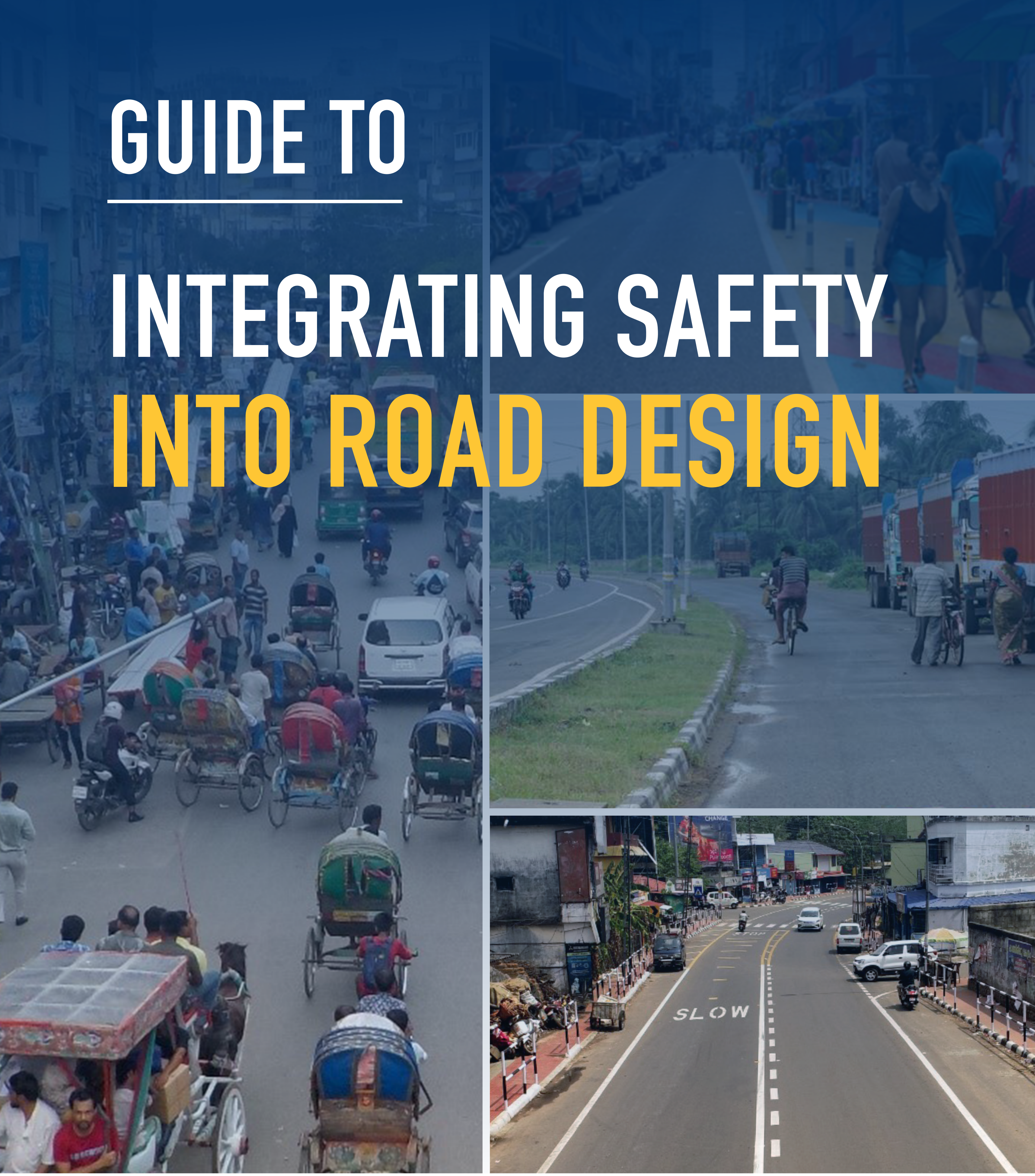

GUIDE TO

INTEGRATING SAFETY INTO ROAD DESIGN

THE WORLD BANK

GRSF
Global Road Safety Facility

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1. INTRODUCTION

1.1. Integrating Safety into Road Design

Road crashes account for an estimated 1.35 million deaths and 50 million injuries worldwide each year, with over 90 percent of the reported deaths occurring in developing countries.[1] Road crashes represent a major burden on health systems and other services, and inflict pain and suffering on communities and individuals. The combined injury and social costs of crashes pose a heavy financial burden on the economy. According to World Bank statistics, in low- and middle-income countries (LMICs) alone, deaths and serious injuries cost economies 1.7 trillion dollars and over 6.5 percent of gross domestic product (GDP).[2] Governments around the world are working to reduce road-related trauma and have agreed to halve the number of deaths occurring on the roads by 2030.[3] There are known, cost-effective solutions that can be implemented to address this global crisis.

The 2030 Agenda for Sustainable Development recognizes that road safety is a prerequisite to ensuring healthy lives, promoting well-being, and making cities inclusive, safe, resilient, and sustainable. The Decade of Action for Road Safety 2011–2020, officially proclaimed by the UN General Assembly in March 2010, had a goal to stabilize and reduce the forecasted level of road traffic deaths around the world. To continue this global focus on improving road safety, the UN General Assembly has adopted a new resolution on global road safety, proclaiming the period 2021–2030 as the Second Decade of Action for Road Safety with the goal to reduce road traffic deaths and injuries by at least 50 percent by 2030.

A substantial reduction in road deaths will only be feasible if concerted efforts are made, following the "Safe System" approach involving all elements of road safety, management, and delivery. This includes all pillars of the Safe System—starting from road safety management, safe roads and roadsides, safe speed, safe vehicles, safe road users, and post-crash care. This guide focuses on elements of safe road and roadside designs for road networks that can provide safe mobility to all road users, as well as complementary changes to improve speeds, vehicle safety, road user behaviors, and post-crash care. A balanced road design must take into account these complementary system elements to maximize safety benefits. The energy carried by a moving object is proportional to the square of its speed. A well-designed "forgiving roadside" ensures that this energy is dispersed in a crash, and as a result, less energy is transferred to the occupants.

Road infrastructure design plays a vital role in road safety outcomes. Safe infrastructure supports other road safety pillars by encouraging appropriate road user behavior (such as appropriate speed and correct lane position) and by providing a forgiving road environment if things go wrong. Poorly designed road infrastructure can give rise to dangerous road user behavior. One of the key realizations of the

> "When a crash occurs, road infrastructure has the most significant influence on the severity of the outcome of a crash. Improvements to infrastructure can contribute substantially to reductions in death and serious injury".
>
> **Source:** PIARC Road Safety Manual

1 World Health Organization/WHO. 2018. Global Status Report on Road Safety. WHO: Geneva.

2 Wambulwa, W.M., and Job, S. 2020. Guide for road safety opportunities and challenges: Low- and middle-income country reports. Washington, DC: Global Road Safety Facility, World Bank.

3 United Nations General Assembly Resolution A/RES/74/299 on Improving Global Road Safety.

Safe System approach is that drivers make mistakes and will continue to do so, even if we can reduce how often these occur. This road user error has long been recognized as a significant contributor to poor road safety outcomes. However, roads of any given speed can be designed to reduce the likelihood of crashes occurring, and there is very clear evidence that the severity of outcomes when crashes do occur is significantly influenced by the road design.[4]. Even if a crash still occurs, improved road infrastructure can save many lives and prevent debilitating injuries.

As examples of the significant benefits that can be obtained through the provision of safe road infrastructure, reductions in deaths and serious injury of up to 80 percent are possible by installing appropriate barrier systems and ensuring that these are adequately maintained, while the same benefits can be obtained from installing well designed roundabouts.[5]

The Safe System approach highlights that a shared response is required to address road safety. This means that road users will continue to take responsibility for their actions, for instance by being alert and compliant with road rules. However, it is also recognized that road managers and designers have a significant responsibility to provide a road system that protects all road users. This can be achieved through appropriate designs of roads.

As an example, if a driver runs off the road and sideswipes a tree at high speed, there is a very high probability of a fatal or serious crash outcome. In this same situation, if road users were protected from the tree by a well designed and installed roadside barrier, the risks to the occupants would be significantly reduced to the extent that it is likely that only minor damage would occur to the car, but that there would be no significant injuries (assuming a reasonably safe and well-maintained vehicle). This is regardless of the cause of the crash: impairment, misjudgment of speed, fatigue, distraction, drugs, or alcohol. The same protection occurs when pedestrians and cyclists are adequately separated from motorized traffic, or when speeds are managed through traffic calming to appropriate levels given the road users present. Similarly, when vehicles travelling in opposing directions at high speeds are separated by barriers, the risk of a head-on crash occurring is greatly reduced. The provision of this safe road infrastructure relies on good decision-making by recognizing key risk factors while planning road infrastructure and incorporating appropriate design elements to address these risks. This also requires an understanding of the key crash types that result in death and serious injury. These crash types include collisions with vulnerable road users (including pedestrians and cyclists); run-off road, head-on, high-angle collisions including right-angle crashes at intersections; and rear-end crashes.

Substantial improvements to road systems are already occurring in many countries. However, efforts to improve the whole system are required, and this will take time and resources. A long-term vision is required to provide improved design to support safe road design and use following safe system principles. Many countries have set a target date of 2050 for an elimination of death and serious injury on the roads (e.g., in Europe[6], [7] and Australia[8]). This will require commitments of key partners involved in decision-making to provide infrastructure that works alongside improvements in vehicle safety as well as other Safe System pillars to produce such outcomes.

4 Stigson, H. Krafft, M., and Tingvall, C. 2008. Use of Fatal Real-Life Crashes to Analyze a Safe Road Transport System Model, Including the Road User, the Vehicle, and the Road. Traffic Injury Prevention ,9:5, 463–471.

5 Turner, B., Job, S., and Mitra, S. 2021. Guide for Road Safety Interventions: Evidence of What Works and What Does Not Work. Washington, DC: World Bank.

6 European Commission. 2011. White Paper "Roadmap to a Single European Transport Area—Towards a competitive and resource efficient transport system," COM (2011) 144 final.

7 Council of the European Union. 2017. Council conclusions on "Road safety endorsing the Valletta Declaration" Valletta, March 28–29, 2017, 9994/17, http://data.consilium.europa.eu/doc/document/ST-9994-2017-INIT/en/pdf.

8 ATC. 2019. Transport and Infrastructure Council Communiqué November 22, 2019, https://www.transportinfrastructurecouncil.gov.au/sites/default/files/documents/12th_transport_and_infrastructure_council_communique_22nov_2019.pdf.

1.2. Safe System Guiding Principles to Safer Design

The following Safe System principles are recommended to ensure safety in sustainable road transport system design:

1. Inclusiveness: Road design needs to be for all road users—not only for motorized vehicles. The implication of this is that designers need to cater for the most vulnerable road users present. In doing so, safety will typically be improved for all road users.
2. Road functionality: Roads serve two functions: "access and mobility" or "movement and place." Roads serve two primary functions or "roles": to facilitate the movement (mobility) of people and goods and to act as places (access) for people. For safe design the "actual function," not the "intended function" should be identified. In cases where mono-functionality cannot be realized in the short term, efforts should be made to provide adequate safety through safe speeds, starting with provision for the most vulnerable road users.
3. Clarity: Design should meet road users' expectations and be free from any surprise to road users. In case of practical limitations, clear delineation (e.g., markings and signs), adequate sight distance (e.g., decision sight distance), and/or speed management should be used to provide safety for all road users. In addition, variations in key design parameters along the road have an impact on traffic flow and safety. Such transitions should be supported by safe speed reductions, for example, traffic calming. This is applicable in case of variation in cross-section design near bridges/culverts, for roads passing through villages and towns, at-grade crossing facilities for vulnerable road users, and so forth.
4. Homogeneity: Design should limit differences in vehicle speed, direction of travel, mass, and size. The design should ensure that vehicles (road users) travelling at different speeds are not able to interact (e.g., fast moving cars and vulnerable road users); that those travelling in different directions are not able to collide, especially at higher speeds, (for example in head-on conflicts), and that road users of different mass or size do not mix (for instance, trucks and vulnerable road users). Where it is not possible to provide designs that ensure separation, speeds need to be low. The implication of this principle includes that:
    - Design should ensure the safe segregation of vulnerable road users from motorized traffic where operating speeds need to be above 30 kph, i.e., conforming to Safe System speed.
    - Designs should ensure, whenever possible, physical separation between bi-directional traffic in situations where speeds are above human tolerance levels (e.g., 70 kph for motorized vehicles that have modern safety features) and more so when visibility is restricted.
5. Safe Speed: Design should support Safe System speeds. The determinant of "safe design" is the safety of the most vulnerable or least protected road user and their tolerance to impact forces during a collision. This survivability is largely dictated by the impact speed for different road users. Hence, similar to "design vehicle," the concept of "design road user" should be adopted to ensure safety, especially when considering the speed environment.
6. Forgiving roads and roadsides: Roads and roadsides should be forgiving, i.e., free from hazards. In higher speed environments roads and roadsides should be free from permanent as well as temporarily fixed objects, such as rigid structures, trees, stopped/parked vehicles, etc., and should be protected if vehicle departure is non-recoverable.
7. Minimized exposure: Design needs to minimize exposure to risk for all users. This can be achieved at the planning stage by providing good quality,

safe infrastructure that encourages modal shifts (e.g., from motorcycles to mass transit systems in cities). Exposure to risk can also be managed through the provision of safe infrastructure elements. As an example, intersections can be designed to remove or eliminate exposure by banning turning movements across multiple lanes of traffic.

8. System design: Road design should be done in a way to support other elements of the Safe System. For example, it may be possible to build post-crash response into the design (e.g., providing shoulders to park disabled vehicles or access of emergency vehicles, providing for safe enforcement activity).

1.3. The Role of Road Design Guides

It is vitally important to understand that guidelines provide broad design principles in both urban and rural settings, as well as technical details, but do not provide full details on design for every situation. These principles and technical details need to be adhered to in order to achieve required outcomes, including a provision for safety. However, every solution is a unique combination of standard elements that requires expert knowledge and local understanding to apply correctly. The Australian Guide to Road Design states the following:

"Every road project is a unique undertaking and can never be precisely repeated. There are no 'off the shelf' solutions that will fully address all situations encountered, and the rigid and unthinking application of charts, tables, and figures is unlikely to lead to a successful design outcome. Good design requires creative input based on experience and a sound understanding of the principles. However, every situation is different, and therefore design requirements will also differ."[9]

This applies to all elements of design, and particularly to safety. The Australian guidance elaborates further on this issue by stating that "designing and constructing roads according to guidelines will not necessarily produce safe outcomes."[10] Based on the outcomes of design and our knowledge of safety performance, this has unfortunately proven to be true in many situations. Safe road design is not like following a recipe, but rather considerable expertise is required to safely design roads for all road users. Because of the complexities of road design, additional checks and tools have been developed to help identify safety risk, and maximize the safety potential through design. These tools include road safety audit/inspection, road infrastructure safety assessments (including international Road Assessment Program (iRAP)), and a Safe System assessment. In addition, greater attention is being paid to the application of relevant safety metrics in project planning and design. These issues and tools are discussed in chapter 7.

Road design guides have always considered road safety. Issues such as sight distance and design speed dictate much of the design process, and these are based fundamentally on trying to achieve safe outcomes for road users. However, roads are still designed and constructed with inherent risks that result in death and serious injury. This lack of safety may be because there is a "trade-off" between safety and efficiency or mobility due to project constraints such as cost, inconsistency in road design, or simply lack of consideration for vulnerable road users, especially in LMICs (see section 2.3 for a discussion on differing vehicle and road user types in this context). However, in many countries this outcome is no longer seen as acceptable. It is no longer acceptable to design or upgrade roads with inherent safety flaws that carry with them unacceptable levels of risk of death or serious injury. We must ensure that designs follow Safe System principles, and as far as practical eliminate death and serious injury.

Safety-related design information often falls into

9 Austroads. 2015. Guide to Road Design Part 1, AGRD01-15, Austroads, Sydney, Australia.

10 Austroads. 2019. Guide to Road Safety Part 6: Road Safety Audit, AGRS06-19, Austroads, Sydney, Australia.

the later stages of design guidance documents. For example, decisions about what type of intersection design to use or availability of a right-of-way are made at the start of the design process. Road designers may either have limited ability to alter this decision, or feel like they cannot. They do their best to design the safest version of what they have been asked to produce. However, there are significant safety implications based on this earlier decision-making process. As an example, roundabouts in higher speed environments typically have much better safety performance than traffic signals. This highlights that planning and policy decisions often have a big impact on design choices and outcomes. However, it also highlights the need for designers to understand the implications of design decisions, and to challenge these decisions where better outcomes are possible.

Knowledge is also improving on safe road design, with new solutions emerging on a regular basis, and in some cases, the basic road design tenets are evolving. As one example, the knowledge base on intersection design is changing, with improved design options such as using platforms to raise intersections to help manage speeds and improve safety (see section 6.4). Because of this evolving knowledge, guidance needs to be continually updated. It is important to understand that guidance updates often take many years, and so current editions of design guides and national standards do not necessarily reflect up-to-date good practices. As an example, globally, the vast majority of existing design guides do not yet reflect the new thinking relating to roadside safety. This guide aims to be as up to date as possible at the time of preparation.

Guidance produced for and in LMICs is often adapted from high-income country's (HICs) best practices. This is because HICs were often the first to produce such guidance, and much of the underlying research on design has been conducted in these countries. In some cases, attempts have been made to reflect local conditions when translating these guides to LMIC use. However, there are significant gaps in knowledge on some issues relating to the design and use of roads in LMICs. As one obvious example, the traffic mix is often quite different, perhaps involving a much higher proportion of motorcycles and other vulnerable road users, and a mix of slower-moving vehicles. Even if the design standards do reflect good practice, they are often applied to the upgrading of existing roads, which can bring challenges. This may lead to the adoption of deviations from design standards to avoid land acquisition or retain an existing alignment; any deviation from the standards should be accompanied by measures to mitigate resulting safety hazards, although this is not always the case (see section 2.4). Similarly, there are often deficiencies in vehicle standards and maintenance. There is also sometimes different unsafe road user behaviors due to lack of enforcement of otherwise common traffic laws and lack of infrastructure. Because of these gaps, there may be deficiencies in the design advice that aligns with the road environment of an LMIC and its users. This may require greater understanding and a need to develop the content of current guidance. This needs to occur in a structured, evidence-based manner (see section 2.6).

In summary, road design guides are technically sound, but they may not meet all objectives around informing designers how to deliver the unique combination of elements in road design and road safety solutions. Most of the constraints identified above are recognized and often documented in the design guides themselves. However, these constraints are often overlooked by practitioners, leading to stringent application without reference to the local context (an issue discussed further in section 2.4). In many instances, this also leads to poor road safety outcomes. Because of the complexities of road design, additional tools have been developed to help identify safety risk and maximize the safety potential through design (see chapter 7). This guide has been designed to address these gaps, including highlighting the safety-related issues that need to be considered when designing roads, as well as the tools and approaches that are needed to ensure safety.

1.4. About This Guide

This guide has been produced by the Global Road Safety Facility (GRSF), which is hosted by the World Bank. A summary of the GRSF program is contained in box 1.1. This document has primarily been produced for those working in the development and implementation of road improvements and safety features in LMICs, although information will also be of interest to those working in HICs. It provides direct guidance on safety-related issues for designs in both urban and rural settings based on experience and a knowledge of LMIC activity from around the world. Thus, this guide should be used by task team leaders of the World Bank and other Multilateral Development Banks (MDBs) to inform LMIC clients on safety issues in design, as well road designers and practitioners involved in road development projects, researchers and academics. The list of common risk factors provided here can be the starting point, and respective design elements should be carefully followed to incorporate safety into road design.

The guide will also be useful for those who want to embed good practice and address safety in their design. Therefore, the information in this guide will be relevant to those working on World Bank–funded projects, but also client countries as well as others involved in road-related activity. It should be used in tandem with local design guidance, and may be useful to draw attention in identifying where safety challenges may arise in a design or simply help identify gaps in the existing guidance. From that perspective, it may also be useful to those in LMICs who are about to update local guidance, or who are trying to adapt guidance from other countries to local conditions.

This guide does not provide detailed information on how to design. The information in this guide will not allow a designer to design a roundabout, a roadside barrier, or a high-speed rural curve. This document does provide external references for this type of advice. Rather, the document will help identify safety-related issues that need attention through design of a roundabout, a roadside barrier, or a high-speed rural curve or similar facilities. It also provides information on tools that should be used as part of the design process to ensure that safety is embedded within projects and policies.

It is not intended that the document will be read from cover to cover, but more that it will be used as a reference for all aspects of the design process to ensure that the safety of road users is at the forefront of design considerations. Suitable dimensions for specific treatments will also rely on appropriate local standards—which may need to be revised to provide adequate safety benefits.

Chapter 2 of this guide addresses some broad road design principles that relate to achieving safe road outcomes. The main content of this report falls within chapters 2 to 6. Within each chapter, various design issues are presented. A description is provided for each of these along with evidence-based information on safety-related issues. Solutions that are applicable in LMICs are provided, along with case studies illustrating these issues and solutions and key references for further reading. Chapter 2 focuses on planning and design, while chapter 4 focuses on vulnerable road user design, including for pedestrians, cyclists, and motorcyclists. Chapter 5 assesses designs related to cross section and alignment, and chapter 6 provides this information for intersections. Chapter 7 provides information on some design-related tools to help achieve safe outcomes.

