station within the area of the intersection itself. Here, both intersecting corridors share a common station building, located in the centre of the intersection.

This is a very safe solution from the point of view of commuter transfer. Here, commuters that want to transfer from one BRT corridor to the other don't have to leave the station building.

The area utilised by the BRT station, and the adjoining BRT lanes, also serves as roundabout to direct mixed traffic. However, one must note that this cannot function as a traditional roundabout because of a number of reasons. Firstly, the presence of the BRT station within the roundabout blocks the view

around the circle for mixed traffic, which is an essential element of safe roundabout design. Secondly, the cuts in the roundabout, on account of the BRT lanes, reduce the weaving length around the circle, which is essential for mix traffic to align themselves in the correct lane around the roundabout.

We, thus, do not recommend that this intersection be un-signalised. Further, we strongly recommend that all potential BRT conflict points with mixed traffic be eliminated, by having separate signal phases. Our proposal for the same is provided in the chapter.

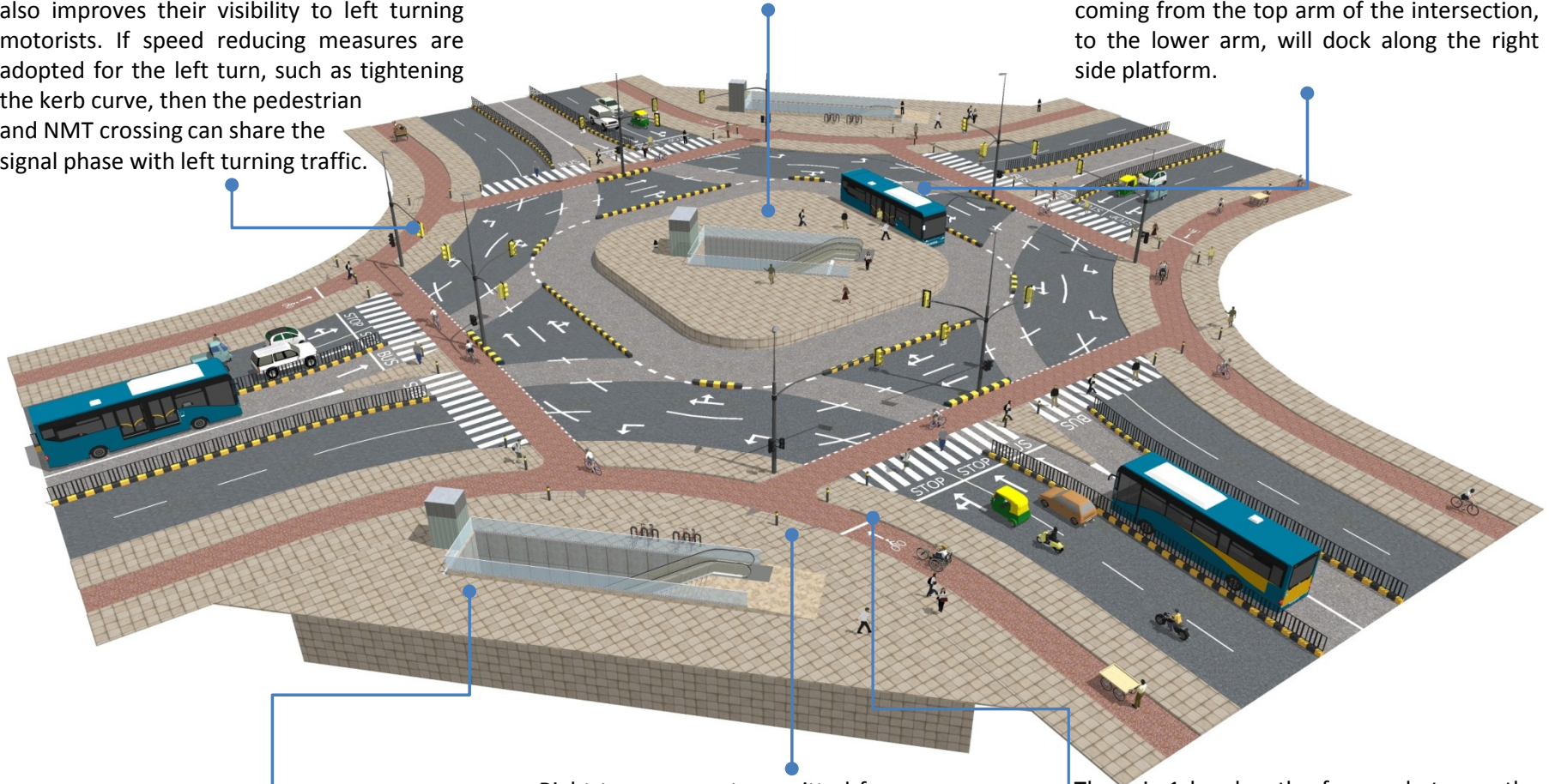
All the safety design features, discussed in the previous two chapters are applicable here.

Recommended Design Template 8: Roundabout intersection of two BRT corridors

The pedestrian and crossings are slightly deflected away from the intersection so that the crossing distances are minimised. This also improves their visibility to left turning motorists. If speed reducing measures are adopted for the left turn, such as tightening the kerb curve, then the pedestrian and NMT crossing can share the signal phase with left turning traffic.

This is the BRT transfer station, where commuters can transfer between routes, without having to exit the station.

There are 4 platforms at each side of the station. The bus docks adjacent to its respective platform. For example, a bus coming from the top arm of the intersection, to the lower arm, will dock along the right side platform.