Chapters 4 to 6 cover the design aspects of various user groups and infrastructure elements. The research cited throughout the sections is primarily based on work in HICs. Where available, specific LMIC research has been cited. However, it must be emphasized that the safety impact of many design features has not been validated in LMICs. It is hoped that this would encourage individual countries and organizations working in LMICs to develop this validation for specific situations, otherwise the same assumptions on untested transferability of measures will continue.

As noted in section 1.1, the provision of this safe road infrastructure relies on good decision-making by recognizing key risk factors while planning road infrastructure and incorporating appropriate design elements to address these risks. To provide a guidance, key risk factors related to road design for each road type are identified in Table 1.1. It is expected that careful considerations will be given while planning and designing infrastructure in such a road environment. These risk factors are further discussed along with their solutions in later sections, as indicated in the table.

Table 1.1: Typical road design risk factors

	Risk factor	Motorways	High-speed inter-urban roads	Urban, residential, and village roads	Go to section:
1.	Inadequate sight distance or line of sight is obstructed with unplanned roadside construction	X	X	X	3.3: Sight distance
2.	Missing, insufficient, or incorrect safety barrier installations (both roadside and centerline)	X	X		5.8: Barriers
3.	Poor combinations of horizontal and vertical alignment, in particular “hidden dips”	X	X		5.3: Horizontal curvature, 5.5: Vertical curvature and gradient
4.	Presence of rigid objects by the roadside posing hazards	X	X		5.7: Roadsides
5.	Insufficient drainage leading to water logging or deep open drainage ditches posing risk	X	X	X	5.11: Drainage
6.	Cross-section with wide, hard shoulders which are (wrongly) regularly used for overtaking		X		5.2: Shoulder width and type
7.	Inconsistent radius sequence of consecutive curves, e.g., sharp curve after a sequence of significantly more gentle curves, erroneous compound curves with high variability of ratio of the radius, broken back curves, etc.		X		5.3: Horizontal curvature
8.	Unsafe routing and insufficient protection of pedestrians, cyclists, and motorcyclists along the road and intersections, including missing/ insufficiently separated pedestrian and cyclist facilities from high-speed traffic and missing/ insufficient crossing facilities	X	X	X	4: Vulnerable Road User Infrastructure Design
9.	Inadequate skid resistance	X	X		5.10: Road surfacing
10.	Lack of climbing lanes in steep upward grades on two-lane roads		X		5.6: Passing lanes
11.	Insufficient superelevation on bends leading to high risk of lateral shift or overturning	X	X		5.4: Superelevation and cross slope
12.	Lack of strong and stable verges		X		5.2: Shoulder width and type
13.	Signal controls that do not consider the needs of all road users, including excessive delays for pedestrians and cyclists		X	X	6.2: Signalized intersections

14.	Lack of protection for left-turning movements in right-driving traffic, and right-turning movements in left-driving traffic		X	X	6. Intersections, 5.13. Road signs, 5.14. Line marking
15.	Inappropriate road widths and cross-sections in built-up areas, e.g., wide road/lane widths at the expense of facilities for vulnerable road users		X	X	5.1: Road width
16.	Narrow lanes on high-speed roads, curves, and turning lanes	X	X		5.1: Road width
17.	Inappropriate parking and loading facilities		X	X	5.7: Roadsides
18.	Missing/ineffective traffic calming measures		X	X	3.2: Speed management and traffic calming
19.	Lack of visual contact between motorists and pedestrians/cyclists			X	3.3: Sight distance
20.	Poor recognition of intersections and rights of way due to a lack of guiding features, e.g., channelization, markings, and signs			X	6.5: Channelization, 5.13: Road signs, 5.14: Line marking
21.	Inadequate signage and pavement markings	X	X	X	5.13 Road signs, 5.14: Line marking

Box 1.1: How GRSF and the World Bank Embed Safe Design into Transport Projects

The World Bank has the twin goals of ending extreme poverty and promoting shared prosperity. As part of these overarching objectives, World Bank is working to promote sustainable mobility around the world. Under the combined effects of globalization, population growth, rapid urbanization, economic development, and technological progress, country needs are growing exponentially, making sustainable transport a vital part of the global development agenda. Improvements in road safety are a core part of delivering sustainable transport solutions. The World Bank and GRSF recognize the significant impacts of road crash fatalities and injuries on economic growth for LMICs and the role of crashes in driving families into poverty resulting from the loss of the family income earner due to a fatality or disability. Thus, road crashes directly impact the World Bank's twin goals.

GRSF has been hosted at the World Bank since its inception in 2006 and has the objective of helping to address the growing crisis of road crash deaths and injuries in LMICs. GRSF delivers funding and knowledge development through research, knowledge transfer, advocacy, and technical assistance to scale up and improve road safety delivery in LMICs.

Road safety is embedded in World Bank activity as part of the Environmental and Social Framework (ESF) through the Environmental and Social Standard 4 (ESS4). The ESF, which took effect in October 2018, requires that road safety is considered in projects and addressed wherever it is relevant. A Good Practice Note has been prepared to guide the implementation of the road safety requirements of the ESF. The requirements now include a road safety indicator for relevant projects to monitor the road safety components of projects. GRSF has developed the Road Safety Screening and Appraisal Tool (RSSAT) (also see section 7.3) that allows assessment of the road safety impacts of planned projects early in project development. This allows for refinement of projects to improve road safety delivery before the project is well advanced and road safety interventions are more challenging to include. The Transport Global Practice has implemented a policy requiring the use of RSSAT on roads and urban mobility projects, including the attainment of minimum safety standards. GRSF is planning to develop RSSAT as a web-based tool and share it publicly, please refer to the GRSF website (https://www.roadsafetyfacility.org/).

In addition, GRSF has been promoting good practice in design through training in LMICs and embeds this good practice in projects around the world. Furthermore, GRSF has partnered with iRAP to develop the Star Rating for Designs tool, which is available for use at no charge. This tool was developed to enable a star rating to be easily incorporated into the road design process. Further details on these tools and ways that they can be used to embed road safety into design can be found in chapter 7.

2. KEY ROAD DESIGN PRINCIPLES IN THE CONTEXT OF SAFE PLANNING

2.1. General Road Design Principles

Road infrastructure design plays a significant role in road safety outcomes, but typically safety is just one consideration among many during the road design process and is often not prioritized. This section outlines some of the broad design considerations. Further details on these issues can be found in several national design guides, such as The Austroads Guide to Road Design,[11]which provides designers with a framework that promotes efficiency in design and construction, economy, and both consistency and safety for road users. Other similar documents include the AASHTO Green Book[12] and PIARC Road Safety Manual, along with many others.

Road design and construction involves the geometric and structural design of a roadway. A key objective of this is to optimize operational safety and transport efficiency within constraints (including budgets, environmental concerns, and other social outcomes). Design needs to consider both the traffic volume and type that would be expected to use the road. This covers all user groups—motorized and nonmotorized.

Highway engineers design road geometry to ensure stability of all vehicles when negotiating curves and grades and to provide adequate sight distances for undertaking passing and stopping maneuvers. The design choices related to geometric road design will depend upon the environment through which the road passes - principally habitation and topography - and the interactions between these design features and the environment have a fundamental impact on safety. Each design situation is unique and there are no 'off the shelf' solutions that will fully address all situations encountered. As discussed in Section 1.3, the rigid and unthinking application of charts, tables and figures is unlikely to lead to a successful and safe design outcome. Good design requires creative input based on experience, knowledge about the local environment (including road user considerations), and a sound understanding of design, allowing evidence-based principles and solutions to be effectively applied with refinements to the exact local circumstances. Processes and tools to ensure safety is embedded in a proactive way in design are also required (see chapter 7).

Any design MUST:

- Address the needs of all road users.
- Be undertaken by a qualified road designer under the supervision of a professional engineer/senior design engineer, both with appropriate road design experience in line with the scope of the project.
- Be safe, ensuring that any recommended safety provisions are not reduced in favor of saving costs during the design and construction process.
- Be context sensitive, including being suitable for the land use.
- Demonstrate cost-effectiveness through value engineering processes, cost benefit analyses, and consideration of whole-of-life costs (which include safety benefits).
- Be fit-for-purpose, i.e., the function it is supposed to serve, while trying to achieve the highest possible

11 https://austroads.com.au/safety-and-design/road-design/guide-to-road-design accessed 07/275/2020.

12 A Policy of Development of Highways and Streets 7th ed. 2018. AASHTO.

standard of design, safety, and operational efficiency within the context of the site, the project scope, and budget.

- Be subjected to an audit process by independent and qualified road safety auditors.

It SHOULD also:

- Be considerate of environmental, cultural heritage, and social requirements.
- Recognize the increasing impact of climate change on the resilience of road infrastructure.
- Maintain or improve the performance of an existing road.
- Fully document the rationale behind design decisions.
- Meet the objectives of the project while being mindful of the objectives for the road link and network.
- Be able to demonstrate it appropriately balances all of the above principles within the limits of the project scope and constraints and is complementary to the network.
- Consider and cater for the interaction between all road users and the roadway.
- Meet current needs while also providing for future needs.
- Be developed in accordance with sound design guidance. Innovative designs may be developed using the foundations provided in accepted design guidance; however, all other road design principles should be maintained.

In the context of designing and providing a safer road environment, the Safe System approach aims to ensure that potential collisions are avoided and, if they occur, that the crash impact forces do not exceed human tolerance. Findings from Sweden identified that, while there was a strong interaction between the three system components of vehicles, road infrastructure, and road user, road-based factors, including speed, were most strongly linked to fatal crash outcomes.[13]

Roads should therefore be designed to reduce the likelihood of crashes occurring and minimize injury to the road users even when a crash occurs, and there is very clear evidence that suggests that the severity of outcomes when crashes do occur is most heavily influenced by the road design. In particular, this includes the features that indicate to drivers the speed at which the corridor is designed to operate and the features which force lower speeds. The elements that are typically thought to impact on efficiency and safety include intersections, horizontal and vertical curves, camber (superelevation), gradients, cross sections (lane and shoulder width, medians and roadside provision), and merge and diverge areas. All these elements (and more) are covered in detail in national/local design manuals and guidelines.

Roads should be designed to cater for a defined function and use (see section2.2). By adopting a consistent and clearly differentiated design for each function group, the road can create a better appreciation of risk in (most) drivers. This in turn encourages road user behavior consistent with the safety standard of the road. The same general functional management principles should be applied in both urban and rural networks.

Appropriate design choices are needed for roads serving different functions to minimize the number of crashes likely to occur and to mitigate injury severity, particularly on higher-speed roads. Further, it is also important to state that a consistent selection of minimum design criteria is not a good practice and that such choices often lead to unsafe and inconsistent design.

While highway engineers concentrate on the geometric parameters, road users are more concerned with the context of the road and rely on visual cues and roadside details to determine safe and appropriate speed and risk. These elements need to be provided in such a way as to give all road users sufficient time to

13 Stigson, H. 2009. A safe road transport system—factors influencing injury outcome for car occupants. Thesis for doctoral degree. Stockholm, Karolinska Institutet.

make appropriate decisions to avoid conflict and injury collisions. A balance is needed between too much and too little information, but whatever is provided needs to enable road users to assess an appropriate and safe behavior. (See section 2.2 for more information on self-explaining roads.)

Road infrastructure should be designed to proactively take account of the same injury tolerance criteria as those developed for vehicle occupant protection and pedestrian impacts, so that roads and vehicles together provide an effective safety system. Below are some associated risk levels for different road users.

Risk to cyclists varies substantially between countries, mainly reflecting the infrastructure provided for them and the motorized traffic levels they interact with.

- Risk for motorized two wheelers is particularly high,[14] and solutions are needed to minimize the severity of injuries resulting from their impact with roadside furniture.
- Among pedestrians, the young and the elderly are most at risk.
- Elderly road users have diminished physical and cognitive capabilities.[15]

Safety is fundamental to the design and operational life cycle of a road. Safety should not be left to reliance on road users behaving safely—the millions of crashes and injuries globally each year show that this does not work. The process should start with a safety impact assessment of a proposal even before a decision is made where to site a new road.

A proactive approach is required to improve road safety. Safety audits are then undertaken at specific points during the design, construction, and post-opening stages to ensure all aspects of detailed design that might affect safety are addressed. A safety audit during the construction phase also helps to ensure that workers and road users are not at risk during developing and changing road conditions.

Once the road is built and accepted by the highway authorities, they have a responsibility to ensure its safe operation. This is best done through a combination of a crash investigation and on-road inspection to enable cost-effective remedial programs to be developed; many tools exist to support these activities. These aspects of proactive assessments and tools are discussed in more detail in chapter 7: Design Tools for Safe Outcomes.

2.2. Road Function and Land Use

Historically, functional classifications have been used to group roads into classes, or systems, according to the character of service they are intended to provide. Functional classification outlines how travel can be channelized within the network in a logical and efficient manner by defining the part that any particular road or street should play in serving the flow of trips through a highway network. Major routes in the road network are most commonly classified by the two functions: Access and Mobility (or movement and place, see Figure and are often known as:

- Principal/Arterial Roads,
- Distributor/Collector Roads, and
- Local Roads.

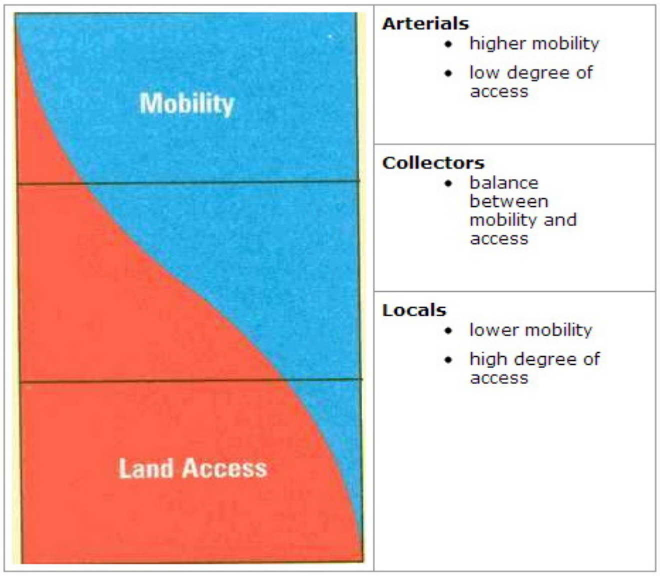
These standard classifications remain constant for the whole route and this has often been used to inform the design and management criteria that are applied to different parts of the network.

Different road classifications offer different levels of mobility and accessibility depending on their overall usage which require different traffic speeds, segregation of users and other driving actions,

14 A study from EU countries reports the fatality risk of motorized two-wheelers to be 20 times higher than for car occupants on average (European Transport Safety Council. 2003. Transport safety performance in the EU: a statistical overview. European Transport Safety Council, Brussels, Belgium, 32. https://etsc.eu/transport-safety-performance-in-the-eu-a-statistical-overview/). The risk in low- and middle-income countries (LMICs) may be much worse due to the existence of contributory factors such as unsafe motorcycles, low helmet use, inadequate helmet standard, weak rider training and licensing, poor enforcement and gaps in regulation, poor road environment, and inadequate post-crash care.

15 FHWA. 2014. Handbook for Designing Roadways for the Aging Population. Accessed at https://safety.fhwa.dot.gov/older_users/handbook/.

Figure 2.1: Access and mobility functions for different classes of roads.



Source: FHWA.

e.g. readiness to deal with cyclists and pedestrians (including young children). Networks in most countries will therefore reflect the development of a hierarchy of motorized use, with motorways/freeways/expressways at the highest level of motorized use[16] and local access roads at the lowest. In practice, a basic hierarchy will occur naturally through the more heavily trafficked routes being engineered to higher standards. But it is important that the hierarchy is established to clear guidelines linking design to actual function to provide the desired levels of mobility and accessibility. In many LMICs, however, this clear hierarchy becomes blurred, with roads serving a mixture of functions; for example, resources can be insufficient to finance a segregated road network, and trunk roads often serve as centers for commercial activity. Additionally, road networks interlace and connect residential, commercial, urban, and suburban areas of cities, towns, and villages. They fulfil many functions along their routes catering for many types of activity, not just journeys by different modes. Thus, roads need to be designed for their actual function, and it should be recognized this may differ along their length.

It is not safe to assume that the intended function of a road will be its function along its whole length, or for its whole lifetime. By failing to take account of the changing context along the route this classification system limits understanding of how improvements, maintenance, or safety should reflect the wider functions that routes serve. This changing context is illustrated by some of the images in figures 2.2 through 2.4.

A clear distinction needs to be made between streets and other types of roads. Local roads within an urban area are often referred to as "streets" and are typically lined with buildings and non-travel activities including trade, play, and other forms of engagement. While movement is still an important requirement on streets, the ability to undertake other functions safely becomes increasingly dominant. In the context of LMICs, these hierarchies often face a major challenge due to the typical distribution of mode shares consisting of a significant portion of nonmotorized road users.

On streets in any given urban area, you might find people walking their dogs, having lunch in a sidewalk cafe, waiting for a friend, or simply watching people. For roads connecting Town A to Town B, you are less likely to find any of this, as mobility is the primary function. The term "street," then, should be specifically applied to local urban roadways. Streets connect people for interaction, while other roads connect towns and cities for travel (although the function may differ for specific points on the road).

In 1997, the collective Dutch road management authorities reached an agreement on a major traffic safety program, called Duurzaam Veilig ("Sustainable Safety"). One of its principles is a clear-cut categorization of roads into a small number of visually distinct and clearly recognizable designs that must be applied consistently throughout the country. Four categories of road seem to be sufficient to cater for all needs;[17] these are:

- Motorway,

16 Highest relates to traffic volume and not necessarily importance.

17 Theeuwes and Godthelp. 1995.Self-Explaining Roads. Safety Science, 19, 217–225.

Figure 2.2: Sellers on the road in Senegal.

Source: © Soames Job/GRSF/World Bank.

Figure 2.3: Shops taking over the footpath and roadway—Nepal.

Source: © Soames Job/GRSF/World Bank.

Figure 2.4: The road is a meeting place in villages in Armenia.

Source: © Soames Job/GRSF/World Bank.

- Major inter-city roads,
- Local roads or streets) to connect residential areas to shopping and services, and
- Woonerfs (or traffic-calmed residential zones).

Many countries now find that they need more categories to cover their full range of road types (e.g., rural access roads, urban collector roads), and the distinction between each category becomes more blurred depending on the various activities that need to be accommodated. The important point is that all roads and streets can be designed to create different expectations about how road users should act on them.

Figure 2.5 shows examples of movement and place matrix from the UK and Australia. The two axes represent the relative priorities of roads to facilitate the movement of people and goods, and to act as destinations for people. The position of the road on the movement axis is based on the strategic importance of the road, identified by its role in the broader network. The position of the road on the place axis is based on the strategic importance and community value of the road to act as a place.

The aim is that different classes of roads should be distinctive, and within each class, features such as

Figure 2.5: Illustration on movement and place status of roads and streets.

Source: UK CIHT, 2010 (left). UK CIHT. 2010. Manual for Streets 2. https://www.ciht.org.uk/knowledge-resource-centre/resources/revising-manual-for-streets/. Wider Application of the Principles. Note that the term "high street" in this diagram relates to a busy commercial shopping street. This is sometimes termed a "main street" in other countries.; Government of South Australia, 2012 (right). Government of South Australia. 2012, Streets for people, Adelaide, Australia.

width of carriageway, road markings, signing, and use of street lighting would be consistent throughout the route and matched to their functional use. Drivers would thus perceive the type of road and "instinctively" know how to behave. The environment effectively provides a "label" for the particular type of road, and there would be less need for separate traffic control devices such as additional traffic signs to regulate traffic behavior.[18] They become "self-explaining," i.e., more intuitive, to all users.

However, simply spending precious resources to achieve consistency on an otherwise safe and efficient corridor might not be acceptable. Therefore, a less onerous philosophy to achieve an acceptable level of consistency of facility along a corridor may be applied.

That philosophy is one of predictability. That is for successive sections along a road within a consistent environment (rural vs. urban), there should be little or no variation in the level of cross section, horizontal or vertical geometric standard, or sight distance provided. A "no-surprises" approach has a consistency of context that provides the users with appropriate and relevant information in a timely fashion to facilitate their decision-making. Any rapid or isolated changes, e.g., sharp curves or shoulder narrowing, would be considered "out of context" and would ideally be eliminated, but if they are unavoidable, then more specific, local treatment should be considered to give advanced warning of their presence to drivers.

Such approaches use simplicity and consistency of

Figure 2.6: A rural highway passing through a market—Chad.

Source: © Soames Job/GRSF/World Bank.

Figure 2.7: Stalls on the road with no separation of through high-speed traffic movements and mixed activity area—Nepal.

Source: © Soames Job/GRSF/World Bank.

Figure 2.8: Main urban arterial separated from the mixed activity area—Qatar.

Source: © John Barrell.

Figure 2.9: National road separated from the mixed activity area—Qatar.

Source: © Soames Job/GRSF/World Bank.

18 https://ec.europa.eu/transport/road_safety/specialist/knowledge/road/designing_for_road_function/self_explaining_roads_en.

design to reduce driver stress and driver error and help guide driver behavior and their speed selection. It is already used for the highest road classes (motorways), but on low-class roads, consistency in design is often compromised by other objectives such as high access levels, variable alignment, mixed use, and variable roadside development, which result in a lack of consistency and a lack of differentiation between road classes.

The implications of self-explaining roads are especially profound for LMICs. Developments affecting parts of the road system that have customarily been used for social or commercial purposes should therefore be handled with particular care. If it is possible to retain the social or commercial function, then care should be taken to separate through traffic movements from the local traffic in mixed activity areas and ensure that a high-speed environment is not imposed on it. If it is not possible to retain the social and commercial functions, then a suitable alternative site for these activities should be found, and the new road facility which replaces the former mixed activity area should be clearly identifiable as primarily a traffic facility. In a situation where high-speed through traffic cannot be separated from the local traffic and activities, downgrading of the functional class is needed to maintain safe travel speeds through such areas with the help of suitable infrastructure design and speed enforcement. Figures 2.6 and 2.7 illustrate the lack of separation of through traffic from local traffic in mixed-activity areas while figures 2.8 and 2.9 illustrate the separation of high-speed traffic.

2.3. Vehicle and Road User Type in LMIC Context

The type, quality, and volume of vehicles and experience of road users are unique in the LMICs, often differing substantially to those in developed countries. This is primarily due to the socioeconomics, affordability of vehicles with modern technologies, and above all, country-level policies. As a result, there are several variants of vehicles under both light and heavy vehicle categories, with a broader range of acceleration-deceleration capability and the top speed that could be maintained. Furthermore, there is also a very high share of two- and three-wheelers, makeshift vehicles, overloaded vehicles, vehicles for agriculture and farming, and animals (e.g., horses) or animal-drawn vehicles. Such a mix of traffic is commonly known as a heterogeneous traffic mix, with a high variation in travel speed. While the vehicle dynamic characteristics vary widely in mixed traffic, there are generally no separate transport facilities in most LMICs; thereby, all vehicles use the same carriageways, often with poor or zero lane discipline. In addition to the motorized vehicles, the share of nonmotorized traffic and pedestrians is very high in any LMIC. However, most often there are no dedicated facilities for nonmotorized transport (NMT) road users, resulting in higher interaction with motorized and NMTs, and a high share of crashes and injuries involving these vulnerable road users, including people with disabilities (see chapter 4, Vulnerable Road User Infrastructure Design). Due to such issues, adopting design configurations and standards directly from high-income countries (HICs) may not be advisable to cater to all road users' needs. This often means that the standard of design and infrastructure provision needs to be higher in developing countries for NMT (e.g., sidewalks are needed much more frequently in Bangladesh than Australia); yet the amount invested per kilometer on road projects is significantly lower. In addition, where significant numbers of animals and animal-drawn carts use a path, consideration for collision risks and slow-moving vehicles should be given to the design to accommodate them safely (e.g., additional width, special signage, fencing, road furniture such as noise barriers or guardrails, segregation at intersections and crossings) (see relevant separate sections for details of these measures, and FHWA [2020]. Improving Safety for Travelers and Wildlife for a comprehensive approach). There is a reality that budgets are limited and so affordability is important in developing countries, but more investment is needed to manage the challenging environment to achieve a safe road

Figure 2.10: Different types of vehicles and high pedestrian volume.

Source: © Soames Job/GRSF/World Bank.

Figure 2.11: Different types of vehicles—Vietnam.

Source: © Alina F. Burlacu/GRSF/World Bank.

Figure 2.12: Four different types of vehicles on highways—India.

Source: © Sudeshna Mitra/GRSF/World Bank.

Figure 2.13: Different types of vehicles.

Source: © Soames Job/GRSF/World Bank.

environment. Figures 2.10 through 2.13 illustrate the different vehicle types in the context of LMICs.

For example, India has a heterogeneous mix of traffic, with a range of vehicle types in the vehicle mix, including passenger cars, motorcycles, light commercial vehicles (such as pickup trucks), motorized rickshaws, and heavy vehicles (such as trucks and buses). These vehicle types have very different acceleration and deceleration capabilities and ease of maneuverability in a traffic mix that does not follow any lane discipline.[19] For example, light commercial vehicles tend to slow down the traffic stream due to their lower mean free speed with higher speed variance (compared to trucks and buses), and these vehicles also have relatively poor acceleration rates at higher speeds.[20], [21] As a result,

traffic streams with a high percentage of these vehicles and lesser percentages of other vehicles are expected to have different traffic characteristics than traffic streams with different compositions, which will also have implications on safety. Additionally, the maneuverability of certain vehicles, especially motorcycles, may have different effects on safety. For example, it is prevalent for motorcyclists to maneuver side by side and weave between two larger vehicles, sharing virtually the same space across a lane, which

19 Mitra, S., Haque, M., and King, M. J. 2017. Effects of access, geometric design, and heterogeneous traffic on safety performance of divided multilane highways in India, Journal of Transportation Safety & Security, 9: sup 1, 216–235.

20 Arasan, V. T., and Koshy, R. Z. 2005. Methodology for modeling highly heterogeneous traffic flow. Journal of Transportation Engineering, 131(7), 544–551.

21 Dey, P. P., Chandra, S., and Gangopadhaya, S. 2006. Speed distribution curves under mixed traffic conditions. Journal of Transportation Engineering, 132(6), 475–481.

Figure 2.14: Mixed vehicle traffic with conflict of different users—Bangokok.

Source: © Alina F. Burlacu/GRSF/World Bank

Figure 2.15: Mixed vehicle traffic with conflict of different users—Philippines.

Source: © Alina F. Burlacu/GRSF/World Bank.

Figure 2.16: Mixed vehicle traffic with conflict of different users.

Source: © World Bank.

Figure 2.17: Mixed vehicle traffic with conflict of different users at intersection.

Source: © World Bank

is less common in largely homogeneous traffic. Slow-moving heavy vehicles are often seen occupying the outer lanes of dual carriageways, encouraging other drivers to overtake on the inside. In addition, the proportion of heavy vehicles has in some cases been found to have a negative effect on traffic safety,[22] and there is evidence that a higher proportion of motorcycles in the traffic stream was positively and significantly associated with rear-end crashes. In contrast, the higher percentage of heavy vehicles in the traffic stream was found to be substantially related to head-on collisions. Various conflicts among road users in mixed-vehicle traffic are illustrated in figures 2.14 through 2.17.

While this identifies problems associated with specific vehicle types, the effects of overall vehicle composition on traffic streams are yet to be studied and investigated further across different regions of LMICs, to provide clear direction on the safety effects of these vehicles on the mix. As a result, it can be said that the safety effects of different compositions of vehicle types in heterogeneous traffic are still an underexplored domain.

Nonetheless, there is evidence that segregating a diverse traffic mix (especially where speed is involved),

22 Robert, R. V., Veeraaragavan, A., and Murthy, K. 2006. Safety relationships for highway segments in developing countries. In Transportation Research Board 85th Annual Meeting (No. 06–0508).

Low-volume roads in low- and middle- income countries

In low- and middle-income countries, there are specific safety issues involving low-volume roads. A low-volume road (LVR) is one which carries few vehicles daily (typically less than 400 vehicles per day) and where the percentage of heavy vehicles is very low (5-10%). They tend to connect rural communities with the strategic road network, in addition to vital public services such as schools, hospitals, farms and markets, and may be either paved or unpaved. LVRs often need to cater to high proportions of non-motorized traffic (NMT), including pedestrians, bicycles, animal-drawn carts, as well as motorcycle traffic. Additionally, existing land use and adjacent properties often limit the effective cross-sectional width that can be constructed without causing major disturbances for the local population and associated costs for land acquisition and compensations.

Conventional highway geometric design relates increasing standards to increasing speed, volume of traffic, and user comfort and convenience. However, design of LVRs focuses on providing sufficient access; speed, volume, comfort, and convenience do not usually control the design. Hence the design of LVRs must aim at keeping traveling speeds relatively low. Provided that low speeds are maintained, normal shoulders or additional width to accommodate NMT facilities may be omitted except in particularly busy areas within villages, trading centers etc.

The geometric design of LVRs needs to be coupled with the following measures:

- Installation of traffic calming measures where required, particularly in areas with a high incidence of non-motorized traffic (NMT), e.g., speed humps, rumble strips, warning, and speed limit signs, etc. (see Section 3.2)
- Fully engineered solutions at potentially hazardous spots that can be achieved within reasonable costs (e.g., road widening/lane separation over sharp crests, alignment improvement to straighten out blind curves).
- Adequate advance warning to drivers and speed-reducing measures where potentially hazardous situations cannot be avoided (see Section 5.13).
- Varying road carriageway width dictated by the amount and mix of traffic and terrain (see Section 5.1).

such as high-speed through traffic and low-speed local traffic with the help of service roads, and separating vulnerable road users such as motorcyclists, cyclists, and pedestrians through the introduction of motorcycle lanes, cycle lanes, and sidewalks or footpaths, respectively, is likely to produce significant safety benefits. section 4 describes the design of vulnerable road users in detail. Finally, integrating public transport facilities (e.g., bus rapid transit, [BRT]) with well-designed crossing facilities is found to be effective in enhancing the safety of public transport users who are mostly pedestrians before and after using public transport facilities.

Further reading:

- Giummarra G (2001). Road Classifications, Geometric Designs and Maintenance Standards for Low Volume Roads. Research Report AR 354, ARRB Transport Research Ltd, Vermont, South, Victoria, Australia.
- Queensland Department of Transport and Main Roads (2013). Guidelines for Road Design on Brownfield Sites. Queensland, Australia.

- Southern Africa Development Community (SADC) (2003). Guideline on Low-volume Sealed Roads. SADC House, Gaborone, Botswana.
- World Bank (2001). Design and Appraisal of Rural Transport Infrastructure: Ensuring Basic Access for Rural Communities. Technical Paper No. 496, World Bank, Washington, DC., USA.
- World Road Association (PIARC) (2016). Human Factors Guidelines for a Safer Man-Road Interface. Technical Committee C3.2, Design and Operation of Safer Road Infrastructure, World Road Association (PIARC), Paris, France

2.4. Context Sensitive Design

A road design cannot be considered safe, fit-for-purpose, or conforming if it simply adopts design minima, particularly in combination, for elements of the design. Most design criteria (range, desirable, absolute) have been researched or developed in isolation from each other (although there may be some implicit relationships) and when used in combination with other elements, while conforming to the published guidelines, may result in a solution that compromises safety or operational efficiency.

Any road also has to operate appropriately within the natural and built environment to meet a range of expectations of the users and the broader community. Consequently, the design cannot be carried out in isolation, but must be sensitive to the context in which the road will operate and, as a result, competing or conflicting criteria often need to be compromised to achieve a balanced, safe and cost-effective solution.

Context-sensitive design (CSD) is an approach that provides the flexibility to encourage independent designs tailored to particular situations[23] while giving due consideration to all factors.

A "design domain" can be thought of as a range of values that a particular parameter might take. This applies to a range of design parameters that, when used in context, provide acceptable safe, efficient, and effective outcomes. They are justified in an engineering sense using a consistent set of principles, based on test data and sound reasoning, for example, and therefore can have a reasonable level of defense if challenged.[24, 25, 26]

The design domain approach places emphasis on developing appropriate and cost-effective designs rather than providing a design that simply meets standards. It comprises a normal design domain (NDD), an extended design domain (EDD) (Figure 2.18) and also design exceptions (DE). These can also be referred to as design standard, relaxation, and a departure from standard. The concept requires a designer to select a value, appropriate to the context, for each design element from a range of values, taking into account the benefits and costs of each selection.

The lower regions of the design domain represent values that would generally be considered less safe or less efficient, but often less expensive than those in the upper regions of the domain. The decision on the values to adopt should be made using objective data on the changes in cost, safety, and levels of service caused by changes in the design, together with a benefit-cost analysis. The engineering principles and target values for each parameter in the design should be agreed at a very early stage in the project. Although these may be varied later in the design process as more information is obtained, early indications from the client to the designer are important to set the expectation of the roads purpose and function, and allow the design to progress with greater certainty of intended outcome.

CSD seeks to produce a design that combines good engineering practice in harmony with the natural

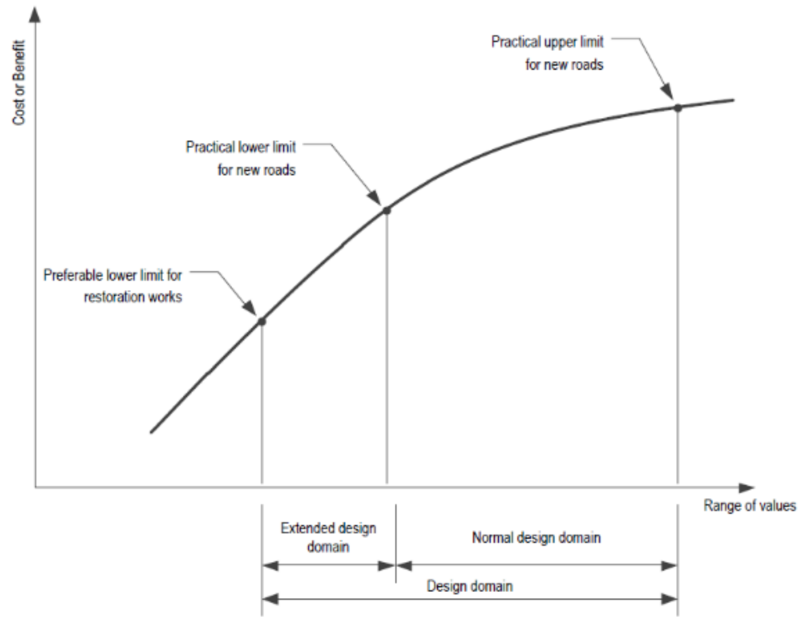
23 FHWA. 2002. Context Sensitive Design/Thinking Beyond the Pavement, Federal Highway Administration (www.fhwa.dot.gov/csd).

24 Transport Association of Canada. 1999. Geometric design guide for Canadian roads: parts 1 and 2, TAC, Ottawa, Ontario, Canada.

25 Cox and Arndt. 2005. "Using an extended design domain concept for road restoration projects." International symposium on highway geometric design, 3rd ed., 2005, Chicago, Illinois, Transportation Research Board, Washington, DC, 20 pp.

26 Department of Transport and Main Roads. 2013. Road planning and design manual, 2nd ed., TMR, Brisbane, Qld.

Figure 2.18: Design domain concept.



Source: Daniel Kueper, 2010. "The Context Sensitive State Design Manual," ITE Journal (www.ite.org), Vol. 80, No. 11, pp. 30–35.
Note:
The value limits for a particular criterion define the absolute range of values that it may be assigned.
The design domain for a particular criterion is the range of values, within these limits, that may practically be assigned to that criterion.

and built environment, and meets the required constraints and parameters for the project. It refers to roadway standards and development practices that are flexible and sensitive to community values. It also makes allowance for the use of narrower lanes, lower design speeds, sharper turns, and special features not included in generic road design guidelines to help create a more balanced and efficient transportation system and meet community land use objectives.

However derived, a design should demonstrate value engineering and acceptable whole-of-life costs to cater for all road engineering disciplines including safety, geometric design, traffic, drainage, pavements, asset management, and stakeholders (e.g., road users, vulnerable road users, freight, public transport, emergency services, environmental), while taking into account current and future needs.

At the beginning of the project lifecycle, the project needs to determine what road users are present and how they will be catered for (see section Design for road user characteristics and compliance2.4.2). The suitability of a design should also consider the effects the design may have on adjoining road sections and the surrounding network.

Designs require decisions to be made on the value of improving the standard of a road and the impact this might have on the ability to fund improvements elsewhere on the road system. Depending on the controlling authority's funding priorities, for example, this may be focused on safety, environment or efficiency, which may drive different outcomes. The most appropriate compromise is usually a balance of all three categories, i.e., the highest value for a money safety solution may be the least attractive from an environmental aspect.

It is therefore important that design decisions are documented and based on sound engineering judgment and rationale to address the problem to be solved. These decisions are subject to appropriate review/governance and should show how they demonstrate value engineering and manage whole-of-life costs within the design constraints and context of the site.

Climate-resilient roads

Road transport plays an important role in the overall socio-economic development of a country. However, road infrastructure is extremely environmentally challenging and highly vulnerable to the impacts of climate change such as flash floods and landslides caused by heavy rains. In addition, rapid growth in vehicle numbers and movement make road infrastructure vulnerable. The road networks of developing countries are generally more vulnerable to climate change impacts due to poor maintenance, a high proportion of unpaved roads and limited resources and technology to adapt.

A climate resilient road comprises a set of technological measures rather than a single technology. These can be either engineering or structural measures or bio-engineering measures. The structural measures include:

- Slope stabilization structures.
- Paving of roads with durable materials.
- Proper alignment of new roads to avoid vegetative loss.
- Improved drainage systems to avoid erosion of road materials.
- Improved planning of roads with proper cross section and standard dimensions.

Design Exceptions

Design exceptions are situations where the design does not conform to the minimum or limiting criteria set forth in the standards, policies, and standard specifications. They are most likely to occur due to challenging terrain; constrictions due to existing infrastructure, services, property boundaries, environmental conditions, cultural heritage and community expectations.

Design exceptions have the potential to negatively affect highway safety and traffic operations. For this reason, consideration of a design exception should be deliberative and thorough, and a clear understanding of the potential negative impacts should be developed through a risk assessment that is unbiased and supported by crash analysis. Sometimes the drivers for adopting design exceptions such as these may be for social, environmental, or economic reasons, however the risk assessment must show that the decisions associated with adopting such a low standard outweigh the potentially higher cost of fatal and serious injury crashes. If the decision is made to go forward with a design exception, it must be formally approved by the relevant road agency and supported by a well-documented justification. It is also especially important that measures to reduce or eliminate the potential negative impacts be evaluated and, where appropriate, implemented.

Documentation for design exceptions should describe all of the following:

- Specific design criteria that will not be met;
- Existing roadway characteristics;
- Alternatives considered;
- Comparison of the safety and operational performance of the roadway and other impacts such as right-of-way, community, environmental, cost, and access for all modes of transportation;
- Proposed mitigation measures; and
- Compatibility with adjacent sections of roadway.

Design exceptions should NOT be used where any one of the following applies:

- There is a crash history linked to the use of the design exception e.g. police crash reports indicate that limited visibility was a contributing factor to the crash(es). This is even more important in the following cases:

  - if more than one such crash is reported
  - mitigating devices are already in place.

- Use of the same, or similar, design exception has been known to cause safety problems elsewhere on the network.
- The value of the design exception is well outside the range of values of the design domain.
- The design exception is an isolated case, for example, if a roadway contains generous horizontal curvature except for one (or a few) very substandard horizontal curves. In this case, drivers become used to the general standard of horizontal curvature and are less likely to adequately perceive and negotiate the substandard element/s. This is different from a roadway comprising tighter, but more consistent horizontal alignment which would cause drivers to be more alert and have a greater expectancy of tight geometric elements.
- A design exception is combined with other geometric minima, especially other design exceptions. The greater the number of minima combined, the lower the likelihood that a design exception can be tolerated as one of these minima.

- On road restoration projects comprising higher function and/or higher traffic volume roads.
- The parameter being considered is intersection sight distance. In this case, the EDD values are the lowest that should be provided.
- Where little effort and expense is required to avoid using the design exception.
- On road restoration or low volume road projects where the pavement is being replaced, especially if minimal earthworks are required.

Reference to aviation industry. Sudeshna to share document

Design for road user characteristics and compliance

Conventional roadway design standards and guidance define features such as lane and shoulder widths, design speeds, and minimum parking supply. They often reflect the assumption that bigger and faster is better, leading to a design that effectively exceeds the standard required for its intended purpose. This can result in higher traffic speeds, increased project costs, and roadways that contradict other planning objectives. For example, wider and straighter roads tend to increase traffic speeds and disperse destinations, which can reduce accessibility, safety, and livability.

At the beginning of the project life cycle, the project needs to determine what road users are present and how they will be catered for. This requires that data are collected about who uses the road and how they use the road e.g., where do pedestrians walk, what percentage of vehicles are motorcyclists and what is the actual speed vehicles travel at. These data are important in understanding the true design environment, as opposed to a design for how people “should” behave. It is also important that at the start of each project phase the road-user and stakeholder requirements are clearly documented so that the designer can clearly understand how to develop a design that addresses the needs and requirements of all road users and balances these within the overall design solution.

Complete streets

The complete streets approach is a modern approach to urban design aiming to address the safety and amenity challenges of all road users and redressing the old school focus on motorized vehicles. Complete streets are streets designed and operated to enable safe use and support mobility for all users. This includes people of all ages and abilities, regardless of whether they are travelling as drivers, pedestrians, cyclists, or public transportation riders. The concept of complete streets encompasses many approaches to planning, designing, and operating roadways and rights of way with all users in mind to make the transportation network safer and more efficient. Complete street policies are set at the state, regional, and local levels and are frequently supported by roadway design guidelines.