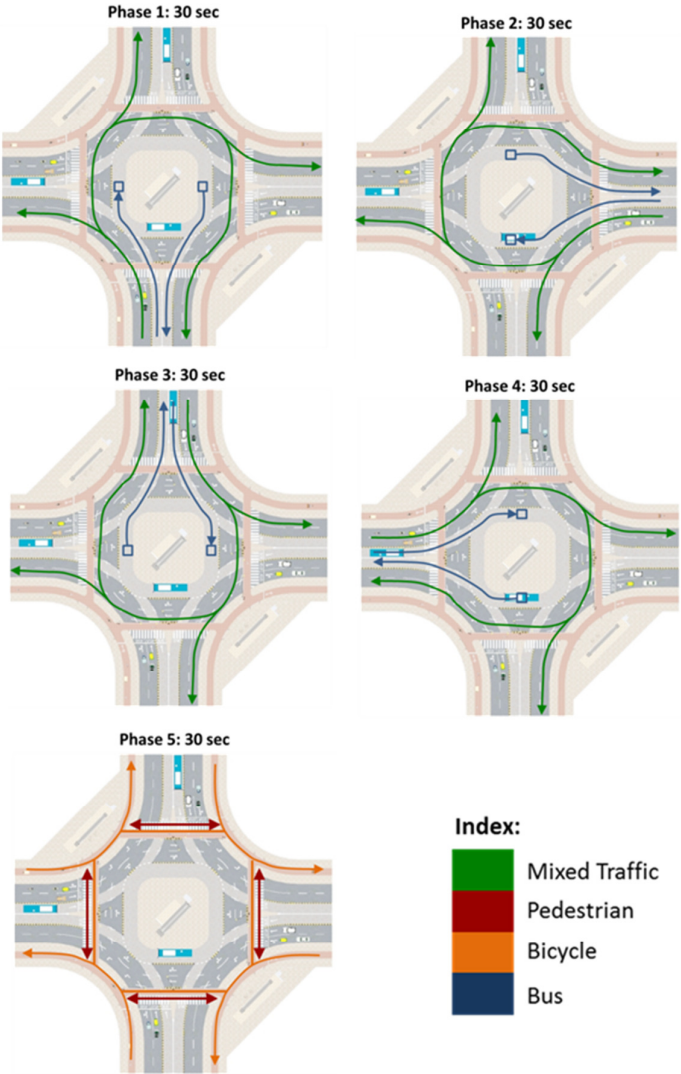


The access to the BRT station should ideally be grade separated, as it is unsafe for pedestrians to cross diagonally into a roundabout.

Right turns are not permitted from any arm of the intersection. Instead this turn can be done by continuing straight, then taking a u-turn followed by a left turn; or taking a left, then a u-turn and then continuing straight.

There is 1 bus length of space between the bus docking area and the pedestrian crossing, so that a bus can wait for a red light, without blocking another bus from loading/unloading passengers at the station.

The recommended signal phasing plan for this design is as follows.



12. BRT WITH EXPRESS LANE SERVICES

The use of express or overtaking lanes is a common feature used for increasing capacity on BRT systems. As some buses can by-pass some stations, the overall throughput of the system can increase considerably beyond what is possible with single-lane operations.

In terms of safety, overtaking lanes introduce a new type of conflict that did not exist in the case of single lane operations – conflicts between buses.

There are several types of conflicts, depending on the overall layout of the station, its number of sub-stops, and the permitted bus merging movements. However, all these crash types have one thing in common – they involve buses leaving the station, entering the express lane, and colliding with buses in that lane. The risk of the crash occurring, and particularly its severity, increases with the speed differential between the two buses. The most serious type of crash involves a local bus leaving the station and colliding with an express bus travelling at high speed in the overtaking lane.

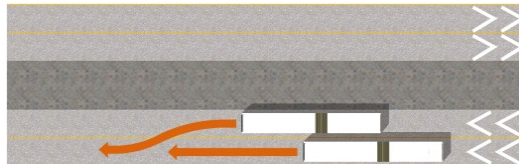


Figure 2: Crash type involving a collision between a local bus leaving the station and an express bus travelling through

A less serious type of crash involves a conflict between a bus leaving the station and another bus attempting to dock at the same time.

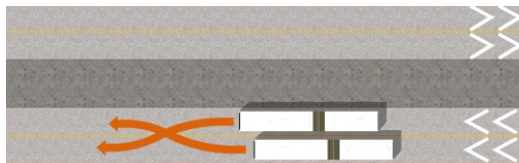


Figure 1: Side swipe between buses at station

This second type of crash usually occurs at a much lower speed, and as a result, it is less serious, rarely resulting in injuries and mostly resulting in damage to the buses.

It is important to establish clear priority rules around stations. Buses in the left (express) lane should always have the priority, and buses in the right (docking) lane should always

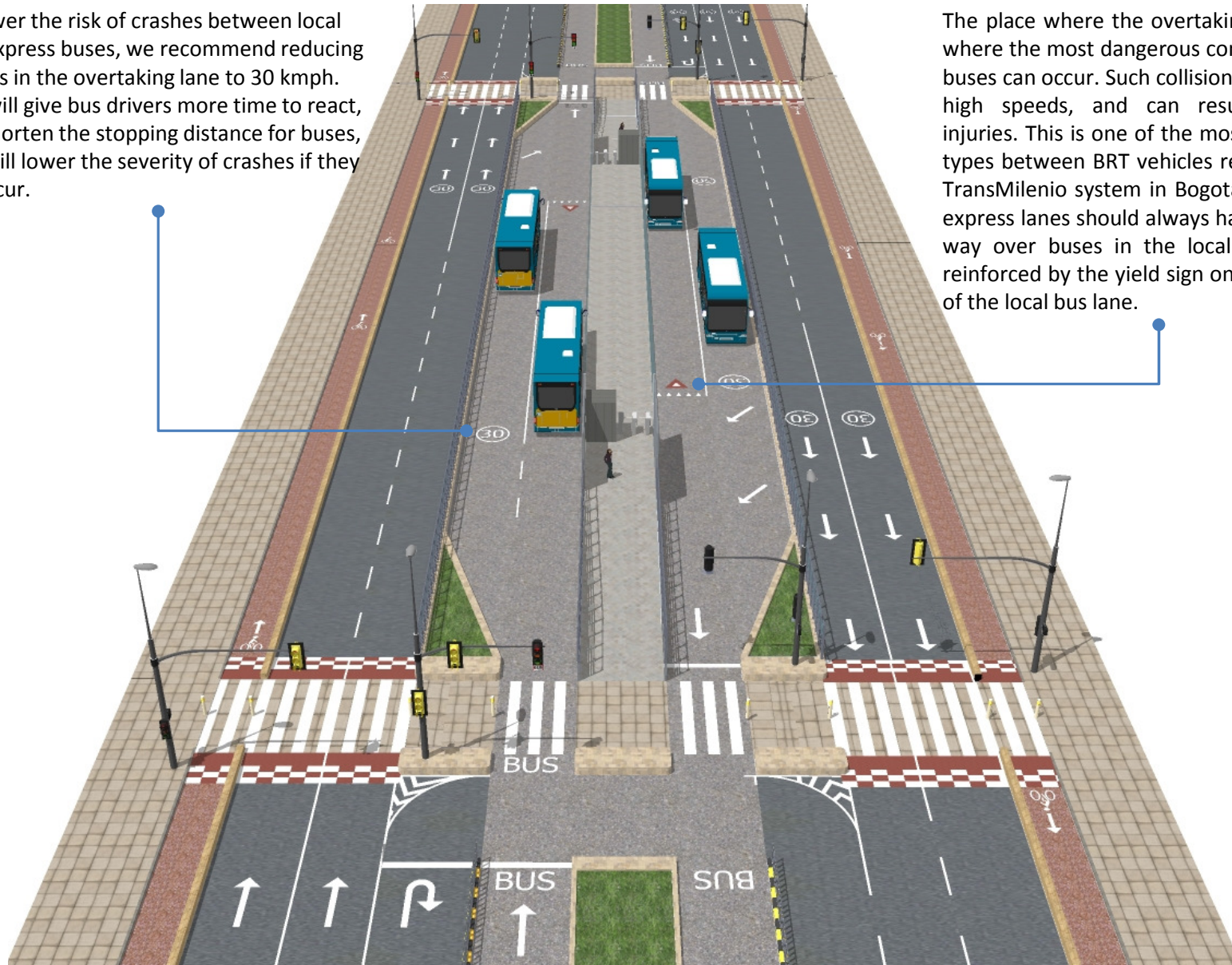
yield to them. This should be enforced through driver training and clear signalisation, as shown in the design template. In addition, speed reductions for express buses can help mitigate this crash risk.