Complete streets approaches vary based on community context. A complete street in a rural area will look quite different from a complete street in a highly urban area, but both are designed to ensure safety and convenience for everyone using the road, including pedestrians with disabilities.

In the context of LMICs, community roads are generally used by all modes of transport, with a high share of nonmotorized users. However, with increased motorization, the streets and roads of LMICs are taken over by motorized vehicles. The safety threats to the nonmotorized users are on the rise due to a lack of planning and design in general, and the lack of speed management in particular. In the context of LMICs, complete street design, especially for the mixed use is very relevant.

Complete streets may address a wide range of elements, such as sidewalks, cycle lanes, bus lanes, public transportation stops, crossing opportunities, median islands, accessible pedestrian signals, curb extensions, modified vehicle travel lanes, streetscape, and landscape treatments (see relevant separate sections for details of these measures; see figure 2.19 as an example of a cross-section in line with the complete streets concept). They also reduce motor vehicle–related crashes and pedestrian crashes, as well as cyclist risk when well-designed cycle-specific infrastructure is included.[27] They can promote walking and cycling by providing safer places to achieve physical activity through transportation, which may in turn have positive impacts on health, including reduced obesity. One study found that 43 percent of people reporting a place to walk were significantly more likely to meet current recommendations for regular physical activity than were those reporting no place to walk.[28]

The process starts by considering the function and form of the street and developing a hierarchy of use by different modes. This hierarchy can change depending on the street function and the complexity/mix of users. The concept is particularly relevant to LMICs where the consistency of place and function is often very indistinct (see section 2.2 regarding road function and land use).

Street design is not simply a technical or quantitative exercise that should remain fixed for generations. Rather, street design requires an observation of how people use the space, from drivers to people sitting on steps and porches. It is with these observations that the best design can then be crafted.

Unlike highway design, street design is iterative. At freeway speeds, one needs uniformity and consistency. As speeds slow, options expand. With more possibilities comes the need to experiment and adjust based on how users react. The design of a street can always be improved. Successful streets cannot be imposed but need a collaborative effort between the highway authority or municipality and the local community which they serve.

Further Reading

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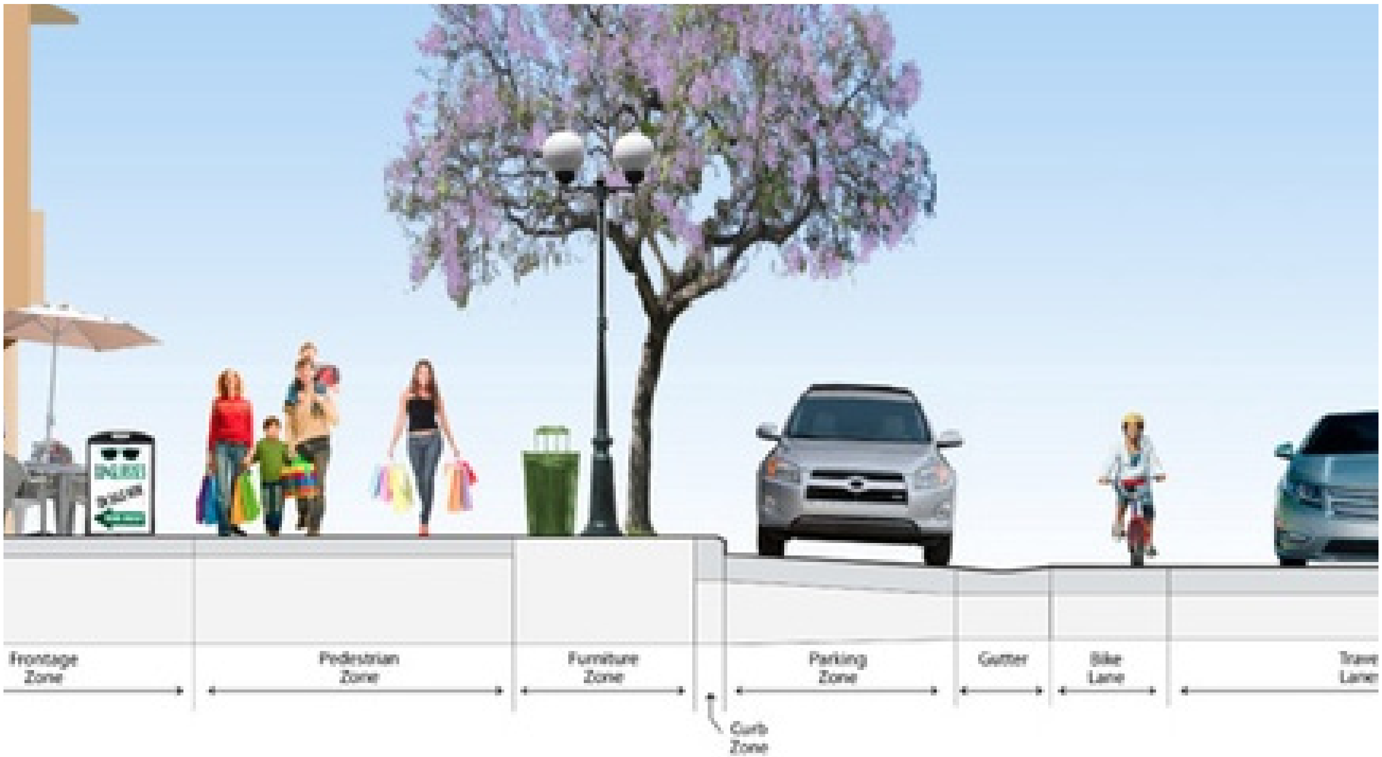
- NACTO. 2011. Urban Bikeway Design Guide. National Association of City Transportation Officials. Accessed at https://nacto.org/publication/urban-bikeway-design-guide/. Must read chapter,

27 Reynolds, C. C. et al. 2009. The impact of transportation infrastructure on bicycling injuries and crashes: a review of the literature. *Environmental Health 2009*, 8:47.

28 Powell, K. E., Martin, L., and Chowdhury, P. P. 2003. Places to walk: convenience and regular physical activity. *American Journal of Public Health* 2003; 93:1519–1521.

Figure 2.19: Complete street concept.



Source: Complete Streets Conference, LA, 2011.

Intersection Treatments; Designing for All Ages & Abilities.

- Active Transportation Alliance. 2012. Halupka, Paul, Lippens, Paul, Persky, Dan, and Woodall, Amanda. "Complete Streets Complete Networks: A Manual for the Design of Active Transportation." Accessed at http://www.atpolicy.org/Design. Must read chapter 2, Typologies; 3, Geometrics; 4, Amenities.
- City of L'viv. 2019. Sustainable Urban Mobility Plan for L'viv. Accessed at https://www.mobiliseyourcity.net/sustainable-urban-mobility-plan-lviv. Must read challenge 1, Traffic Safety.

2.5. Community Engagement

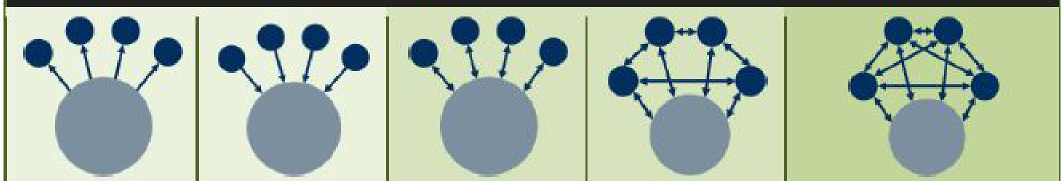
Community refers to people whose homes, workplaces, education institutions, shops, and social, recreational, and religious facilities are located in a defined geographic area, including their representative organizations such as nongovernment organizations (NGOs), community-based organizations (CBOs), cultural and sporting groups, and service and religious organizations. These are the people who are directly affected and possibly benefitting from a project. NGOs may include those whose activities are not limited to road safety as well as those that are dedicated primarily, if not solely, to road safety.

Community engagement is a systematic process of involving the local community in the development and implementation of road safety programs, policies, and projects. It can occur at many levels, ranging from information sharing and consultation, through to active involvement in decision-making processes. The various levels are summarized in Figure 2.20.

In road projects, community engagement is an inclusive process conducted throughout the project life cycle: during conceptualization, design, construction, maintenance, and operation. It is important that at the start of each project phase the road user and stakeholder requirements are clearly documented so that the designer can understand how to develop a design that addresses these needs and requirements. The process should be well thought through and planned, with clear programs for facilitators and experts. If done well, it will enhance local ownership and create an interface between the road implementing organizations and the community. The benefits of community engagement include:

- Providing an opportunity to inform the community about why there is a need for the project, including the safety and broader benefits. That way the community can understand the options and make informed decisions.
- Good decision-making resulting from accessing good/additional information.
- Establishing new networks and relationships (and further developing of existing networks).
- More local ownership of solutions to current problems and a higher level of responsibility for creating that future.
- Increased local support for change, or even the power of community in demanding change.
- Strengthening communities by keeping them informed about local issues.
- Building trust and confidence among stakeholders and the community.
- Contributing to the identification and development of leadership in community road safety.
- Providing a say to those who tend to be less involved in or have barriers to participating in decision-making processes.

Figure 2.20: Levels of community engagement



Inform	Consult	Involve	Collaborate	Empower
Description				
Participation The first two public participation levels—*Inform* and *Consult*—typically occur when a decision has already been made, and government wants to either communicate that decision to the public, or seek opinions on the decision.		**Engagement** The third and fourth public participation levels— Involve and Collaborate—have two-way information flows, and include sharing information within and across stakeholder communities during the decision-making process. When undertaking Engagement, decision makers commit to using stakeholder feedback to inform the decision and shape the outcome. Activity that occurs at the Collaboration level is also sometimes referred to as partnering.		**Empowerment** The fifth public participation level—Empower—is also often referred to as co-production, where decisions are made jointly between government and the community. This is typically when decision-making authority has been delegated to a group including members from both the government and the community/industry.
Objectives:				
To provide balanced, objective information to support understanding by the public.	To obtain public feedback on analysis, alternatives and/or decisions.	To work with the public to ensure concerns and aspirations are understood and considered.	To engage with the public on aspects of the decision, including the development of alternatives and a preferred solution.	To create governance structures to delegate decision-making and/or work directly with the public.
Commitments				
To keep the public informed.	To listen and acknowledge the public's concerns.	To work with the public to exchange information, ideas and concerns.	To seek advice and innovations from various public parties.	To work with the public to implement agreed-upon decisions.

Source: VicRoads. 2017. VicRoads. 2017. Traffic Engineering Manual: Speed Zoning Guidelines. https://www.vicroads.vic.gov.au/. Originally adapted from the International Association for Public Participation's Public Participation Spectrum.

- Extending democratic processes to stakeholders and the community in regard to community road safety.
- Fostering a sense of belonging and empowerment from working together.

Engagement with a community can be especially important in situations where difficult decisions need to be made. As examples, decisions on land acquisition, provision of bypasses, and changes in speed limits are areas where a community has a big role in improving safety. It is important to work closely with communities on these and similar topics to ensure all stakeholders have inputs to decisions and understand the broad implications of these decisions.

The time it takes to get community partnerships established is very worthwhile, as the people can provide valuable insights in relation to problem identification and the design of actions, and can act as “key informants,” providing qualitative data that can help prioritize the problems identified by a data analysis.

Where crash statistics are inadequate, as is the case in many low-income countries (LICs), it is even more important that road users are consulted so that local knowledge helps ensure the correct problems and appropriate, acceptable solutions are identified. For example, the community can provide information on hazardous locations (where crashes often occur) and participate in offering solutions and developing measures aimed at addressing safety issues. These may include the addition of footpaths, median barriers, bridge upgrades to accommodate pedestrians, improved lighting, signage, and fencing, as well as alignments around crossings with the purpose of reducing speed. An important outcome of this approach is the information gathered from the community, which would not have been available through the normal processes of visual assessments and data collection and analyses. At the same time, the community takes ownership of the solutions implemented to address the problem.

The importance of stakeholder engagement and information disclosure is also highlighted in the Economic and Social Framework (ESF) of World Bank (2016). To improve the process of engagement and consultation the ESF proposes a documented approach to:

1. Stakeholder identification and analysis;
2. Developing a Stakeholder Engagement Plan;
3. Disclosure of information;
4. Meaningful consultation with stakeholders;
5. Addressing and responding to grievances; and
6. Reporting to stakeholders.

Challenges associated with community engagement:

- Difficulties may arise in defining communities. Established CBOs will often include the influential and already vocal, and not usually vulnerable road users, i.e., pedestrians and cyclists, or the poor and women. Thus, special efforts and monitoring will be required to ensure the most vulnerable are consulted and considered.
- Community partnerships involve people who are affected by road safety problems and can play an important role in solving those problems, but their everyday business may not be road safety. It will take time to get everyone on board with a shared understanding of both the problem and the solution.
- There may be public demand against change/the project—perhaps through poor knowledge—which can be a major barrier to road improvements.
- There may be misunderstandings on the role and resources of community partners. For instance, few NGOs will have the capacity to undertake research studies, yet this task has often been assigned to them in a road safety action plan.
- Data collection may be linked to workplace key performance indicators, and sharing the data publicly may impact on perceptions about the efficiency or effectiveness of government departments.

Case Study: Speed management and community involvement on the N2 highway in Bangladesh

The N2 national highway connects the capital Dhaka to the Sylhet district. It is a single carriageway two-lane asphalt road. Three villages on this highway were selected as intervention locations. All villages were rural community settlements with activities on both sides of the highway. The risk of road crashes was high due to the combined effect of fast-driving buses and cars, considerable numbers of pedestrians crossing the road, the mix of low- and high-speed traffic, traffic coming from side roads, and vehicles changing speed to pick up and/or drop off people (figures 2.21 and 2.22). In addition, reliable road crash data from police and other sources were absent.

The integrated intervention program had multiple components, including a program for active community involvement, infrastructural measures, and educational interventions. The infrastructural measures consisted of speed humps, rumble strips, pedestrian crossings, bus bays, and road markings (figures 2.23 through 2.25). The program included educational interventions for school children and awareness campaigns for bus drivers and pedestrians. A measurement system was created using speed measurement with a laser-gun (also in control locations), the video recording of near accidents, and the use of local record keepers (people from the local community who record road crash data).

The interventions resulted in a reduction of the average speed of motorized traffic from 63.6 kph to 51.1 kph—a reduction of 12.5 kph (19.7 percent). The number of fatalities fell by 67 percent, and the number of serious injuries declined by 59 percent. There was strong support from the local communities for the program. Key innovative successes included the integrated intervention program, the active

Figure 2.21: Village settlement along the highway.

Source: Martijn Thierry/Jasper Vet—Safe Crossings.

Figure 2.22: Fast-driving buses and overtaking near settlement.

Source: Martijn Thierry/Jasper Vet—Safe Crossings.

Figure 2.23: Rumble strips.

Source: Martijn Thierry/Jasper Vet—Safe Crossings.

Figure 2.24: Speed hump.

Source: Martijn Thierry/Jasper Vet—Safe Crossings

Figure 2.25: Pedestrian crossing.

Source: Martijn Thierry/Jasper Vet—Safe Crossings.

involvement of the local communities, and the use of local record keepers for road crash data recording. Replication of the intervention program in other countries is possible and requires a good baseline assessment, customization of the intervention program dependent on the outcome of the baseline assessment, appropriate funding, creation of a strong implementation team, and approval by the authorities as needed.

Safe Crossings (www.safe-crossings.org) initiated and managed the intervention program. Implementation was done together with the Centre for Injury Prevention and Research Bangladesh (CIPRB) (www.ciprb.org). For more information see:

- Horst, A. R. A. van der, Thierry, M. C., Vet, J. M., and Rahman, A. K. M. F. 2017. An evaluation of speed management measures in Bangladesh based upon alternative accident recording, speed measurements, and DOCTOR traffic conflict observations. Transportation Research Part F (2016). http://dx.doi.org/10.1016/j.trf.2016.05.006.
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2.6. Innovation

As identified in section 1.3, it may be many years and up to two decades from when new solutions or approaches are identified, introduced and evaluated, and then adopted into formal design guidance.[29] In other cases, there may be a need to identify new solutions, because no solution currently exists, or existing solutions are not fit for purpose (e.g., not producing the required safety benefits; costing too much; or changing demands, including from road users). For these reasons, there is often a need to go beyond what is currently included in design guidance in order to achieve objectives. Innovation is often needed to deliver safety and other project outcomes. However, this innovation must be done in a considered, evidence-based manner. Risks (whether safety related, financial, or other) need to be minimized, and so a robust process is required. There is also a need to document this process, and share the results of this learning—whether positive or negative. Many widely applied safety designs used today were not known 20 or even 10 years ago, and have only reached broad application because the knowledge of their effectiveness has been shared.

There are a number of reasons that some very effective designs and interventions are not used

29 Jurewicz, C. 2017. Innovation and Safe System Road Infrastructure, Proceedings of the 2017 Australasian Road Safety Conference, Perth, Australia.

in some countries. The *PIARC Road Safety Manual*[30] suggests the following reasons in regard to road safety interventions:

- Lack of knowledge regarding the treatment and its effectiveness
- Lack of experience of how to install and maintain a treatment
- Issues regarding transferability and differences in local conditions
- Concern about legal liability if something goes wrong
- Concern about public understanding or acceptability.

There is a need to take care when trying innovative approaches, and new designs should be tested and shown to have positive benefits with no unacceptable negative impacts before they are implemented more widely. This may involve identification of positive case studies from other jurisdictions and further analyses (including reviews of literature on effectiveness and broader impacts; communication with those who have tried an innovative approach), small-scale trials (on-road, or off-road if risks are high), larger-scale implementation (including as part of demonstration projects), and then eventually full adoption. Each stage requires careful monitoring and documentation; based on the learnings from each stage, refinements might need to be made.

Tactical urbanism

Tactical urbanism (also known as guerrilla or pop-up urbanism) is a citizen-led approach to community building characterized by short-term, low-cost, and scalable interventions intended to catalyze long-term change. It is commonly applied in demonstration projects and pilot/interim projects for defined time periods to engage the public in city making and to test the designs before investing. Tactical urbanism has also proved to be a powerful tool for cities in responding to the COVID-19 pandemic due to their low cost and quick to implement nature. For example, cities have been transforming their streets using paint, chalk, barricades, and other low-cost materials to increase space for walking and cycling designed to help people move around while maintaining physical distance.

Case Study: HP intersection improvement, Mumbai, India

WRI India partnered with the Mumbai Traffic Police and the Mumbai Municipal Corporation in 2017 to audit and improve high-risk intersections across the city as part of the Bloomberg Philanthropies Initiative for Global Road Safety. The HP Petrol Pump intersection in Mumbai was selected for the first trial. Many decades ago, there was a roundabout at the intersection that connected three arterial roads which was later removed to increase traffic capacity. However, the intersection remained very large, which made it hazardous to cross for both motorists and vulnerable road users. Prior to the transformation, mobility patterns at the intersection were studied which showed that over 5,000 vehicles and an equivalent number of pedestrians traversed the intersection during peak hours. Unfortunately, there was no infrastructure provided for vulnerable road users, and city authorities had been primarily concerned with vehicular capacity up to that point.

The proposed redesign involved creating dedicated pedestrian infrastructure and redistributing space to accommodate all road users. This included expanding the sidewalks, extending the medians and introducing pedestrian refuge areas at the medians, reclaiming space from the residual areas of the intersection to create refuge islands, reclaiming space from slip lanes to create public spaces, and streamlining the traffic lanes to ensure a smooth flow of traffic. This design created a compact intersection area and reduced pedestrian crossing distances by 50 percent.

A trial (using chalk, paint, and barricades that were

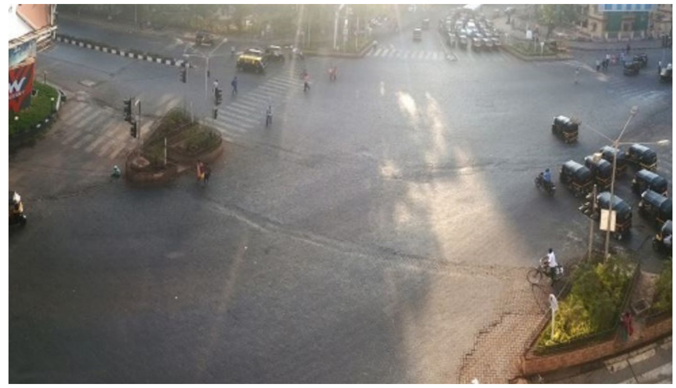
30 https://roadsafety.piarc.org/.

applied and installed overnight) was first tested for a span of 45 days. This allowed a series of interviews with pedestrians, traffic police, residents, and shopkeepers to be conducted to solicit feedback and input that fed into the final design. Crash conflict at the intersection was also analyzed during the trial, which showed that average vehicle speeds dropped by 15 percent and high, medium, and low risk conflicts reduced by 71 percent, 68 percent, and 60 percent, respectively. Additionally, the data collected showed that traffic capacity was not adversely impacted, and in some instances traffic flow improved due to more streamlined and clear movements. Following the successful trial, city authorities decided to permanently implement the recommended design in December 2018. Figures 2.26 through 2.28 show the transformation of the intersection.

As suggested above, a thorough, documented process is required when innovating. The following steps are adapted from the PIARC Road Safety Manual:

- Know your problem. Identify the target crash type, the road user type, and the locations that need to be targeted.
- Identify possible solutions. This can include solutions that are used overseas, or it can be an adaptation of an existing treatment.
- Assess the solutions. It is important to research treatments thoroughly to ensure they are likely to be beneficial for safety outcomes in this new context, and their likely application elsewhere, as well as for other policy objectives. This assessment can be based on documented experience from other road agencies. For newer treatments, driver simulators are sometimes used to determine the likely effects. In some instances, treatments can be installed in a controlled environment (e.g. ,off-road, or in a low-speed area) to determine the likely effects.
- Trial the selected solution. A demonstration project can be an effective way to test the treatment within a specific context and in a controlled environment. This can also help prepare for a wider rollout.

Figure 2.26: Before the HP intersection improvement in March 2017.



Source: © Saurabh Jain/WRI India.

Figure 2.27: Shops taking over the footpath and Figure 2.27: Temporary low-cost interventions implemented (using paint, chalk, and barricades) during the trial (April 2017).

Source: © Saurabh Jain/WRI India

Figure 2.28: The changes were made permanent in December 2018.

Source: © Saurabh Jain/WRI India.

Intelligent transport systems

Intelligent Transportation Systems (ITS) is defined as a set of information and communication systems that work in harmony to provide transport and traffic management services. ITS brings together various technologies such as data collection, communication, data mining, machine learning, artificial intelligence, and database management to provide applications intended to improve the efficiency and safety of transport systems.

The use of ITS on the highway and street system continues to grow in coverage and diversity of technology and applications such as speed feedback signs, rural intersection active warning systems, computerized traffic signal control, incident management systems, traffic enforcement systems, intelligent speed adaptation, connected and autonomous vehicles, and emergency management systems. ITS considerably modifies interactions among road users, and there is potential for ITS solutions to contribute to road safety. For example, Advanced Traffic Signal control (ATSC) systems, which aim to optimize the traffic light cycle with respect to the traffic flow, have been found to reduce angle crashes at intersections by up to 19.3% in Michigan USA[a] and to reduce total crashes by 34% and fatal and injury crashes by 45% in Pennsylvania USA.[b] Although the evidence on safety of these new infrastructure solutions is still increasing, practitioners should be open to the possibilities that ITS solutions can deliver significant safety outcomes. (see 3.2, Speed management and traffic calming for an example of speed feedback signs, Woolley, J., Stokes, C., Turner, B., and Jurewicz, C. 2018. Towards safe system infrastructure: a compendium of current knowledge (No. AP-R560-18), Austroads, for a number of ITS infrastructure examples).

a Fink, J., Kwigizile, V., & Oh, J. S. 2016. Quantifying the impact of adaptive traffic control systems on crash frequency and severity: Evidence from Oakland County, Michigan. Journal of safety research, 57, 1-7.

b Khattak, Z. H. 2016. Evaluating the Operational & Safety Aspects of Adaptive Traffic Control Systems in Pennsylvania (Doctoral dissertation, University of Pittsburgh).

- Monitor, analyze, and evaluate the trial. Ensure that the outcomes are as expected, and that there are no adverse effects to any road user's safety. This evaluation should include an assessment of the cost-effectiveness of the new treatments, especially when compared to an existing option.
- Roll out the solution on a wider scale. Continue to monitor and evaluate the treatments, including crash analysis once sufficient data have been collected. Include design and operational information in guidance documents.
- Inform others. If the new treatment is effective, it is important to let others know of this. Information on treatments that have not performed well is also very important for the international road safety community.

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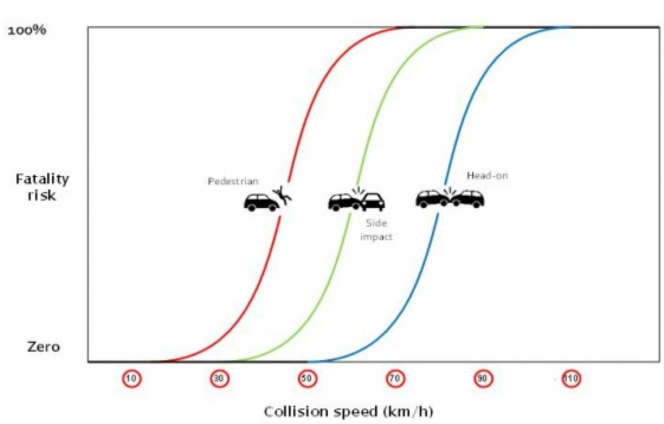
3. KEY ROAD DESIGN ASPECTS IN THE CONTEXT OF SAFE ENGINEERING

Speed is an important aspect closely linked with road design. In road design, “design speed” is used as a design control and is used to determine the various geometric features of the roadway. The assumed design speed should be logical for the topography, anticipated operating speed, adjacent land use, and functional classification of the road. On the other hand, travel speed or “operating speed” is the speed at which vehicles generally operate on a road. Excessive speed is the most significant contributor to fatal and serious crash outcomes. When a pedestrian is struck by a car at 30 km/h, they have a reasonable chance of survival, but above this, the chances reduce dramatically. The critical threshold for cars colliding at an intersection is 50 km/h, above which chances of survival decrease rapidly. For head-on crashes, the figure is 70 km/h for well-designed vehicles of equal mass (figure 3.1). Providing effective speed management can have profound benefits in terms of safety and other positive outcomes for urban, interurban, and rural roads.

Figure 3.1: Speed/injury risk curves.



Source: Greater Wellington Regional Council, Survivable Speeds, Wellington, New Zealand. 2015. For additional information see www.gw.govt.nz/survivable-speeds/.

3.1. Design speed and operating speed

General description

Design speed is defined as “the maximum safe speed that can be maintained over a specified section of a highway when conditions are so favorable that the design features of the highway govern”. In many countries, there are also concepts of ruling design speed and a minimum design speed for a particular type of facility. While the idea is to use the ruling design speed for the design of geometric elements, in no case should it go below the minimum design speed for that facility. Minimum design speed is specifically crucial to avoid inferior design due to restrictions in land availability and so forth.

Unfortunately, a designer has few variables that may be used to convey the design speed to a driver, especially outside built-up (urban) areas. The relationship between the ruling design speed, curve radii, and their superelevation, that is, side friction demand, should be consistent and so should the forward sight distance along the route or at intersections. Therefore, the level of demand on the driver is very important. See section 2.2 for more information regarding the principle of predictability and “no surprises.”

There are significant safety factors built into the parameters that are dependent on the selected design speed. As far as practicable, the road should be designed to operate at a speed equal or slightly higher (5 km/h) than the posted speed limit. This can be assessed by “sensitivity testing” the design for drivers travelling at higher speeds. Two examples of how this could be achieved are assessing the superelevation on the curves and the sight distance requirements. However, it should be acknowledged that geometry is not an appropriate mechanism by which to control speed, primarily because it relies too heavily on driver interpretation and feel. This is particularly relevant, for example, when horizontal straights and straight gradients are used in generally flat terrain.

In current practice, the term "operating speed" is defined as the speed at which drivers are observed operating their vehicles during free-flow conditions. This may not be at a safe speed and should not be used to define the appropriate speed limit. The 85th percentile of the distribution of observed speeds is the most frequently used measure of the operating speed associated with a particular location or geometric feature (Fitzpatrick et al. 1995). However, there have been many definitions of the operating speed (NCHRP 2003). (See references in Further Reading.)

The posted speed or speed limit is the speed displayed with a regulatory sign and is used in most countries to set the legal maximum or minimum speed at which road vehicles may travel on a given stretch of road. Speed limits are often close to the 85th percentile operating speed of the facility, but as highlighted above, this measure should not be used to set speed limits for existing roads. However, in many low- and middle-income countries (LMICs), speed limits are set at levels that are too high given the prevailing road corridor conditions (geometry and roadside) and the mix and volume of road users, particularly near built-up and market areas where there are many pedestrians and cyclists. It thus becomes difficult to achieve safe travel conditions under these circumstances, and several infrastructural, and enforcement-related interventions become essential.

Safety implications

While the relationship between the operating speed and posted speed limit can be defined, the association between design speed and either the operating speed or posted speed limit cannot be defined with the same level of confidence. Further, below are common challenges that may arise while working with design speed.

- First of all, it is possible that due to higher design standards and prevailing traffic conditions, the operating speed of a particular facility ends up being higher than the design speed. Such high operating speed would result in unsafe conditions for the existing land use and endanger road users of the facility.
- On the other hand, it is also possible that due to restrictions of site conditions, the minimum design speed could not be followed, which raises the issue of consistency in design.
- Additionally, design elements following minimum design speed as a criterion may lead to value design that may not always lead to safer performance.

Good design practice/ treatments/solutions

- Setting a target maximum operating speed is often very important, especially in LMICs, where speed enforcement is mostly absent.
- It is also essential to use infrastructure-based as well as enforcement-based road safety interventions to help restrict the maximum operating speed in a facility.
- The importance of such interventions is increased when the difference between the operating speed and posted speed limit is high, and the consequence of higher operating speed may lead to fatal and severe crashes.
- Infrastructure-based management of speed should ideally limit speeds to safe levels, which certainly means at the design speed. Often even this is not enough for safe operation.

Further Reading

- NCHRP Report 504. 2003. "Design Speed, Operating Speed, and Posted Speed Practices." National Cooperative Highway Research Program, Transportation Research Board of the National Academies, Washington, DC. ISBN 0-309-08767-8 Must read:

chapter 3, Interpretation, Appraisal, Applications.

- Fitzpatrick, K., Blaschke, J. D., Shamburger, C. B., Krammes, R. A., and Fambro, D. B. 1995. "Compatibility of Design Speed, Operating Speed, and Posted Speed." Final Report FHWA/TX95/1465-2F. Texas Department of Transportation, College Station, TX. Must read: 5, Concerns with design speed, operating speed, and posted speed relationships; 7, Conclusions and recommendations.

3.2. Speed Management and Traffic Calming

General description

Effective speed management involves identifying the actual functional road use for different parts of the network (reflective of all road user groups), selecting a safe speed limit to match that use, and providing appropriate infrastructure to support these speed limits where required (also see the discussion in section 2.2 on self-explaining or predictable roads). This can include developing treatments to reinforce the change in the road environment and appropriate speed requirement. It may also require support from police in enforcing the required speeds, particularly where matching the safe speed, design speed, and speed limit has not been adequately considered in the design process. Increasingly, in-vehicle technologies are assisting in ensuring appropriate speeds are maintained.

In regard to road design, speed management needs the strong support of road infrastructure to ensure road users can clearly understand their required speeds. Particularly in lower speed environments, well-designed roads also contribute significantly to a road user's choice of speed. This can often be achieved through traffic calming measures including:

- Gateway treatment at the entrance of the settlements and/or speed management and traffic calming along the highways with a higher need for access due to the change in land use.
- Narrowing through:
    - Widening sidewalks,
    - Adding bollards or planters, or adding a cycle lane or on-street parking,
    - Widening the centerline (figure 3.2),
    - Curb extensions/buildouts (figure 3.3),
    - Narrowing the width of the roadway at

Figure 3.2: Carriageway narrowing, delineators, and speed humps.

Source: Afukaar F. K. 2008. Evaluating Road Safety Interventions: The case of Ghana. Accessed at https://rtirn.net/PDFs/Evaluating_Road_Safety_Intervention_The_case_of_Ghana.pdf. December 12, 2019.

Figure 3.3: Road narrowing with traffic islands and extended curbs.

Source: Ghana Highway Authority, 2007.

Figure 3.4: Rumble strips on highways.

Source: © Sudeshna Mitra/GRSF/World Bank.

pedestrian crossings,

- Chokers (localized narrowing),
- Road diets which reallocate space on a street, for example, allowing parking on one or both sides of a street to reduce the number of driving lanes, or adding a central turning lane, and
- Pedestrian refuges or small islands in the middle of the street to reduce lane widths.

- Vertical deflection, or raising a portion of a road surface as a platform can create discomfort for drivers travelling at high speeds including the use of:
  - Speed bumps, humps, cushions, and tables,
  - Raised pedestrian crossings and intersections,
  - Speed dips,
  - Changing the surface material or texture, and
  - Rumble strips (figure 3.4).
- Horizontal deflection which requires vehicles to deviate slightly, and includes chicanes, pedestrian refuges, curb extensions, and chokers. Roundabouts also reduce speeds through this mechanism.
- Blocking or restricting access measures to block or restrict access such as:
  - Median diverters to prevent left turns or through movements into a residential area.
  - Converting an intersection into a cul-de-sac or

Figure 3.5: Speed bump placed by community on road passing through village—Ethiopia.

Source: © Soames job/GRSF/World Bank.

Figure 3.6: City street in Colombia with makeshift rumble strip.

Source: © Soames job/GRSF/World Bank.

dead end.

  - Boom barrier, restricting through traffic to authorized vehicles only.
  - Closing of streets to create pedestrian zones.

It is worth noting that people generally understand the high risk of speeds and often want lower speeds on roads passing through towns and settlement areas. It is however best if the design of speed humps and other traffic calming infrastructures are not left to communities who feel neglected as shown in figures 3.5 and 3.6.

Safety implication

- Effective speed management can reduce vehicular travel speeds, with subsequent safety benefits.
- Where safe speeds are provided (matching required road and roadside activity), there can be a significantly reduced frequency and severity of

collisions (up to and even exceeding 60 percent reductions in death and serious injury).[31]

- Even with minor changes in speed, there can be significant safety benefits.
- Appropriate speed management can reduce the need for police speed enforcement, freeing up resources for other enforcement activity.
- There are also numerous benefits beyond those for road safety, including potential greater incentives for using active modes (particularly walking and cycling, which produce broader health benefits; reduced emissions, noise and fuel consumption; and more "livable" space for residents and visitors.

Good design practice/ treatments/solutions

The current implementation factors in traffic calming include:

- For maximum effect, combinations of traffic calming measures should be used, preferably as part of an integrated transport strategy.
- Community engagement on safety benefits may be required to avoid negative public feedback due to perceived inconvenience and a misconception of additional injury. This should be factored into timelines for project delivery.
- Where relevant, schemes should be designed to cater for cyclists and essential emergency services and other heavy vehicles so that these are not hindered.
- Narrowing the vehicle travel lanes is effective at reducing speed and providing space for sustainable modes.
- Cost-effective traffic calming design solutions should be used.
- In many cases cheaper options (such as line markings to narrow lanes rather than fully constructed islands) can be as effective.
- Monitoring the effects of the treatments is also important, potentially starting with the lower cost, to fully understand how each one contributes and therefore where the highest value is achieved.
- Clear signing may be required, especially at isolated traffic calming devices, to alert road users and prevent traffic calming measures from becoming traffic hazards. Some treatment types can act as a road or roadside hazard.
- Speed limits should be consistent and aligned to the function, standard, and use of the road.
- Speed humps and other devices need to be well designed to provide maximum safety benefits. Nonstandard designs that are not well understood by road users may create a hazard.
- Some treatment types (humps, rumble strips, chicanes) can act as roadside hazards if not properly designed, signed, and maintained.
- Speed limits should seem realistic and credible so that drivers will adhere to them.
- Maintenance of speed calming infrastructure should be prioritized after implementation to ensure continuous safety.
- As an interactive traffic calming measures using technologies, a speed feedback sign (also called a driver feedback sign, or variable message sign) is used in some countries such as Australia, Canada, the United Kingdom, and the United States. A speed feedback sign is generally constructed of a series of light emitting diodes (LEDs) that displays actual vehicle speed to drivers as they approach the sign (figure 3.7). A US study found that speed feedback signs can be effective in reducing mean and 85th percentile speeds in a variety of situations[32] (see 5.13 Road signs for sign installation).

This unmarked speed hump (figure 3.8) increases road

31 Damsere-Derry, J., Ebel, B. E., Mock, C. N., Afukaar, F., Donkor, P., and Kalowole, T. O. 2019. Evaluation of the effectiveness of traffic calming measures on vehicle speeds and pedestrian injury severity in Ghana. Traffic Injury Prevention, 20(3), 336–342.

32 Forbes, G., Gardner, T., McGee, H. W., and Srinivasan, R. 2012. Methods and practices for setting speed limits: An informational report (No. FHWA-SA-12-004). United States. Federal Highway Administration. Office of Safety.

crash risk compared to appropriate marking (figure 3.9) due to failure to see the speed hump by motorists. Speed humps and other traffic calming measures should be clearly marked and signed; adequate funds should be allocated for maintenance.

Figure 3.7: Speed feedback sign.

Source: Richard Drdul/FHWA.

Figure 3.8: Unmarked ("invisible") speed hump—Zanzibar.

Source: © Alina F. Burlacu/GRSF/World Bank

Figure 3.9: Marked speed hump for traffic calming

Source: © James Robert Markland/World Bank

Case Studies

Speed calming infrastructure in South Africa

Figure 3.10: Raised pedestrian crossing and mini circle

Source: Arrive Alive. Traffic Calming, Speed Calming and Road Safety; Traffic Calming and Pedestrian Safety. Accessed at https://www.arrivealive.mobi/. December 17, 2019.

Figure 3.11: Use of mixed traffic calming infrastructure—narrowing, speed humps, and delineators

Source: Arrive Alive

In South Africa, more than 35 percent of road crash fatalities are pedestrian fatalities. The South African road authority uses a prioritization system for traffic calming infrastructure due to limited funds. The requests to implement traffic calming measures such as speed humps, raised pedestrian crossings, and mini circles (as shown in figures 3.10 and 3.11 above) come from the public, councilors, staff members, and observations by authorities. A sample of the results in South Africa show that the traffic calming humps improved safety with respect to the severity of collisions. Serious pedestrian-vehicle collisions (PVCs) dropped by 23 percent and 22 percent, while fatal collisions decreased by 68 percent and 50 percent in some areas.[a]

Traffic calming has been shown to be effective in reducing the number of PVCs but needs to be supported by additional measures to further improve the safety of pedestrians.

a Nadesan-Reddy, N., and Knight, S. 2013. The effect of traffic calming on pedestrian injuries and motor vehicle collisions in two areas of the eThekwini Municipality: A before-and-after study. SAMJ: South African Medical Journal, 103(9), 621–625.

Figure 3.12: Children had no safe and dedicated crossing point and very often were in constant conflict with motorists.

Source: (left) Lusaka Times. Vera Chiluba Primary School: Road re-design that promotes road safety. Accessed at https://www. lusakatimes.com/2019/11/11/why-we-support-mayor-sampa-lowering-of-speed-limits-around-schools/. December 17, 2019. (right) Guardian News & Media Limited. Why are Ghana's roads so deadly? Latest fatality sparks fury in Accra. Accessed at https://www.theguardian. com/cities/2018/nov/27/why-are-ghanas-roads-so-deadly-latest-fatality-sparks-fury-in-accra-adenta-madina. December 19, 2019.

Figure 3.13: School children are protected by an elevated zebra crossing which is a traffic calming feature in itself.

Source: (left) Lusaka Times, (right) Poswayo A. Street Shaper. December 2018. Accessed at https://globaldesigningcities.org/2018/12/12/street-shaper-december-2018/. December 19, 2019.

Speed calming infrastructure for school zones in Zambia and Ghana

The Zambia Road Safety Trust (ZRST) is concerned about the impact of road traffic on children. About 1,550 children were killed or injured in 2014 in road traffic. The Lusaka mayor together with the ZRST plan to reduce speeds limits at all school zones from the widespread 40 km/h to 30 km/h. This has been done through improvement of pedestrian infrastructure—footpaths, zebra crossings, speed humps, road signs, and more (see figures 3.12 through 3.14 for before and after photos).

These improvements are part of an NGO, Amend, School Area Road Safety Assessments and Improvement (SARSAI) program focused on reducing injuries around school areas in urban Africa where children are known anecdotally to be at very high risk of a road traffic injury (RTI).

Figure 3.14: Installing speed table with checker marking. Left: before the intervention; Right: After the intervention.

Source: safe-crossings.org.