Unlike the previous templates, this design uses a road of more than 38 meters. This is necessary in order to accommodate all the regular continuous elements of the road, and include one additional continuous element, namely the express lane. Express service BRTs are only viable on roads that are wide enough to accommodate this additional requirement.

Recommended Design Template 9: BRT with express lanes

To lower the risk of crashes between local and express buses, we recommend reducing speeds in the overtaking lane to 30 kmph. This will give bus drivers more time to react, will shorten the stopping distance for buses, and will lower the severity of crashes if they do occur.

The place where the overtaking lane ends is where the most dangerous conflicts between buses can occur. Such collisions are usually at high speeds, and can result in serious injuries. This is one of the most severe crash types between BRT vehicles reported on the TransMilenio system in Bogota. Buses in the express lanes should always have the right of way over buses in the local lanes. This is reinforced by the yield sign on the pavement of the local bus lane.



13. BRT TERMINALS

Integrated terminals, featuring cross-platform transfers between different trunk and feeder routes, are the safest transfer options for passengers. The recommended layout is a single platform with trunk lines stopping on one side and feeder lines docking on the opposite side. A single platform configuration eliminates any incentive for passengers to cut across bus lanes when transferring between lines.

The main safety risk to consider is the access point to the terminal for buses. It is important to avoid bottlenecks and to clearly separate different directions of traffic. TransMilenio recorded a fatal crash occurrence at the Portal de Usme terminal when a trunk line and a feeder line collided head-on at the entrance to the terminal, injuring several passengers and killing one. The safest option would be grade separated access for different buses via overpasses or underpasses, but this would only be a good option for a terminal situated at the urban periphery. In a denser urban area, bus conflicts should be addressed by signaling the access points to the terminal.

Depending on the location of the terminal and the route structure, the biggest pedestrian flows might be transfers between bus routes, in which case it becomes important to design access to the different platforms, or access to and from the terminal, in which case the design of the pedestrian access point becomes crucial.

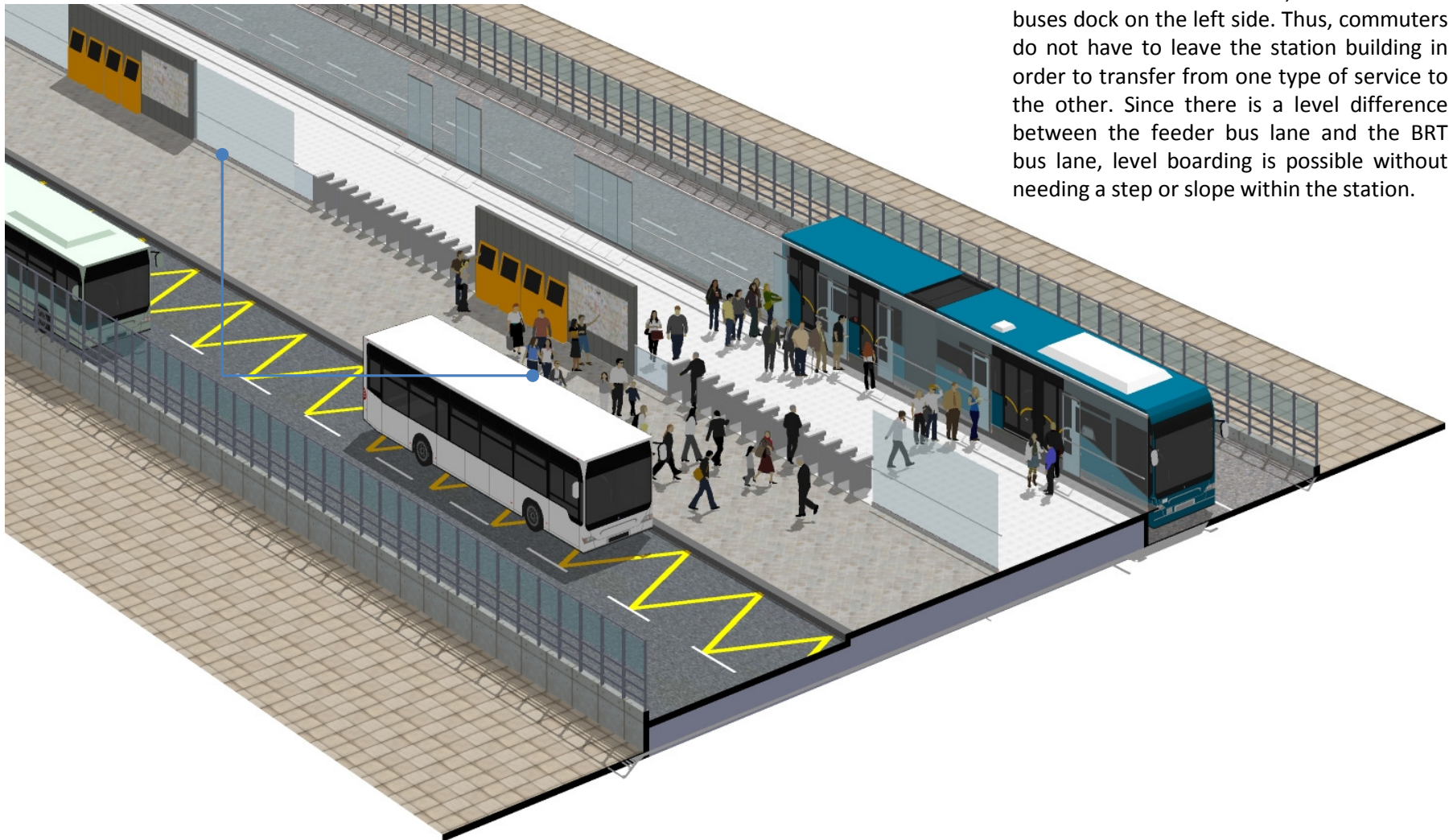
As a general rule, pedestrians and buses should never cross at-grade inside a terminal, since this can easily become a black spot for pedestrian crashes. It is also important to provide sufficient platform width to accommodate the expected volumes of passengers. If the platforms become overcrowded, there is a risk that passengers will end up walking in the bus lanes - particularly on the side of the terminal with low platforms.