Further Reading

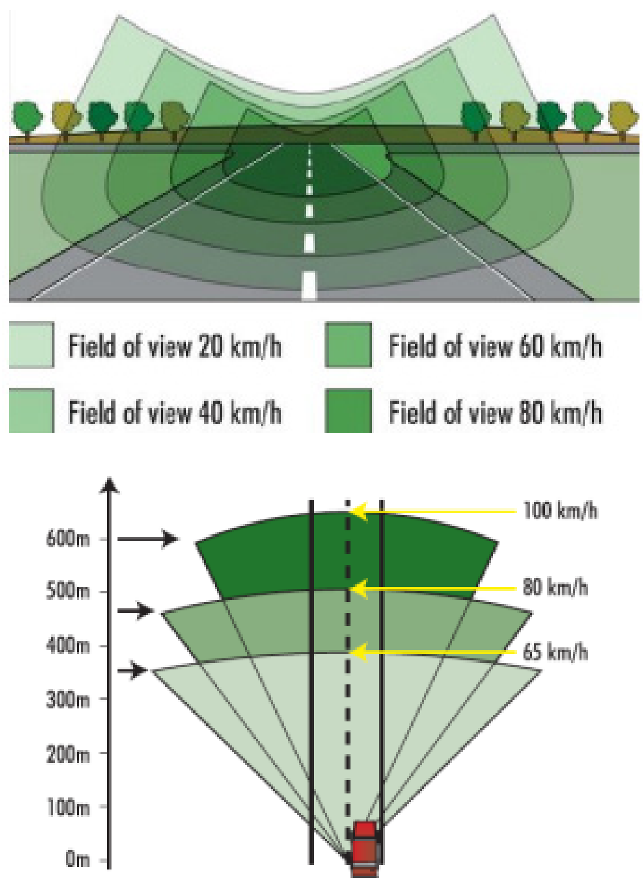
- South Central Regional Council of Governments. 2008. Traffic Calming Resources Guide. Must read chapter 2, Toolbox; chapter 3, Contents.
- GRSP Speed Management: A guide for practitioners and policy makers. GRSP, Geneva. Must read Appendix 4 and chapter 3 under subtitle 3.4.
- FHWA Traffic Calming Guidelines. Must read chapter 1, Introduction and Appendix A.

3.3. Sight distance

General description

- Sight distance is needed to provide drivers with enough reaction and maneuvering (including braking) time to adapt to the road conditions.
- Decision sight distance is provided in complex or unexpected situations and allows for increased decision time.
- From human factors research, drivers need 4–6 seconds to respond to a new situation; this means 110 - 170 m ahead if the speed limit is 100 km/h or 90–135 m for 80 km/h. The faster people drive, the further they need to look ahead and vice versa (figure 3.15), in order to read, understand, and react

Figure 3.15: Example of speed and peripheral vision and speed and focus point.

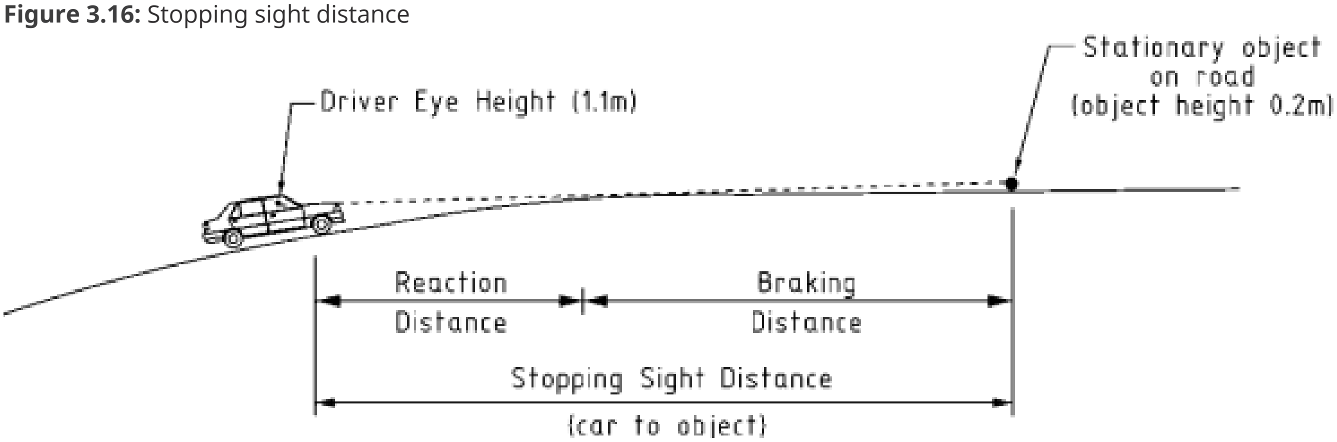


Source: PIARC, 2003.

in time to a hazard. Warning and information signs may sometimes be so sited that they have poor conspicuity, and the detailing of the road may not provide sufficient additional clues as to the hazard or decision ahead.[33]

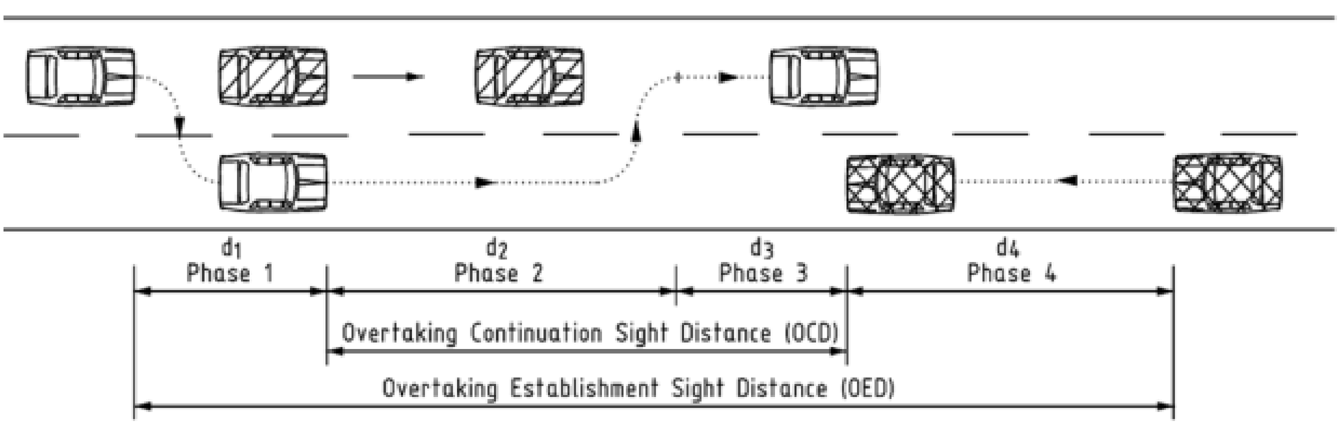
- Stopping sight distance is the minimum sight distance that must always be provided at any point on a roadway.[34]
- Stopping sight distance ensures a driver travelling at an appropriate speed can safely and effectively bring the vehicle to rest, including being able to see any objects along the vehicle path (figure 3.16).
- Passing or overtaking sight distance is provided in locations where passing in the opposing lane is allowed and allows for the safe completion of a whole maneuver (figure 3.17).
- Intersection sight distance involves a triangle of sight distances (figure 3.18) that enhance visibility and awareness for all road users.
- Intersection sight distance is typically defined as the distance a motorist can see approaching vehicles before their line of sight is blocked by an obstruction near the intersection.[35] The driver of a vehicle approaching or departing from a stopped position at an intersection should have an unobstructed view of the intersection, including any traffic control devices and sufficient lengths along the intersecting roadway to provide the driver with enough

Figure 3.16: Stopping sight distance



Source: Austroads, 2021. Austroads. 2021. Guide to Road Design Part 3: Geometric Design.

Figure 3.17: Overtaking maneuver and sight distance.



Source: Austroads. 2021. Guide to Road Design Part 3: Geometric Design.

33 PIARC. 2018. Practical Guide for Road Safety Auditors and Inspectors.

34 Austroads. 2016. Achieving Safe System Speeds on Urban Arterial Roads: Compendium of Good Practice.

35 FHWA Federal Highway Administration. 2011. Intersection Safety: A Manual for Local Rural Road Owners, US.

time to anticipate and avoid potential collisions.

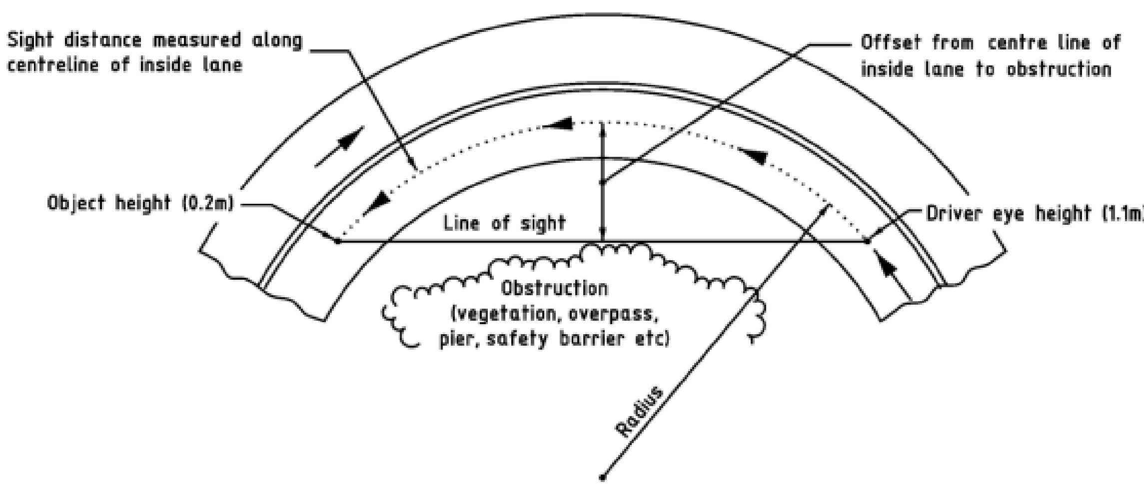
- Pedestrians also need to see and be seen, and crossing movements are often concentrated at or near intersections.
- Meeting sight distance provides for narrow roads and allows for the closing speed of opposing vehicles.
- In urban areas, corners frequently act as a gathering place for people and businesses, as well as the locations of bus stops, cycle parking, and other elements. The design should facilitate eye contact between these users, rather than focus on the creation of clear sightlines for moving traffic only.[36]
- Insufficient sight distance can be a contributing factor in crashes. Examples of obstructions include herds of animals, plants, parked vehicles, utility poles, buildings, and the horizontal and vertical alignment of the roadway (see sections on Horizontal curvature and Vertical curvature and gradient). Figure 3.19 illustrates sight distance at a curve including necessary offsets from obstructions.

A UK study shows improved visibility and/or increased

Figure 3.18: Examples of driver's sight triangles at intersections

Source: NACTO, 2019

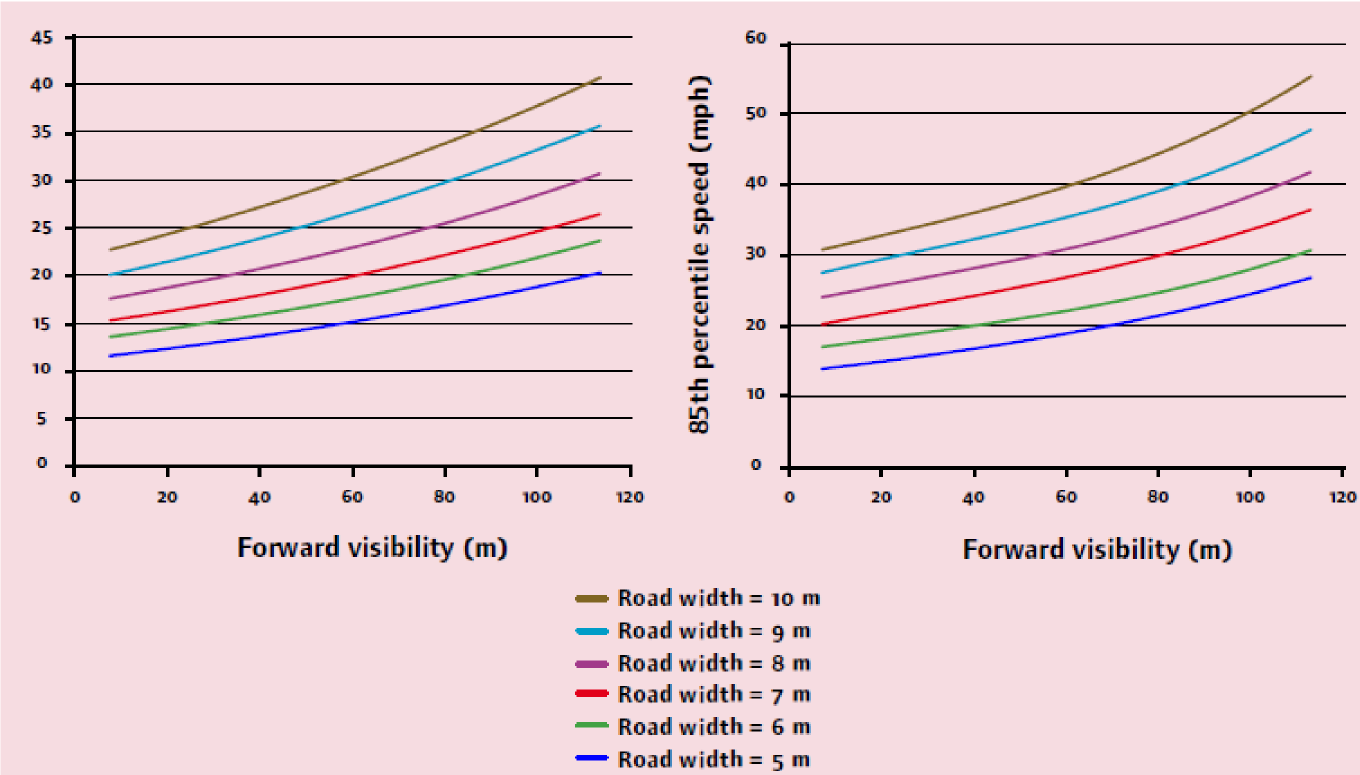
Figure 3.19: Illustration of driver's sight distance at curves.



Source: NACTO. 2019. Urban Street Design Guide: Accessed at https://nacto.org/publication/urban-street-design-guide/.

36 NACTO. 2019. Urban Street Design Guide: Accessed at https://nacto.org/publication/urban-street-design-guide/.

Figure 3.20: Correlation between visibility and roadway width and vehicle speeds.



Source: Department for Transport, UK.

roadway width were found to correlate with increased vehicle speeds (figure 3.20). Increased width for a given visibility, or vice versa, was found to increase speed. This implies that reducing sight distance can contribute to reducing vehicle speeds at intersections (noting that minimum sight distance criteria must be maintained).

Safety Implication

- Insufficient sight distance, and the corresponding reduced time to react, increases the risk of rear-end crashes on the approaches and high angle crashes within the intersection. This is because motorists may be unable to see and react to traffic control devices (i.e., signals and stop signs) or approaching vehicles from both major and minor roads.
- There are clear increases in safety risk because of reduced visibility and significant legal implications if any crash were to happen as a result.
- In Australian studies, sight distance improvements result in a reduction of about 30 percent of crashes for both the open roadway and at intersections where crashes had frequently occurred previously—a medium level of confidence is placed in this figure.[37]

Good design practice/treatments/ solutions

- Adequate sight distance is essential to provide drivers with enough reaction and maneuvering time to adapt to the road features and to other road users. This involves improving the triangle sight distance at intersections, enhancing visibility for all road users at the intersection, and, in some cases,

37 Austroads. 2012. Effectiveness of Road Safety Engineering Treatments.

reducing excess sight distance that could encourage early decision-making, bearing in mind that it is always necessary to maintain the minimum sight distance required.

Countermeasures for insufficient sight distance in specific situations (e.g., horizontal curves, intersections, etc.) are detailed in each section. Below is a summary of strategies to improve sight distance. Depending on the crash risks and crash types, a combination of countermeasures should be considered. The measures taken should aim to achieve a situation in which the available sight distance is made sufficient through reduced operating speeds (not just speed limits) or other measures.

- **Signs and markings:** For a conventional unsignalized intersection, an enhancement to the typical signs and pavement markings should be considered, although the effect may be limited.
- **Traffic calming devices:** Sight triangles required for stopping and approach distances are typically based on ensuring safety at intersections with no controls at any approach. This situation rarely occurs in urban environments and occurs only at very lowspeed, lowvolume junctions. At uncontrolled locations where volume or speed presents safety concerns, add traffic controls or traffic calming devices on the intersection approach52 (see section 3.2 on Speed management and traffic calming).
- **Relocating obstacles:** If the most frequent crash types are angle crashes due to insufficient sight distance with an overgrowth of foliage, the most effective countermeasure would be to clear the intersection's sight triangles to improve sight distance. Similarly, signals, signs, buildings, and so forth also should be relocated when they obscure sight distance.
- **Physical barriers and medians:** As only placing signs is proven to be unreliable to control movements, physical barriers and medians should be installed to reinforce to drivers what is expected as far as safe maneuvers are concerned. In general, where locations have insufficient visibility, passing maneuvers that involve crossing the centerline of undivided roadways or crossing the median of the roadways without physical barriers or auxiliary lanes must be prohibited [38] (see section 5.6 on Passing lanes).
- **Conversion of Y-type junction to a perpendicular junction (T-type) with signalization as necessary:** This will not only improve visibility, but also give a clear explanation on the right-of-way, resolve dangerous conflict points, and improve safety conditions for pedestrians and other vulnerable users. It is a relatively cheap and safe solution. It should be checked that the visibility at the T-junction is adequate on both the minor road and major road, and signalized where necessary.
- **Reconstruction of intersections and curves:** Modifying a horizontal/vertical alignment is often too costly and can have significant impacts to adjacent land uses. It is much better to design the road well before it is built than to rebuild it.

Further Reading

- AASHTO. 2018. The Green Book. Must read chapter 3.2, Sight distance.
- PIARC. 2019. Road Safety Manual. Accessed at https://roadsafety.piarc.org/en. Must read chapter 8.2, Designing infrastructure to encourage safe behavior.
- Austroads. 2016. Achieving Safe System Speeds on Urban Arterial Roads: Compendium of Good Practice. Must read chapter 4, Speed as a contributor to urban arterial crashes; Appendix A Engineering treatments.
- FHWA. 2011. Intersection Safety: A Manual for Local Rural Road Owners. Accessed at https://safety.fhwa.dot.gov/local_rural/training/fhwasa1108/. Must read chapter 3, Safety analysis.

38 AASHTO. 2011. A Policy on Geometric Design of Highways and Streets, 6th edition.

- NACTO. 2013. Urban Street Design Guide. Accessed at https://nacto.org/publication/urban-street-design-guide/. Must read chapter, Intersections; Intersection design elements.

3.4. Linear Settlements

General description

Linear settlements (figure 3.21) are a group of buildings, small villages, or other developments (including residential properties, roadside stalls, markets and other businesses) along major routes, leading to a mismatch between road design and use of the road. This situation also applies where trunk roads pass through towns. Traffic problems occur due to poor road network planning, poor enforcement of planning rules (where these do exist), and pressure from local businesses who see these locations as providing useful commercial access to passing motorists. These problems are accentuated by a lack of understanding of the safety risks that are present.

Safety implications

- Linear settlements lead to a mixing of high speed through traffic and local slow-moving traffic and vulnerable road users. This mixed function can lead to very high risks, particularly for vulnerable road users who may be attempting to cross and walk alongside the road (figures 3.22 through 3.26 illustrate dangerous pedestrian crossing movements in such high-risk environments due to lack of/poorly designed facilities).
- Other risks include poorly designed pickup and set down points for public transport (whether formal or informal), which also pose risks for pedestrians attempting to cross or walk along the road.
- There may also be slow-moving local traffic which may be maneuvering, including turning movements into and out of local access points or side roads, and making U-turns. Despite these road user movements, the design of these roads often remains unchanged, with wide roads, poor facilities for vulnerable road users and local traffic, and high speeds.

Figure 3.21: Example of a linear settlement.

Source: © 2021 CNES/Airbus/Google Earth

Figure 3.22: No footpath or crossing facility for pedestrians.

Source: © Soames Job/GRSF/World Bank.

Figure 3.23: Lack of pedestrian crossings.

Source: FIA Foundation

Figure 3.24: Pedestrian bridge but not used.

Source: © Alina F. Burlacu/GRSF/World Bank.

Figure 3.25: No footpath for pedestrians.

Source: © Soames Job/GRSF/World Bank

Figure 3.26 Poorly designed median for no crossing location—Romania.

Source: © Alina F. Burlacu/GRSF/World Bank.

- In essence, what were previously highways have been converted over time to local streets in regard to road use, but the road design may be unchanged. This creates confusion for road users and high levels of risk. This issue can occur at very discrete points on the road (one or two vendors selling goods to passing road users) through to sections that may be several kilometers in length.

Good design practice/ treatments/solutions

Various solutions can be applied to addressing this problem of linear development. These solutions are of two main types: regulatory and infrastructure.

- Regulatory approaches include development and enforcement of strict road and land use planning to prevent the development of houses and businesses at the side of the road. This may also require appropriate legal and enforcement powers and adequate resources to apply these. These approaches may also require education of the local community regarding the road safety risks and possible penalties for breaking planning laws.
- Roadside markets (e.g., informal commerce/vendor) pose a major hazard in linear settlements and road users by obstacles (e.g., stalls, shoppers, and parking for shopping) and narrowing of the footpath/road (figure 3.27). These must be addressed through the provision of safe off-road market facilities with parking spaces (figure 3.28).
- A variety of infrastructure solutions are also available. The highest cost and most substantial response are to provide a bypass road around the affected area (figure 3.29). It is important to ensure the new route has strict planning controls, and that new residential and commercial development are

Figure 3.27: Hazardous roadside stall

Source: © Kafkasyali/deamstime.

Figure 3.28: Separated roadside market space with parking, Dar es Salam corridor between Morogoro and Mafinga, Tanzania.

Source: © James Robert Markland/World Bank.

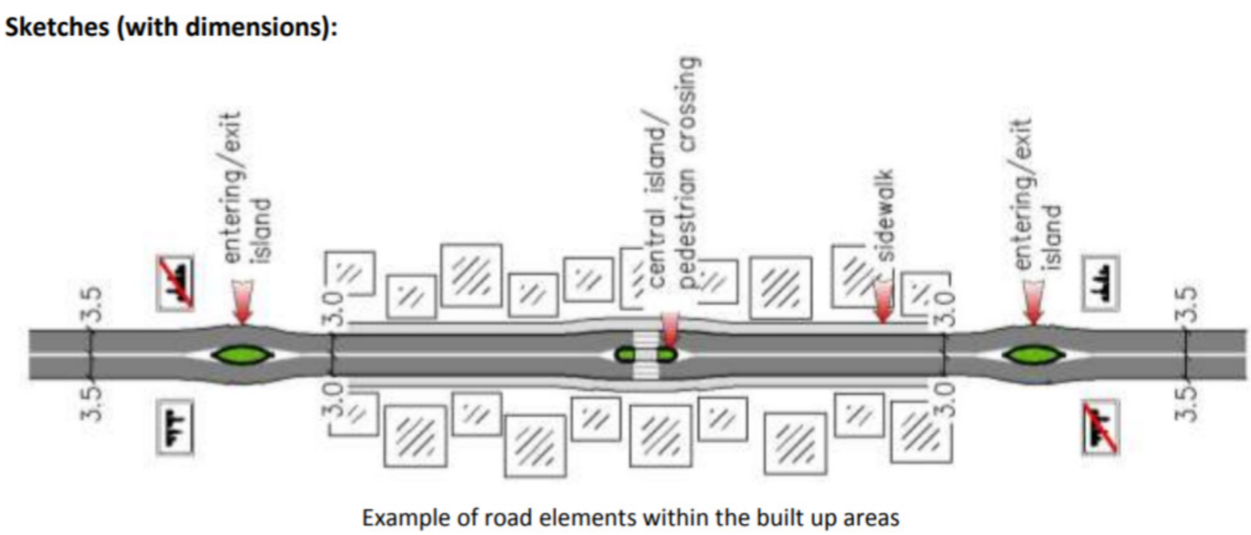
Figure 3.29: Examples of bypass roads.

Source: © Google Earth.

not allowed on this bypass route. This approach also requires infrastructure improvements for the linear settlement (the existing road) to provide better, lower speed facilities to cater for the road users that are present. This often involves road narrowing, widening of footpaths, and the provision of safe pedestrian crossing facilities. With significant reductions in traffic, what may have been a four-lane road (two lanes in each direction) can now be narrowed to just two lanes, with adequate provision for pedestrians and other slower road user groups. Figure 3.30 shows an example of road elements along a road in a built-up area.

- Other options include provision of a service road which provides lower speed access for local traffic and vulnerable road users (figure 3.31 and 3.32). These may be used as a location for permanent businesses, public transport stops, or for temporary markets and sellers. For smaller areas of roadside activity, a well-designed lay-by may be adequate. Further measures are likely to be required on the main through road, as there will typically be a need for local road users to cross the road. There also needs to be good provision for entry and exit points between the through road and service road.
- A further option includes reduction in speeds for all road users, supported by infrastructure. This typically includes provision of "gateway" treatments (figures 3.33 through3.35) prior to the start of the area of increased development. These encourage lower speeds on approaches through oversized signs on both sides of the roadway, narrowing (either through constructed or painted islands), or even different road texture or coloring. These

Figure 3.30: Sketch of road elements within built-up areas.



Source: Vollpracht et al. 2018

Figure 3.31: Service road—India.

Source: © Sudeshna Mitra/GRSF/World Bank.

Figure 3.32: Moldova—service road for slow vehicles

Source: © Alina F. Burlacu/GRSF/World Bank.

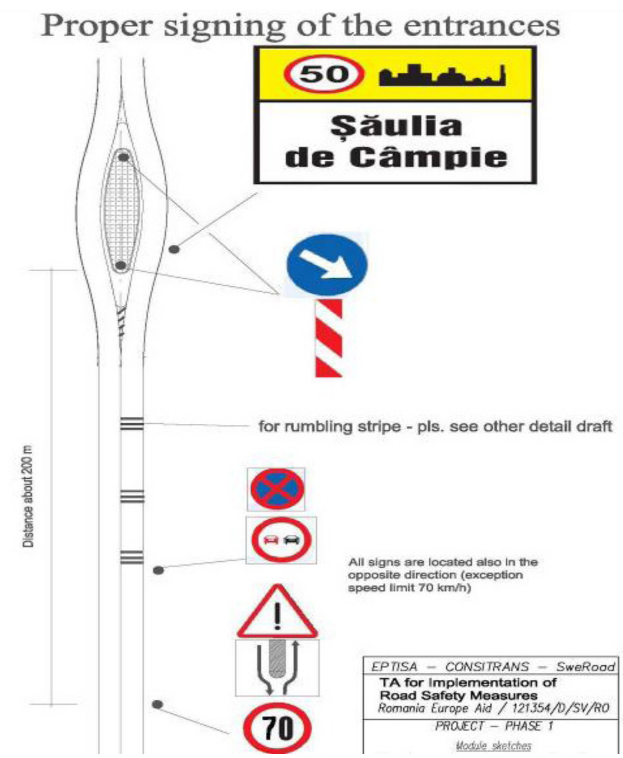
Figure 3.33: Speed sign and speed hump for gateway treatment—India.

Source: © Sudeshna Mitra.

Figure 3.34: Gateway treatments in India

Source: © Sudeshna Mitra.

Figure 3.35: Mixed gateway treatment—Romania



Source: Compania Nationala de Autostrazi si Drumuri Nationale. 2007. Catalog de măsuri pentru siguranţa circulaţiei în satele liniare.

measures can often be low cost and have been shown to produce considerable road safety benefits. The reduced speed may need to be sustained through other infrastructure features, including road narrowing, humps, and other traffic calming (see section 3.2). Particular care is required to provide low speed, safe crossing points for pedestrian (also see section 4.2).

Further Reading

- Kostic, N., Lipovac, K., Radovic, M., and Vollpracht, H. 2013. Improvement of Road Safety Management and Conditions in Republika Srpska, World Road Association (PIARC), Routes/Roads 360, 54–63.
- Vollpracht, H. 2010. They call them coffin roads, World Road Association (PIARC), Routes/Roads 347, 42–52.
- DfID. 2003. Roadside, Village and Ribbon Development, Highway Design Note 4/01, UK Department for International Development, United Kingdom. http://transport-links.com/research-archive/case-highway-design-note-4-roadside-village-and-ribbon-development/.
- Brumec, U., and Bricelj, A. 2011. Urbanism as a major factor of roads' function and safety, 14th International Conference on Transport Science, Portoroz, Slovenia. Must read chapter 2 and chapter 4.
- Sharma, A. K., Bahadur, A. P., and Tandon, Yashi. 2011. Linear Settlements and Safety Issues along Highways in India: A Case for integrated Approach for Highway Development, 24th World Road

Congress, Mexico City, Mexico. Must read: chapter 1, Background and chapter 2, Highway improvement typologies-traffic segregation

- Vollpracht, H. et al. 2018. Practical Guide for Road Safety Auditors and Inspectors, Automobile and Motorcycle Association of Serbia. Accessed at https://amss-cmv.co.rs/wp-content/uploads/2017/12/Practical-Guide-for-Road-Safety-Auditors-and-Inspectors-EN.pdf. Must read chapter 1, Road function.

3.5. Access Control

General description

Access management/control is one of the critical elements of geometric design and is related to the management of interference with through traffic. Where access to a highway is managed, interference due to vehicles', pedestrians', and cyclists' entrance and exit is minimized, and the road users get designated entry and exit from the highway as per the desired mobility and surrounding land use. Roadside businesses develop haphazardly in the absence of access management, which has emerged as a major road safety concern in LMICs. While access and mobility are two major functions of a road system, these functions need to be balanced to maintain the road's purpose. A high-speed road with unlimited access will not serve the purpose of mobility, and at the same time, will pose a high risk to its road users. However, in the context of LMICs, the balance between access and mobility (movement and place) remains a significant challenge due to the high share of nonmotorized modes. The planning and design of the high-speed facilities often overlook nonmotorized vulnerable road traffic users' needs, leading to safety risks. A high share of nonmotorized road users requires innovative thinking to accommodate all road users' needs in LMICs.

The aims of access management are to limit the number of conflict points, separate the conflict points, and remove turning volumes and queues from through movements. The benefits include not only reducing crashes but also increasing capacity and reducing travel times.

Safety implications

The safety issues commonly found in a mixed traffic context are as follows:

- Imbalance of access and mobility (movement and place) leading to high-speed environments where nonmotorized and vulnerable road users are not separated from high-speed traffic (figures 3.36 and 3.37).
- Inadequate consideration of the travel needs of nonmotorized road users in the planning and design process (figure 3.38).
- Improper and unsafe crossing opportunities for nonmotorized road users (figure 3.39).

Figure 3.36: Local traffic not isolated from the expressway.

Source: World Bank.

Figure 3.37: Direct access from local road to expressway

Source: World Bank

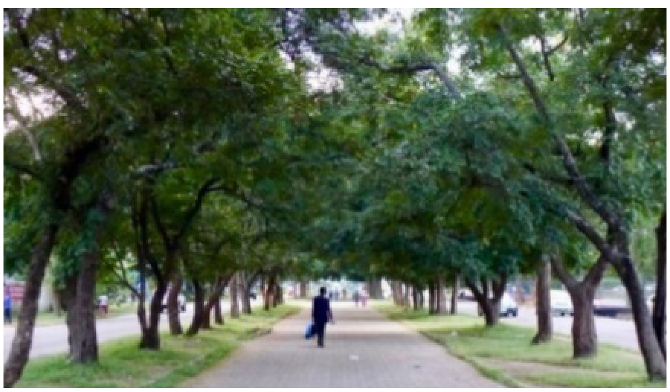
Figure 3.38: Lack of pedestrian footpath.

Source: © ONG LEESA/World Bank.

Figure 3.39: Opaque apron on footbridge may deter pedestrians from using the facility due to security concerns

Source: © World Bank.

Figure 3.40: A median walkway in Lusaka, Zambia.



Source: ITDP Africa.

Figure 3.41: Walking and cycling facilities with buffer zone.

Source: Shreya Gadepallii, Ranchi Mobility for All.

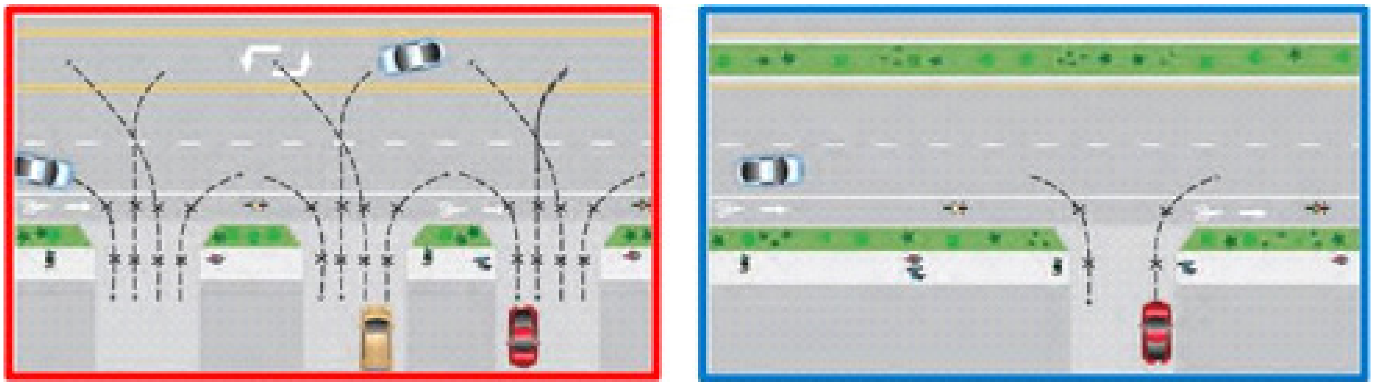
- The unsafe crossing of pedestrians in a high-speed environment, with large numbers of uncontrolled access from local streets onto the main highway.

Good design practice/ treatments/solutions

For better safety outcomes, it is helpful to have separate corridors that have designated restricted usage or priorities, that is, not all corridors are provided for all users. Some may be designated to the movement of freight/car priority with limited access to vulnerable road users, while others prioritize public transport and cycling with high accessibility. In case such separation is not possible, to tackle the issue of unsafe access management, the following treatments and design practices need to be followed whenever a highway enters built-up areas and settlements.

- At-grade crossing facilities with marked uncontrolled crossings at two-lane and controlled and/or grade-separated crossings for wider roads such as four, six, or higher lane highways.
- Provision of footpath/sidewalk and cycle lanes to separate pedestrian and cyclist traffic from through traffic (figures 3.40 and 3.41).
- Provision of pedestrian guardrails to channelize pedestrians only at the marked crosswalk such that random crossing of roads at undesignated locations could be prevented.
- Safe and marked public transport stops with bay facilities for boarding and alighting.

Figure 3.42: Access management.



Source: Michele Weisbar/Los Angeles County. 2011. Model Design Manual for Living Streets. Accessed at http://modelstreetdesignmanual.com/model_street_design_manual.pdf.

- Where major roads are bordered by commercial or residential development, multiple minor accesses may be connected to a service road that connects into the main highway via a properly designed junction. See also section 3.4.

The presence of many driveways in addition to the necessary intersections creates many conflicts between

vehicles entering or leaving a street and bicyclists and pedestrians riding or walking along the street. When possible, new driveways should be minimized and old driveways should be eliminated or consolidated, and raised medians should be placed to limit left or right turns into and out of driveways (figure 3.42).

There is evidence from research conducted in LMICs that pedestrians prefer to cross at-grade and often don't use grade-separated crossing facilities (Tiwari et al.). The success of the usage of the grade-separated facilities thus depends on the ease of access, and the amount of diversion, security, and control of alternative access to unsafe crossings. Therefore, it is essential to make a balance and use innovative design, such that extra distance walked by the pedestrians could be reduced, which is probably the most critical challenge currently facing the road development projects in LMICs.

3.6. Construction, Operation, and Maintenance

General description

As part of the construction, maintenance, and operation of a highway network, there will be a requirement to review safety features and implement measures to ensure safe use of the network by all users. This will often require road works, temporary closures, or incident management while allowing traffic to flow as freely as possible. In addition, additional reviews of safety features will be needed throughout the lifetime of the road to ensure that safe operation of the highway is maintained. Figures 3.43 through 3.47 illustrate some safe and unsafe practices in work zones.

To ensure that the safety benefits of the road are maintained during its operational life, it is important to continue periodic reviews of the network in use. This is achieved through a regular program of road safety inspection and assessment. It involves the examination of an existing road with the objective of identifying aspects of the road or the road environment that contribute to safety risk, and where safety can be improved by modifying the road environment. This should not be confused with routine maintenance

Figure 3.43: Complete lack of signing and control—Kenya.

Source: © John Barrell.

Figure 3.44: Uncontrolled signing—Romania

Source: © Alina F. Burlacu/GRSF/World Bank.

Figure 3.45: Well signed and controlled site—Tanzania

Source: © John Barrell.

Figure 3.46: No provision for pedestrians—Qatar

Source: © John Barrell.

Figure 3.47: Well signed and guarded work zone—Abu Dhabi.

Source: © John Barrell.

inspections which examine the condition of the existing road infrastructure.

Even when no works are being undertaken on the operational network, it is still necessary to assess the safety of its use and performance. And even when roads are constructed to the latest and best safety standards, because of the continuously changing interaction between vehicle performance, road user behavior, and road infrastructure, the performance of highway features can change over time.

Safety implications

- Even the best design will produce poor outcomes if construction is poor (including not following design, use of different materials or design solutions during construction, and not adequately adapting to local factors (such as utilities and traffic mix).
- Poorly defined work zones can increase road safety risk for all users (figures 3.48 through 3.51).
- Even where adequate and comprehensive work zone traffic management arrangements are provided, they do not change with each phase of operation and materials and objects are often not protected or are left behind when construction is completed in that area (figures 3.52 and 3.53).
- Construction materials/objects are often not removed even after the road is open to the public.
- Lack of maintenance and review of safety features can result in poor driver behavior (figures 3.54 and 3.55).
- Relatively little is known about the true effectiveness of the treatments under different circumstances in LMICs.
- Proper evaluations of road safety actions and interventions worldwide are rarely undertaken, and this is especially the case in low- and middle-income countries.
- It is necessary to rely on (and extrapolate from) evidence on the effectiveness of measures from high income countries where road user behavior and traffic mix will not be a perfect match.

Figure 3.48: Construction work going on without any temporary safety measures—West Bengal.

Source: World Bank.

Figure 3.49: Major excavation with no protection or segregation of work zone and general traffic—Kenya.

Source: © John Barrell

Figure 3.50: Construction with no protection or segregation of work zone and general traffic—Romania.

Source: © Alina F. Burlacu/GRSF/World Bank

Figure 3.51: Complete lack of roadworker protective clothing or adequate workzone demarcation.

Source: World Bank.

Figure 3.52: Unprotected work areas and materials—India

Source: World Bank

Figure 3.53: Stacked construction material unprotected or contained along the highway—India

Source: World Bank.

Figure 3.54: Poorly maintained road surface—Romania.

Source: © Sudeshna Mitra/GRSF/World Bank.

Figure 3.55: Well-maintained road with clear road markings—India.

Source: Martijn Thierry/Jasper Vet—Safe Crossings.

Good design practice/ treatments/solutions

- All work activities should be planned to optimize road safety, road space, and work efficiency while minimizing congestion, delays, and inconvenience for all road users.

Construction and maintenance

- All reasonable steps should be taken to ensure that disruption due to the work is reduced to a minimum.
- Work zones must be clearly defined and protected to allow both roadworkers and the general public to adapt safely to the change in space and alignment.
- Traffic and roadworker safety in a roadworks work zone should be integral and high priority elements of every road construction project or road maintenance activity, from the planning process until project construction or maintenance work is complete.
- Work zone traffic management must not be associated with substandard traffic safety and if anything, the unusual and/or restrictive conditions found in work zones can require even higher standards of safety.

- Subject to achieving an acceptable level of road user and worker safety, traffic amenity in a work zone should be as close as possible to that provided for in the normal operation of the road, including speed, permitted movements, access to abutting property, and provisions for non-vehicular traffic. However, in many cases restrictions on some or all of these aspects are necessary. These restrictions require clear advance warning, signage, and direction to operate safely.
- The same geometric and safety design principles which apply to the design of permanent roadways also govern the design of work zone traffic management treatments. For example, lane drops, lane narrowing, sharp curves, or other abrupt or frequent geometric changes must be appropriately designed and implemented in terms of design speed, advance warning, signage, and delineation to provide road users with effective clear and positive guidance.
- This may also require the introduction of geometric changes in individual steps or stages, for example, the closure of two lanes on a multilane highway should be done in two individual stages to allow traffic to change lanes smoothly and safely, and a lane closure should not end and a sharp horizontal curve begin at the same point, but should be separated.

Note: The topic of work zone traffic management is a whole manual in itself and there is not sufficient space within this document to cover it fully. Numerous national guidelines are readily available as exemplars of good practice—see further reading below.

- Road construction materials (whether in use or surplus) should be contained within a demarcated construction zone. If materials need to be placed along the highway, delineation, demarcation, and signage should be given to warn and guide drivers.
- All construction materials/stored materials on the Right of Way (ROW) which can potentially harm road users or cause them to behave in such a way that can potentially lead them to an unsafe situation should be removed.
- All construction phases (i.e., different site layouts and access/routing arrangements) need to be subjected to an independent road safety audit.
- The whole of the construction process should be subject to a thorough safety assessment that considers the risk to both roadworker and road users during the implementation of any works, including road safety audits during construction. This is sometimes referred to as a “Safety in Design” Review. This compares options for design, construction, operation, and decommissioning of the asset and assesses which has the lowest risk to the workforce and the travelling public during each phase. This does not necessarily lead to a change in preference for options; however, the risks should be identified so that they are taken into account during subsequent phases of the project. A specific Traffic Management Plan needs to be developed that demonstrates safe routing of motorized and nonmotorized traffic during construction, together with appropriate protection of construction site workers.
- It is essential that the cost of routine inspections and maintenance are embedded in scheme appraisal and design from the outset.

Operation

- When a scheme is implemented and open to use, it is still important to monitor and review the safety performance of the design to ensure that the predicted safety is achieved.
- Before implementing proposed treatments, it is normally necessary to assess their potential impact in order to make a business case for investment. Information on the effectiveness of treatments has generally been compiled from research undertaken in countries in Europe, and in the US and Australia.