If a large number of passengers arrive from outside the terminal, then it should be considered to also create grade separated access for pedestrians, via an overpass or an underpass. This type of solution should always be context specific, since grade separation

may not always work and pedestrians will rarely use bridges or underpasses if the street to be crossed is not very busy or if the pedestrian infrastructure is not clean, secure and well maintained.

Recommended Design Template 10: BRT terminal

Here, the feeder buses dock on the right side of the terminal station, while the BRT buses dock on the left side. Thus, commuters do not have to leave the station building in order to transfer from one type of service to the other. Since there is a level difference between the feeder bus lane and the BRT bus lane, level boarding is possible without needing a step or slope within the station.



14. IMPACT OF THESE RECOMMENDATIONS ON MIXED TRAFFIC CAPACITY

BRT and road capacity

A BRT carries multiple times more people per lane than mixed traffic lanes. Yet, the negative impact that BRT has on vehicular capacity is often cited as a criticism against BRT. Opponents of BRT argue that the congestion faced by all other traffic completely offsets any benefit of time saved for BRT commuters, even though, in terms of numbers, the BRT lanes carry more people than the mixed traffic lanes. This has become a deal breaker for some BRTs in India, notably the New Delhi BRT.

Since a BRT is typically built along existing roads, some impact on mixed traffic capacity is unavoidable. However, evidence from past BRT systems indicates that conditions in the mixed traffic lanes rarely reach the worst-case scenarios suggested by some critics.

Table 1: Mixed traffic volumes on the Macrobus BRT corridor in Guadalajara

Date	Total traffic (% change from '08) ⁵	Vehicles/lane (% change from '08)
2008 (pre-BRT)	3605	450
2009 (post-BRT)	3213 (-11%)	803 (+78%)
2010 (post-BRT)	2102 (-42 %)	525 (+17%)

The capacity for mixed traffic on the Macrobus BRT corridor in Guadalajara, Mexico reduced from 8 lanes to 4 lanes after the BRT was implemented in March 2009. Traffic counts from June 2009 show that overall traffic volumes decreased slightly, but the number of vehicles per lane increased by 78%, to the point where the mixed traffic lanes were operating at or near capacity during the peak hour. However, one year later, traffic volumes had decreased further, to the point where the number of vehicles per lane was within 17% of what it had been before, even though the number of mixed traffic lanes was cut in half. Other BRTs have had a similar

⁵ Weekday PM peak hour traffic counts, provided by E.P.S. Guadalajara and CTS-EMBARQ Mexico.

impact on traffic. After the implementation of the Istanbul BRT in Turkey, for example, annualized average daily traffic (AADT) volumes for private cars on the corridor decreased from 166,425 to 142,217, a 15% reduction.⁶ Overall, the data indicates that drivers generally tend to adapt to the presence of the BRT, by either switching routes or switching modes, so that traffic volumes eventually adapt to the new conditions.

There is an important caveat to consider here. Guadalajara, as most cities in the Americas, has a dense street network, with average block lengths of 50 to 170 meters. With a street grid this dense, it is not difficult to reroute traffic on one or more parallel streets to the BRT corridor. Indian cities, on the other hand, often tend to have much sparser street networks. Delhi, for example, has average block lengths of 800 to 1900 meters in the area around the Delhi BRT. This is ten times as long, on average, as the typical city blocks of a city in the Americas. Indian cities have

⁶ Source: EMBARQ Turkey

considerably lower motorisation rates than the US or Europe, but already face significant congestion, and the sparse street networks in India are a major contributing factor to the problem.

On the one hand, this suggests that if a BRT is implemented in an Indian city on a street that is already operating near capacity, there are few options for rerouting that traffic on other streets. On the other hand, the low vehicle capacity offered by the sparse street networks in Indian cities is a strong argument in favour of promoting high passenger capacity modes, such as BRT.

It is important to note in this context, that the implementation of a BRT often reduces vehicle throughput on a street (Table 1), but always increases passenger throughput (Figure 4). We estimate that the Macrobus corridor in Guadalajara carried 69% more passengers during the peak hour in 42% fewer vehicles after BRT was implemented (Table 1 and Figure 4).

On a more detailed level, decisions regarding intersection geometry and signal phasing can also impact mixed traffic capacity on BRT corridors.



Figure 3: Comparison of number of through north-south streets in 4km² in four cities around the world

The development of the BRT results in reengineering of the road, which may correct previous impediments that were affecting traffic flow. Further, the BRT restricts cross movement to an extent, which can also help in improving throughput capacity. Finally, the BRT takes slow-moving and frequently-stopping buses out of the traffic mix. This also helps to create a smoother traffic flow.

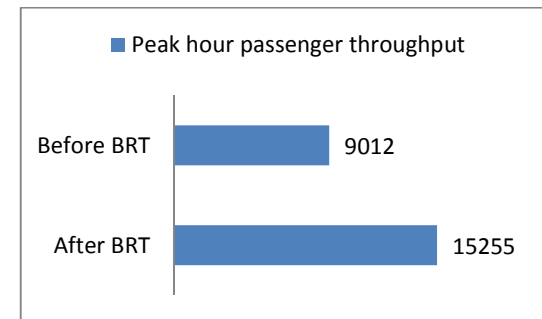


Figure 4: Passenger throughput on the Macrobus corridor in Guadalajara, before and after BRT implementation

However, a poorly designed BRT creates unnecessary bottlenecks that reduce traffic capacity. This is especially true at intersections, where poor traffic signal management further aggravates the situation.

15. DESIGN OF SIGNAL CONFIGURATIONS

Finding the right signal configuration for intersections and mid-block crossings is the key to ensuring that BRT performs well for all the key indicators listed in this guidebook, safety, operating speed, and passenger capacity. A good signal configuration can give priority to the BRT system, ensuring fast, high capacity service, while also providing pedestrians with adequate time and low delays for crossing the corridor safely. At the same time, it can avoid creating congestion in the mixed traffic lanes.

Signal timing is very sensitive to the prevailing local traffic conditions. Thus, designing an effective and optimal signal system requires inputs of traffic volumes, turning counts and mode splits. This data needs to be categorised by the time of day and collected separately for each intersection/midblock section.

These Guidelines suggest signal plans designed to cater to the peak-period congestion in India. However since these Guidelines are to be applied in cities across India, we do not wish to tailor the system to any one city or specific input data. We

propose a general signal configuration making certain assumptions and recommend that these timings be iteratively refined during their application by observing local traffic behaviour. Further, signal plans designed for peak periods may be inappropriate for off-peak periods and vice-versa. This must also be taken into consideration while refining the proposed signal timings.

Road capacity and level of service (LOS)

A road's capacity is defined as the maximum hourly volume (passenger car units or PCU per hour) at which vehicles can traverse a uniform section of that road. Capacity varies by time period and prevailing roadway conditions.

The Indian Roads Congress (IRC) gives tentative capacities for urban roads between intersections⁷. The actual capacities depend on the geometric configuration of the network and the peak direction of travel. Capacities also depend on short-term conditions such as weather, traffic management strategies,

⁷ IRC: 86-1983. Geometric Design Standards for Urban Roads in Plans, Table 4.

fringe access etc.

Level of service (LOS) is defined as a qualitative measure describing operational conditions within a traffic stream and the perception of drivers/passengers. Six levels of service are recognized commonly, designated from A to F, with LOS A representing free-flow and LOS F representing a complete breakdown of traffic movement.

LOS varies by time of day and tends to deteriorate during peak hours. The IRC specifies the LOS for which roads are to be designed but not the LOS which may be reached during peak hours. We refer to the Highway Capacity Manual (HCM)⁸ which recommends that in general, urban arterials are to be operated at LOS D or higher.

However, the peak period traffic conditions in Indian cities often approach congestion with low average speeds and significant intersection approach delays. We expect LOS

⁸ Transportation Research Board, Highway Capacity Manual, Special Report 209, CMP Level of Service Criteria for Arterials Based on Volume-to-Capacity Ratios

to deteriorate to E during this period and thus use a volume-to-capacity ratio of 0.92 in our signal timing calculations.

Principles used in signal timing design

One of the key principles we used to guide our signal configuration design was keeping overall cycle length low.

A long cycle length results in long queues forming on all approaches to the intersection and tends to increase the average delay both for vehicles and pedestrians. Since BRT vehicles are less frequent than mixed traffic, they tend to be more adversely affected by long cycles. The *BRT Planning Guide* recommends a range of cycle lengths for BRT corridors based on international experience which is primarily between 60 to 90 seconds, rising to 120 seconds or higher only at major intersections or during peak hours.⁹

Long cycle lengths also have negative implications for pedestrian safety. The longer pedestrians must wait for a green light, the more likely they generally are to cross on red.

⁹ Wright, L., W. Hook, eds. 2007. *Bus Rapid Transit Planning Guide*. ITDP.

The Highway Capacity Manual (HCM) recommends keeping pedestrian delay under 30 seconds, and ideally bringing it under 10 seconds if possible, in order to ensure pedestrian compliance with traffic signals. The formula for calculating pedestrian delay is given below:¹⁰

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

Where d_p is pedestrian delay, C is the cycle length, and $g_{walk,mi}$ is the effective walk time for pedestrians (generally calculated as the length of the green phase plus four¹¹, all measured in seconds).

Table 2: Examples of various signal configurations and their associated pedestrian delay

Cycle length (sec)	Pedestrian green phase (sec)	Pedestrian delay (sec)
80	40	8.1
120	30	30.8
300	25	122.4

¹⁰ Source: Equation 18-71, HCM 2010

¹¹ Source: Equation 18-49, HCM 2010; the added 4 seconds account for pedestrians crossing during the “blinking red” phase

The methodology we use for calculating the length of each phase and the total cycle length is specified in the Highway Capacity Manual as the “Critical Intersection Method”. This method first specifies the signal plan according to vehicle counts and then checks for compliance to non-motorised user requirements.

In each phase, we determine the specific movement which has the most participation. Once we know the “critical” movement volume in each phase, we use a formula specified in the HCM to determine the minimum cycle length required for this intersection. This cycle length is rounded to the next highest multiple of 5. Then we compute the minimum time required by non-motorised users to negotiate the intersection and either add this time to the cycle length as a “scramble phase” or include it in one of the other phases. This entire process is detailed below.

In general, it is recommended that cycle lengths over a corridor be multiples or sub-multiples of each other. This is done so that signal coordination may be possible in future once all individual block distances have been laid out.

The intersection of two BRT corridors is likely to be the one which sees the maximum traffic volumes and thus the signal plan designed for this intersection is used as a baseline for all other intersections/mid-block sections i.e. all other cycle lengths are set to be multiples or sub-multiples of this intersection's cycle.

Intersection of two BRT corridors

Approach road category: 4-lane urban Indian road with two way traffic; frontage access but no standing vehicles and high-capacity intersections

We use the following parameters from the Highway Capacity Manual since IRC does not directly recommend values.

- Lost time per phase = 4 seconds (3 to 6 seconds recommended by HCM)
- Saturation flow rate = 1900 PCU per hour (recommended by HCM)
- Tentative capacity of approach road according to the IRC: 2500 PCU per hour (two-way)
- Assumed LOS during peak-hour: E
- Volume-to-capacity ratio at this LOS: 0.92

The total design service volume for the

approach road is given by:

$$v_{total} = 0.92 \times 2500 \text{ PCU/h} = 2300 \text{ PCU/h}$$

The volume per direction is therefore equal to half of that, or 1150 PCU/h.

Phase 1: N-S, S-N, left turn to the east, left turn to the west

- Assumed percentage of through traffic = 75% (includes those who take the U-turn later since they were not allowed to take a right at the intersection)
- Assumed percentage of left-turn traffic = 25%

Therefore, critical volume for this phase for two lanes is given by:

$$v_{critical} = 0.75 \times 1150 = 862.5 \text{ PCU/h}$$

Phase 2: E-W, W-E, left turn to the north, left turn to the south

- Assumed percentage of through traffic = 75% (includes those who take the U-turn later since they were not allowed to take a right at the intersection)
- Assumed percentage of left-turn traffic = 25
- Critical volume, similarly, is equal to

862.5 PCU/h

Phase length required for motorized movements therefore is:

$$g_{veh} = 2 \times \frac{4}{1 - \left(\frac{862.5 + 862.5}{1900} \right)} = 86.86 \text{ sec}$$

The total length of each pedestrian crossing is 31.6 meters. Assuming a walking speed of 1.2 meters per second and adding a four second buffer, the length of the pedestrian signal phase would be 30.33 seconds.

There are several possible cycle configurations for this intersection. The simplest one would consist of two 45 second phases – one for each corridor – which would allow left and through movements for motorized traffic and also pedestrian crossings along the same direction.

This option would have a short cycle length of 90 seconds, a very short pedestrian delay of 9.3 seconds, and would also mean that pedestrians only need to cross about 10 meters before reaching a refuge island. However, this would pose the problem of conflicts between left turns and pedestrians. The green to cycle (g/C) ratio for each BRT

corridor would be 0.5 under this configuration, which is compatible with high speed, high capacity operations.

If the left turn conflicts occur primarily at one corner of the intersection, they could be solved by adding a third phase with a protected left turn movement in that particular location. Through traffic along the same corridor would also have a green light, but the pedestrian signal for that specific movement would be red during that time. This would have the effect of increasing green time on one BRT corridor and reducing it on the other, and it should be checked against the expected demand and the desired operating speeds on each corridor.

Another option is to create an all pedestrian “scramble” phase. This would stop all motorized traffic on both corridors and allow all pedestrians and cyclists to cross in all directions at once.

The length of the “scramble” phase should be calculated based on the diagonal of the intersection, since pedestrians should be allowed to cross diagonally during the scramble phase. The length of the diagonal can be calculated as the hypotenuse of a right

triangle, in which the two other sides of the triangle are the respective lengths of the pedestrian crossings along each of the two intersecting streets. The required phase can be estimated from this, using a 1.2 meters walking speed and adding a 4 second buffer:

$$g_{scramble} = \frac{\sqrt{31.6^2 + 31.6^2}}{1.2} + 4 = 41.24 \text{ sec}$$

The total cycle length is the sum of this phase and the two vehicle phases, or 128.1, which we round up to 130 seconds. Pedestrian delay under this configuration is just over 27 seconds, an acceptable value according to the HCM.

A safety concern under this configuration is that pedestrians must cross around 40 meters diagonally without a refuge island in-between. 40 meters is quite long for a pedestrian crossing, though the length of the phase should allow sufficient time for pedestrians to cross in one phase. The two-phase option described above would perform better in this regard. In addition, the scramble phase would add delays and reduce capacity for both BRT corridors, by significantly increasing their respective red times and bringing their g/C ratios close to 0.3, significantly below the

generally recommended value of 0.5. Yet another issue with this signal configuration is that 130 second cycle breaks away from the rule of having all cycles be multiples or sub-multiples of each other, and may make signal coordination difficult. We would therefore recommend that the two-phase option be given priority for this type of intersection and that a scramble phase only be used if the pedestrian / left turn conflicts are serious.

An important detail for this intersection is the coupling of its signal configuration with that of the downstream U-turns. Instead of allowing cars to make a right turn at the intersection (a major safety concern for BRT operations), we allow a left turn, immediately followed by an U turn, which can allow a driver to complete the same manoeuvre within one signal phase, while avoiding conflicts with the BRT.

Mid-block crossing

We have determined previously that the time required for pedestrians to safely complete the crossing of a 31.6 meter wide road is approximately 30 seconds.

We also know that the cycle length for the mid-block crossing can be shorter than the

one for the four-leg intersection since the volume of traffic handled here is much smaller. We choose 90 second which is a sub-multiple of 120 second. We allocate 30 second to the pedestrian phase and the remaining time to mixed traffic.

Mid-block U-Turn

The configuration of this signal is identical to the mid-block crossing with the only difference being that U-turns are allowed during the pedestrian phase, since they do not conflict with the crossing movement.

T-intersection

We allow free merging from the minor road onto the main corridor in anticipation of low traffic volumes coming going in and out. This saves us a separate phase for minor road traffic. The bicycle lane for the T-intersection is also specially adapted by introducing a kink (see chapter on T-intersection model for more details). This helps us to eliminate an exclusive cyclist phase.

Thus, through innovative design we are able to cut down on phases and stick to short cycle

of 90 second here as well. Of this, we allocate 30 second to pedestrians and the rest to mixed traffic.

Mid-block station

The signal configuration for a mid-block station is very similar to that of a mid-block U-turn with the only difference being that signals on both sides of the station need to be in-sync.

Roundabout Interchange

We need a dedicated phase for mixed traffic from each approach road since vehicles are allowed a range of movements. They can go left, go straight through, take a right or even take a U-turn. Combination of vehicular movements from different approach roads is impossible. However, some non-conflicting bus movements can be inserted into each phase by taking advantage of the roundabout design. This has been demonstrated in the report (chapter on roundabout interchange). Overall we have 5 phases; one for each approach road plus 1 scramble phase for pedestrians and cyclists.

The large number of phases demands a higher cycle time than the four-legged intersection of the BRT corridors. We chose 150 second (multiple of 30 and compatible with the other 90 and 120 second cycles) and split the time evenly between the 5 phases.

Summary of signal configurations

The analysis provided in this chapter illustrates that the implementation of our safety recommendations (particularly turning restrictions and green phases for pedestrians allowing them to cross the entire street in one phase) do not have a negative impact on mixed traffic operations. It is possible to provide an acceptable level of service to motorized mixed traffic while also implementing a BRT with a high standard of safety and quality of service.

16. SAFETY AND BRT PASSENGER CAPACITY

The two previous chapters dealt with the impact of a BRT (and of the added safety features we recommend) on mixed traffic along the corridor. We showed that if implemented correctly, our recommendations should not negatively impact other travel modes on the corridor. In this section, we discuss how our safety recommendations might impact the passenger capacity of the BRT.

The factors that influence the passenger capacity of a BRT

The passenger capacity of a transit system is usually broken down into two key components, that of a transit way and that of a transit station. “Way capacity is the maximum number of passenger spaces that can be transported in vehicles past a point in one direction per hour without stopping. Station capacity is the corresponding number of spaces in vehicles stopping at stations.”¹² The overall passenger capacity of a system is

¹² Vuchic, V. 2005. *Urban Transit. Operations, Planning, and Economics*. Hoboken, New Jersey: John Wiley and Sons, p.79

likely to be constrained by station capacity, which is generally lower than way capacity, due to longer headway requirements.

Station capacity for centre-lane BRT corridors

We use the following formula for calculating passenger capacity at stations, derived from Hidalgo et al. 2011:¹³

$$Ca = \sum_{i=1}^{N_{sp}} x_i \times \frac{3600}{T_{sb} \times (1 - Dir) + T_o} \times Cp \times LF$$

Where: Ca [pax/hour] is the passenger capacity of the station, N_{sp} is the number of sub-stops per station, x_i is the acceptable saturation rate at stations,¹⁴ 3600 is the number of seconds in an hour, T_{sb} is the boarding and alighting time, in seconds, Dir is the percentage of buses that do not stop at

¹³ Hidalgo D., G. Lleras, E. Hernandez. 2011. *Passenger Capacity in Bus Rapid Transit Systems - Formula Development and Application to the TransMilenio System in Bogota, Colombia*, presented at Thredbo 12 Conference, Durban.

¹⁴ The saturation level of a station refers to the percentage of time that a vehicle stopping bay is occupied. Wright, L., W. Hook, Eds. 2007. *Bus Rapid Transit Planning Guide.*, 3rd edition. Institute for Transportation and Development Policy (ITDP), New York, vol. 1, p.246

the station (i.e. express services), T_o is the minimum interval between two buses or convoys, Cp [pax/convoy] is the passenger capacity of a convoy; if convoys is not used on the corridor, then this simply becomes the capacity of a bus, LF is the load factor for buses (i.e. the percentage of offered capacity that is utilized during the peak hour).

The BRT systems currently in operation or in the planning stages in India use standard 12-meter buses with a capacity of 70 passengers per bus. We therefore used this value for our capacity calculations, so that our estimates can be compared to observed peak loads in operating systems. Most of the other values would normally be determined through field observations. However, since we did not have field observations in the Indian context for these types of variables, we started with default international values derived from Hidalgo et al. (2011) and Wright and Hook (2007) and used professional judgment to adjust those parameters to bring them closer to their expected values in the Indian context. As an example, the average boarding and alighting time achieved by TransMilenio using

articulated buses with simultaneous boarding / alighting via four doors is 16.3 seconds. In the case of India, this value is likely to be higher, since boarding is usually done via a single, wider door, as in the case of the Janmarg BRT in Ahmedabad. We estimated that boarding and alighting times would actually be closer to 20 seconds in this case.

We developed four different scenarios for estimating station capacity. The reason for this is that the passenger capacity of a BRT station can vary greatly depending on service characteristics, such as the use of limited stop services, overtaking lanes, and multiple sub-stops per station. The first full-fledged BRT to be implemented in India, the Janmarg system in Ahmedabad, had relatively low peak loads (1,780 pphpd) and daily passengers (35,000), especially when compared to previous BRT applications in Latin America.¹⁵ Transit mode share in India is still fairly low outside of megacities such as Delhi or Mumbai, representing between 15 and 30% of trips in cities of under 5 million inhabitants, where

non-motorized modes are predominant.¹⁶ However, as cities continue to grow in size and as the Indian economy continues to grow, the rate of motorized trips, including transit, is expected to rise.¹⁷ Therefore, while relatively low demand may be the norm in Indian BRT systems in the short term, it reasonable to expect that demand will increase in the medium and long term. The four different capacity scenarios are designed with this in mind.

Scenarios 1 and 2 closely replicate the conditions on the Ahmedabad BRT and the Delhi Busway, with peak loads of 1,700 to 6,500 pphpd. This is what we would expect to see in Indian BRTs in the short term. Scenario 3 represents a slight increase in capacity, through the use of overtaking lanes, while scenario 4 is an ultra-high capacity case modelled on Bogota's TransMilenio system, featuring multiple sub-stops and express services. While not a realistic scenario in the short to medium term for the Indian context, it represents the upper range of passenger capacities achievable by BRT, and can serve as

a useful point of comparison. When we propose a design concept and estimate the capacity of the BRT at that particular location (e.g. intersection, mid-block crossing) we can compare that number with both the typical capacity of an Indian BRT (scenarios 1 or 2) and to what could be achieved by implementing high capacity station designs (scenarios 3 or 4). This allows us to offer a comprehensive review of how the safety concepts incorporated in our design may impact the passenger capacity of the BRT. The operational characteristics of each of the four scenarios are described in more detail below.

Across all scenarios, we used standard 12-meter buses with a capacity of 70 passengers per bus, since this is the type of BRT vehicle commonly used in the Indian context.¹⁸ A common response from BRT agencies to increased demand on their system is to upgrade to larger articulated or even bi-articulated buses. It is likely that this would also happen in Indian BRTs. However, the main objective of our capacity calculations is to compare the capacity of our proposed intersection designs to that of the stations, in order to check that our recommendations do

¹⁵ Hidalgo, D., A. Carrigan. *Modernizing Public Transportation. Lessons learned from major bus improvements in Latin America and Asia*. WRI Report, World Resources Institute, Washington DC, 2010.

¹⁶ Tiwari, G. *Key Mobility Challenges in Indian Cities*. International Transport Forum, Discussion Paper 2011 – 18, Leipzig, Germany, 2011.

¹⁷ Tiwari, G. Op. cit.

¹⁸ Wright and Hook, op. cit., volume 1, p. 266, table 8.6.

not restrict capacity. For this purpose, it made sense to keep bus capacity constant across all examples, so that the different estimates would be comparable.

Scenario 1: Single lane BRT with one platform per station per direction and no overtaking lanes or convoying (Janmarg BRT, Ahmedabad)

This is the most basic type of BRT operation, featuring one dedicated bus lane per direction and a single platform per station per direction.

Scenario 2: Single lane BRT with two platforms per station per direction and use of convoys without coordinated dispatch, and different services in each platform (Delhi Busway)

This scenario more closely resembles the operation of the Delhi Busway. The corridor still features only one bus lane per direction, but multiple bus services with different origins and destinations share the same bus lane and stop at the same stations. Each bus service has its designated platform at the station, but there are no overtaking lanes. If two buses from separate services arrive at the station in the right order, they are able to dock at their respective platforms at the same time.

However, since there is no coordinated dispatch, there is no way to control the order in which buses arrive. When they do not arrive at the same time, one bus is forced to wait behind the other, incurring delays. Hidalgo et al. (2011)¹⁹ recommend that in such cases, we should use a conservative estimate of 0.25 for the probability of two buses arriving in the correct order. While the impact of different types of convoying is not addressed explicitly in the equation 1, it is captured in the default values used for dwell time (T_{sb}) and minimum interval between buses (T_o) in table A120. Despite its limitations, this configuration provides a marginal capacity increase compared to scenario 1.

Scenario 3: Single lane BRT with one platform per station per direction, with express services and overtaking lanes

This option increases capacity through the use of overtaking lanes at stations. The presence

¹⁹ Hidalgo D., G. Lleras, E. Hernandez. 2011. *Passenger Capacity in Bus Rapid Transit Systems - Formula Development and Application to the TransMilenio System in Bogota, Colombia*, presented at Thredbo 12 Conference, Durban.

²⁰ The values for T_{sb} and T_o are based on field observations conducted by Steer Davies Gleave for TransMilenio in Bogota, (Hidalgo et al. 2011, op. cit.)

of overtaking lanes allows express or limited stop services to skip some stations, increasing throughput. The impact of express services is captured in the $(1 - Dir)$ term in equation 1. When $Dir = 0$, the system does not have any express services, and the capacity is identical to scenario 1. If the value of Dir is increased to 0.7, capacity increases, assuming all other parameters remain constant.

Scenario 4: (High capacity) BRT with two sub-stops per station, two platforms per sub-stop, and overtaking lanes.

This scenario features considerably longer stations, with two sub-stops each, storage capacity for buses, and double platforms. This configuration, together with the presence of express lanes at stations, can help increase the capacity of the BRT (table A2).

Table A1 lists the default values we used based on operational scenarios (i.e. convoying with coordinated dispatch, no convoying, etc.) and their respective source.

Table A1: Default values used in station capacity calculations

Parameter	Parameter values				Source (if applicable)
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	
N_{sp}	1	1	1	2	
x_i	0.6	0.6	0.6	0.6	Hidalgo et al. (2011)
T_{sb}	20	36.3	20	20	Adapted from Hidalgo et al. (2011)
T_o	14.5	21	27	14.5	Hidalgo et al. (2011)
Dir	0	0	0	0.7	
LF	0.9	0.9	0.9	0.9	Wright and Hook (2007)
C_p	70	140	70	70	

Figure A1 illustrates the different components of a BRT station, including the difference between platform, sub-stop, and station.

Figure A1: The different components of a BRT station

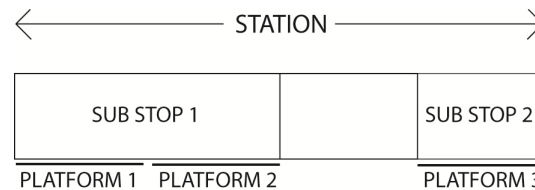


Table A2: Station layout diagrams and capacity estimates for the four scenarios

Station design scenario	Station layout diagram	Capacity (pphpd), from eq. 1
1	STATION PLATFORM BUS LANE	3,950
2	STATION PLATFORM 1 PLATFORM 2 BUS LANE	4,300
3	STATION PLATFORM BUS LANE OVERTAKING LANE	5,500
4	STATION SUB STOP 1 PLATFORM 1 PLATFORM 2 BUS LANE OVERTAKING LANE	13,300

Estimating the impact of our station design recommendations on capacity

Our recommendations for station design focus on the following key areas: better control of pedestrian access to stations, discouraging jaywalking, preventing passengers from accidentally falling in the bus lanes, and slight speed reductions for express buses as they pass through stations. None of these should have any impact on passenger capacity, since they do not affect any of the terms in equation 1. This means that the only way in which our recommendations might impact capacity is if we end up reducing the capacity of an intersection or mid-block crossing to the point where it is less than station capacity.

Lane capacity for centre-lane BRT corridors

Way capacity – or bus lane capacity in the case of a BRT or Busway – at an intersection or signalized mid-block crossing is a function of the green time available for buses, the signal cycle time, the number of lanes, and the saturation flow rate.²¹ For an exclusive central bus lane, we used the following equation for calculating capacity:

²¹ Hidalgo et al. 2011, op. cit.

$$Ca \left[\frac{pax}{h} \right] = C_v \left[\frac{pax}{veh} \right] \times LF \times N \times s \times g/C$$

Where Ca is capacity of the corridor in terms of passengers per hour per direction at a given intersection or mid-block crossing, C_v is the average passenger capacity vehicles operating in the bus lanes, LF is the load factor for buses (i.e. the percentage of offered capacity that is utilized during the peak hour), N is the number of bus lanes per direction, s is the saturation flow rate for a through bus lane (vehicles per hour of green time), g/C is the green time to signal cycle time ratio for buses at that particular location.

For our calculations, we used a saturation flow rate for dedicated bus lanes of 738 vehicles per hour, based on recommended values from Hidalgo et al. (2011). Just as for station calculations, we used a passenger capacity of 70 persons for a standard bus, and assumed a 0.9 load factor during the peak hour (i.e. buses are 90% full). Table A3 lists the estimated passenger capacity for the BRT for the intersection and mid-block crossing design concepts included in this guidebook, based on the parameters listed above and the proposed signal configuration and timing, and compares that capacity to that of the stations under

each of the four scenarios discussed in tables A1 and A2.

Table A3: Intersection capacity for Indian BRT systems and ratio to station capacity.

Type of intersection	Ratio to station capacity			
	Scenario 1	2	3	4
4-way intersection of two BRT corridors	4.4	4.1	3.1	1.3
Mid-block crossing with U turns	7.9	7.2	5.6	2.3
Mid-block crossing without U turns	7.9	7.2	5.6	2.3
T intersection	7.9	7.2	5.6	2.3

Estimating the impact of our intersection design concepts on capacity

None of the ratios in table A3 are lower than 1, which indicates that none of our proposed signal configurations and geometric designs for intersections will lower capacity of the BRT below that of the stations. In other words,

even if the planners of a new BRT choose a station configuration geared towards high-capacity operations, our safety recommendations can still be implemented without creating bottlenecks on the corridor.

One could, however, point out that the intersection between the two BRT corridors has a capacity only 1.3 times that of a high-capacity station from scenario 4, sufficiently close to indicate that it might become an issue if operating conditions become slightly less than ideal.

However, systems that feature stations such as the one in scenario 4 (e.g. TransMilenio in Bogota and Metropolitano in Lima) commonly use two dedicated bus lanes per direction throughout the entire length of the corridor. Our calculations for intersection capacity all assume one dedicated bus lane per direction. This means that the actual capacity of the intersection would be higher in that case. However, it would likely not be the double of our current estimate. Hidalgo et al. (2011) point out that while systems such as TransMilenio feature two dedicated bus lanes per direction, many of the major intersections also have stations adjacent to them. The presence of the stations – where one of the

two bus lanes effectively becomes a bus docking bay on one side of the intersection – means that the effective number of lanes per direction is actually 1.5. In this case, our intersection of two BRT corridors would have a capacity of 26,152 (=17,435 x 1.5) and would no longer risk being a bottleneck for the system.



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