- Low- and middle-income countries should seek to build an evidence base of what does (and does not) work in their own situations. This can be advanced by closely monitoring the safety performance of new and existing roads when in use.
- An understanding of local effectiveness will only be established if road authorities monitor and evaluate the performance of any measures implemented.
- Organizations therefore need to introduce a system for monitoring and reviewing the performance of any implemented road safety inspection or road safety assessment recommendations. This can then be used to identify the most appropriate safety improvements to incorporate into revised design standards. This is particularly important in any country where development of the road network is occurring at a fast pace and where research concerning road characteristics and their impact on road safety outcomes are not available.
- Road safety audit (see section 7.3) includes the post opening stages of a new road and reviews the actual safety in use compared with what was anticipated. A regular program of post-opening safety reviews can feed back into design changes relevant to local circumstances.
- A regular sequence of inspection and action ensures that both road condition and safety are reviewed, and appropriate remedial actions implemented to maintain optimum performance of the network.

Further Reading

Wisconsin Department of Transportation. 2019. Work Zone Guidelines for Construction, Maintenance, and Utility Operations.

National Academies of Sciences, Engineering, and Medicine. 2018. Estimating the Safety Effects of Work Zone Characteristics and Countermeasures: A Guidebook. Washington, DC: The National Academies Press. https://doi.org/10.17226/25007.

European Union Road Federation. 2015. Towards Safer Workzones—A constructive vision of the performance of safety equipment for work zones deployed on TEN-T roads.

African Development Bank. 2014. Road Safety Manuals for Africa:

1. New Roads and Schemes Road Safety Audit,
2. Existing Roads—Proactive Approaches,
3. Existing Roads—Reactive Approaches.

4. VULNERABLE ROAD USER INFRASTRUCTURE DESIGN

General description

Vulnerable road users generally refers to those modes of travel that do not include cars, public transport, or licensed commercial vehicles—those where the road users are protected from injury by an enclosed vehicle. It includes both nonmotorized travel and motorcycles.

Motorcycle and moped use are on the increase. These offer a solution to growing traffic congestion, parking problems, and the high cost of private car ownership. Users range from leisure bikers on high-powered machines to young people and professionals commuting by moped. More detailed discussion on their safety issues is provided in section 4.3.

An emerging form of personalized travel is the use of e-scooters, which are being used extensively in several countries. However, at the time of writing no specific consensus has yet been reached in many cases regarding the legal situation on their use on either roadway or footway/cycleway. Their relative speed to both normal motorized and nonmotorized traffic is a particular concern, as is adequate protection of riders.[39]

Independent nonmotorized travel (NMT), which includes both walking and cycling, is an essential part of any journey in low- and middle-income countries (LMICs), and all trips include an element of walking or independent movement. However, the provision for undertaking these types of trips is often disjointed or included as an afterthought of the improvement of motorized travel.

Increasing global problems of climate change and obesity are emphasizing the importance of such independent movement, which is often the only form of travel available in many LMICs, to increase personal health and reduce CO2 emissions. The development of appropriate and continuous networks that allow for as much independent travel as possible is a key element in sustainable travel. The positive improvement of these forms of travel in any road safety work is essential.

LMICs are particularly favorable for implementing independent NMT policies. While policies in many Western countries are focused on increasing the share of nonmotorized trips, LMICs already have a substantial proportion of their residents moving in a sustainable way.

The key to successful designs for safe NMT is to ensure that these trips should be direct, coherent, comfortable, safe, and enjoyable. There is also evidence from LMICs that NMT users, particularly cyclists, prefer safer routes compared to shorter routes within certain limits.[40] While in many cases NMT users will follow the motorized route network, this should not be a precondition. Independent networks free from motorized traffic provide safer, more direct, and enjoyable routes.

Where they do have to follow motorized routes then they need to be incorporated as part of a “complete streets” design (see section 2.4.3). In 2012 international Road Assessment Programme (iRAP) reported that 84 percent of the approximately 50,000 km of roads

39 ETSC. 2019. Safer Roads, Safer Cities: How to Improve Urban Safety in EU.

40 Majumdar, B. B., and Mitra, S. 2018. Analysis of bicycle route-related improvement strategies for two Indian cities using a stated preference survey, Transport Policy, Volume 63, pages 176–188.

assessed in low- and middle-income countries where pedestrians are present carry traffic at 40 km/h or more and have no footpaths.

Safety implications

- Roadway design generally caters for the needs of four-wheeled motorized traffic, neglecting the needs of pedestrians, cyclists, or motorcyclists.
- Facilities for a "typical" pedestrian may not accommodate a significant portion of users, including older adults, people with disabilities, and children.
- Increased vehicle speeds are associated with increased injury severity and death for vulnerable road users. The provision of arterial roadways, intersections, and fast traffic lanes without adequate attention to facilities for other modes results in an increased likelihood that they will be killed or injured when using the road.
- Motorcycles, bicycles, and pedestrians are less easy to see, especially by faster moving vehicles.

Figure 4.1: Separation of a vehicular travel way, cyclist path, and walkway on an urban arterial with concrete paving blocks on walkway and sealed cyclist path.

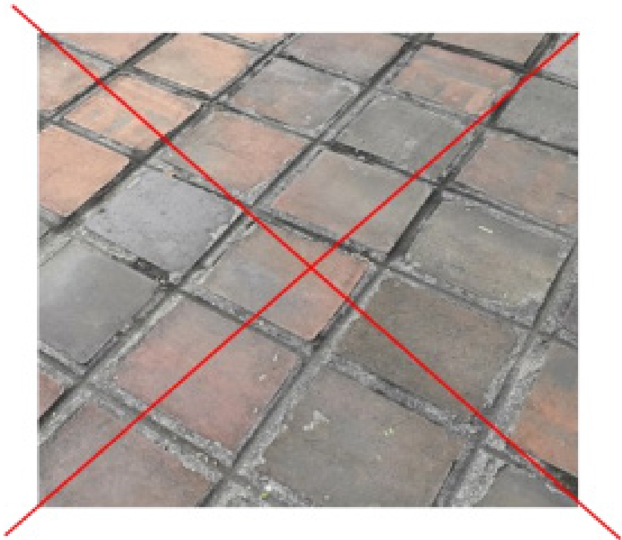
Source: ITDP, 2019

- High speed and volumes of motorized vehicles require the separation and protection of both pedestrians and cyclists (figure 4.1). The risk of pedestrian injury is high when pedestrians share the road with vehicles travelling at fast speeds (greater than 30 km/h). Vehicle–pedestrian collisions are 1.5 to 2.0 times more likely to occur on roadways without sidewalks.[41]
- Roadway designs in which facilities such as defined walking routes and signalized crossings are missing, inadequate, or in poor condition increase the risk of injury for pedestrians.
- Pedestrians falling into roads occurs where there is too little friction or traction between the footwear and the walking surface due to wet surfaces, weather hazards, and flooring or other walking surfaces that do not have same degree of traction in all areas (figure 4.2). In addition, obstructed visibility of footpaths (e.g., improperly placed signs or trees, poor lighting) also increases the risk. The quality of footpaths is important for the safety of footpath users, including people with disabilities. Disable-friendly
- Intersections are associated with high rates of collisions and injuries because they include many conflict points.
- Uncontrolled intersections exacerbate such conflicts, as vulnerable users may encounter oncoming vehicles that are not required to stop or yield travelling at elevated speeds.
- Vertical separation (overbridges and underpasses) is expensive and require large amounts of space. They may also be inaccessible to some users, or even be unsafe from a personal security perspective.

Specific design requirements for pedestrians, cyclists, and motorcycles are considered in the following sections.

41 Knoblauch R. L., et al. 1988. Investigation of exposure-based pedestrian accident areas: crosswalks, sidewalks, local streets, and major arterials. Washington, DC, Federal Highway Administration.

Figure 4.2: No tripping hazards or slipper floors.



Source: Deep Dive on accessibility and transportation/The World Bank.

4.1. Pedestrian Facilities Design—Footpaths

Good design practice/ treatments/solutions

Separate footway provision

- In LMICs, mixed use of the road space is common in both urban and rural areas. A key consideration in providing safe routes and facilities for vulnerable users is the speed, size, and volume of all vehicle types.
- To promote a safe environment for walking, pedestrians must be provided with a complete network with sufficient space to walk along the public right-of-way.
- In urban and suburban areas where pedestrian volumes may be high, the most common form of provision is the inclusion of a paved or sealed footway immediately adjacent to, and raised above, the vehicular carriageway (figures 4.3 and 4.4).
- If speed and volumes are low, then less segregation and protection are necessary, and in certain instances the vulnerable users may dominate the street space (figures 4.5 through 4.7).
- 1.8m is considered the absolute minimum clear width to allow pedestrians to pass each other without having to move into the vehicular path. Increased width may be needed as pedestrian flows increase to prevent overspill into other use areas (i.e., cycle lanes or traffic lanes).

Note: COVID-19 implications on footway width may require an increase to 2.5 m.

- A positive crossfall toward the roadway is required on footways to assist drainage. Typically this is 2.5 percent or 1 in 40, although lower gradients may be used in areas with harsh winters and ice. Gradients greater than 3.3 percent (1 in 30) make it difficult to walk on, particularly when pushing strollers or for wheelchair users.
- The width of footpaths, a necessity for safe footpaths, is primarily determined by the type and density of land development and the volume and needs of pedestrian and vehicular traffic. Typically, these are expressed in different levels of service for

Figure 4.3: Typical Urban footpath—Ghana.

Source: © John Barrell.

Figure 4.4: Urban footpath with protection from traffic and dangerous slope, Ghana.

Source: © John Barrell.

Figure 4.5: Shared space in urban area.

Source: © Soames Job. .

Figure 4.6: Shared space—India.

Source: © Soames Job

Figure 4.7: Mixed traffic in rural road.

Source: World Bank

pedestrian footpaths based on flow rates, space per person, and description of flow.

- In addition to the minimum passing width noted above, it is also necessary to consider the adjacent land uses and the likelihood of encroachment into the clear pedestrian route.
- A zoning concept that divides the corridor into three main zones—the frontage zone, the pedestrian zone, and the furniture zone—can allow for the safe and convenient use of pedestrian space. Each of these zones plays an important role in a well-functioning pedestrian corridor.
- Footways should be raised above the vehicular carriageway by at least 75 mm, with a defined boundary on both sides.
- If motorists are known to regularly mount the edge of a footway along a length of curbline, the use of a high curb face should also be considered as an alternative to using a line of bollards. A curb face of 125 mm–140 mm will usually stop motorists mounting the edge of the footway when stopping.
- It is crucial that the footpath is not obstructed for pedestrian use and to understand the characteristics of the full range of the pedestrian population that may use the facilities to ensure the design of pedestrian facilities accommodates the range of pedestrian abilities (figure 4.8).

Figure 4.8: Obstructed footpath, and lack of drop curb in Manila.

Source: © Blair Turner/GRSF

Figure 4.9: Well zoned footway with clear pedestrian route and tactile guidance in China.

Source: © John Barrell

Figure 4.10: Poorly maintained pedestrian guardrail—Maintenance Inspection.

Source: TRL.

Figure 4.11: Unprotected footpath on rural national road.

Source: PIARC

- Pedestrians have a wide range of characteristics and needs, such as walking speed, spatial needs, mobility issues, and cognitive abilities. They need clear guidance for safe routes and identification of conflict points with vehicles, for example, the use of tactile paving and a visual contrast of surfaces (figure 4.9).
- Pedestrian facilities need to be regularly maintained to ensure their safety and function (see figure 4.10 for an example of poorly maintained guardrails).
- In rural areas, where pedestrian traffic might be less frequent, walkable shoulders may be sufficient where vehicle flows are high. Care will also be needed to ensure that these shoulders do not become running or stopping lanes that might endanger pedestrian use (see figure 4.11 as an example of pedestrians exposed to high risks due to the lack of protection from vehicle traffic).
- For low vehicle flows and low speeds, no provision of separate footways may also be an appropriate solution, but care is needed to both manage vehicle speed and make sure that vulnerable users are not hidden by the alignment.
- Separate trails or shared-use paths can safely convey pedestrians along rural routes either adjacent to the vehicle route or completely separately (figure 4.12).

Figure 4.12: Segregated pedestrian/nonmotorized transport facility on rural road.

Source: PIARC.

Figure 4.13: Clear urban footway on median—Kenya.

Source: © Watetu Mbugua/GRSF/World Bank.

Figure 4.14: Lively sidewalk project—transformation from no footpath to protected footpath.

Source: Prefeitura Municipal de Fortalenza and Bloomber Philanthropies, PIARC

- On rural routes, and particularly on high volume urban highways, adequate separation and protection for the pedestrian route are essential (figure 4.13).
- Ideally pedestrian routes should be separated to the rear of the clear zone to minimize impact from errant vehicles
- A buffer zone between pedestrian movement and vehicles can be provided for signage, lighting, or planting. Care should be taken that these do not form roadside hazards (See section 5.7 on roadsides).
- If segregation is not possible, then an adequate vehicle restraint system needs to be provided. This may also deter pedestrians from crossing the route; however, additional measures may also be necessary to prevent unsafe interaction between pedestrians and traffic and safe convenient crossing points provided to deter the unsafe crossing.
- Pedestrians and vehicles are able to share the same space safely where speeds are less than 20 km/h. In these shared zones, pedestrian movements have equal priority with vehicles and vehicle speeds are low. Often this is a result of the high number of pedestrian movements compared to vehicles. Crucially these are not major transport corridors, and alternative through routes for vehicles must be available.
- At speeds of 30 km/h, separate provision needs to be made where frequent pedestrian use is expected (see figure 4.14).

4.2. Pedestrian Facilities Design—Crossings

Good design practice/ treatments/solutions

A crucial aspect of designing a safe and accessible pedestrian route is adequately dealing with crossing requirements of the motorized corridor. This can be done in several ways that are dependent on the concentration and volume of pedestrian and vehicle movements.

Often pedestrians need to be guided to appropriate crossing points or deterred from crossing in unsafe locations. This is often achieved by using pedestrian fencing or guardrails close to the curb edge. Unless alternative safe crossing points are available that are perceived as being convenient to use, any barriers may soon become damaged or stolen to recreate the more direct (even though dangerous) crossing point.

When considering pedestrian crossings at intersections, the ability to cross the minor road safely is as important as the crossing of the main road in order to provide consistent route continuity for pedestrians. The level of provision on the minor road need not be the same as on the major road, but it is usually safer to maintain the same level of control on each arm.

Additional consideration may need to be given at school crossing locations given the extra vulnerability of children. This may include lower speed zones, additional signage, enhanced crossing facilities, or even crossing supervisors. Equal consideration needs to be given to pedestrians' crossing of minor roads and accesses away from formal junctions.

Grade-separated/controlled crossing

- Grade-separated crossings (figures 4.15 through 4.17), whether under or over roadways, are expensive pieces of infrastructure to install and need to be justified by demand and provide convenient crossing, otherwise they will be ignored.
- Where high volumes of pedestrians are concentrated in infrequent and specific locations, grade-separated crossings can be appropriate, either as a pedestrian overbridge or underpass. They involve separating pedestrians from traffic by placing them at different levels and are often used where pedestrian crossing signals would cause delays and queueing or crashes (due to high traffic speeds). Pedestrian overpasses and underpasses require users to deviate from their preferred desired line—a direct crossing from A to B. Pedestrian route selection is typically determined by the shortest, fastest, or most convenient route.[42]

Figure 4.15: Grade separated footbridge—Ethiopia.

Source: © John Barrell.

Figure 4.16: Grade separated underpass—US.

Source: Greenbelt. Accessed at https://greenbelt2012.wordpress.com/2012/12/17/greenbelts-original-pedestrian-underpasses/.

Figure 4.17: Well designed foot bridge—Shanghai.

Source: © Alina F. Burlacu/GRSF/World Bank.

42 A. Agrawal, M. Schlossberg, and K. Irvin. 2008. How far, by which route and why? A spatial analysis of pedestrian preference Journal of Urban Design, Vol. 13. No. 1, 81–98.

Figure 4.18: Signalized pedestrian crossing.

Source: iRAP.

- Any deviation from this straight line, either vertically or horizontally, reduces the attractiveness of that route and increases the likelihood that it will not be used. Closure or obstruction of the direct route is needed to encourage use of the safer alternative.
- Ideally these facilities should have ramps rather than steps to accommodate the mobility impaired, but this often increases the length of any diversion (see 5.12 Curbs for good design examples at crossings).
- Clear sight lines on approach and through the crossing and sufficient lighting must be provided with no places for people to hide, as they can be seen as a security hazard with the opportunity for personal attacks, especially at night.
- The risk of personal attack reduces their attractiveness and increases the likelihood that crossings will not be used.
- To be effective they need very careful design and location to ensure ease of access. They also require sufficient lighting, adequate drainage, and proper maintenance to keep them in clean and tidy conditions.
- Often the provision of planned retail or vendors is good for increased security. Such design should be encouraged.
- Once constructed they cannot easily be moved to accommodate changing movement patterns!
- For underpasses it is possible to use a reduced height (2.5 m) and raise the carriageway by a maximum of 1.5 m, as well as lowering the footpath to reduce both cost and impact.

Figure 4.19: Scramble Intersection.

Source: London Evening Standard April 13, 2012.

Pedestrian crossing signals

It is much easier to provide crossings at the same level as the rest of the route, but then this requires segregation in time, i.e., specific times for pedestrians and vehicles to use the same space.

- Signalized pedestrian crossings at intersections (figure 4.18) aim to reduce vehicle/pedestrian conflicts.
- They provide right-of-way access to pedestrians during a green pedestrian phase when conflicting or all traffic is stopped.
- At intersections with high pedestrian volume, it is also common to treat them as scramble intersections (figure 4.19), where pedestrian movements from all directions are allowed in a single green phase, including diagonal movements.
- Pedestrian green time should be timed to give pedestrians long enough to complete their crossing before the signals change to allow vehicle traffic to start passing through the crossing again. (Assume pedestrian walking speed 1.2 m/s.)
- Long waiting times for pedestrians can increase the likelihood of violations.
- Sufficient time is needed for pedestrians to clear the crossing before traffic can start when neither movement is permitted to start (blackout period or “all red”).
- There can be compliance issues with vehicles failing to obey signals, or failing to give way when turning at signals is a common issue. A lead phase

Figure 4.20: Well defined at-grade crossing—Rwanda.

Source: © John Barrell.

Figure 4.21: Raised crossing to slow approach speeds—Kenya.

Source: © John Barrell.

Figure 4.22: Well defined crossing with signing—Singapore.

Source: © Alina F. Burlacu/GRSF/World Bank

can be included at signals to give pedestrians an early start at signals before other road users are allowed to start. This is useful to reduce the incidence of turning vehicles striking pedestrians at intersections, as this gives greater visibility to crossing pedestrians.

- Tactile paving should be provided to guide the visually impaired pedestrians through the crossing, and parking should be removed from the immediate vicinity of the crossing to provide adequate sight lines.
- To maintain the safety and segregation of uses, it is important that filter lanes are omitted where pedestrian crossings are in place.
- Countdown timers at signals can also provide phase duration information to pedestrians. The timers display the time remaining until the end or start of a pedestrian green phase and remove some of the doubt for all users.
- In addition to signalized crossings, other crossings that give priority to pedestrians typically consist of signs and painted road markings (“zebra crossings”).
- These formalize the crossing location giving pedestrians the right-of-way over vehicles. They also increase the awareness for other road users that pedestrians may be present, improving expectations about the need to stop.
- They also cater for the mobility impaired with footways ramped down to carriageway level or the carriageway lifted to footway level.
- Audible and tactile warning of the pedestrian crossing phase can also be provided on the traffic signal pole.
- Especially where vehicle approach speeds are high, at-grade raised pedestrian crossings can improve safety, but need to be clearly signed and have sufficient advance warning for drivers to react to their presence (figures 4.20 through 4.22).
- Extra care is required when designing signalized pedestrian crossings either at intersections, or away from intersections, in higher-speed, multi-lane environments. Vehicles may fail to stop either because they fail to see the signals or do not comply, and this results in high severity outcomes.
- Raised pedestrian crossings have a similar profile and speed reduction effect as flat top speed humps (safety platforms), but they differ in that they give priority to pedestrians rather than motorists.
- They consist of a raised platform with a marked pedestrian crossing on top.
- The raised crossing serves the purpose of slowing vehicles, as a speed hump or platform, but also increases the visibility of pedestrians due to the increased height.
- As they are raised to footway level, they do not need a ramped approach, but still need tactile paving to assist the blind and partially sighted.

Figure 4.23: Pedestrian refuge alone

Source: © John Barrell.

Figure 4.24: Controlled crossing with refuge.

Source: © John Barrell.

Figure 4.25: Lack of pedestrian space on median—mauritius—safety inspection.

Source: TRL.

Figure 4.26: Painted and narrowing approach to crossing.

Source: © Alina F. Burlacu/GRSF/World Bank.

- Other speed reducing features can be used in advance of pedestrian crossings and typically result in a lower likelihood of a crash occurring, and lower severity when collisions with pedestrians do occur.
- Narrowing of the roadway can also provide a safety benefits; as pedestrians have less distance to cross, facilities can be included to make pedestrians more visible, and speeds may be reduced. Alternatively, the crossing movement can be split into two with provision of a protected median or refuge for pedestrians (also see uncontrolled crossing section below).

Uncontrolled crossings

- Wide crossings (of more than two lanes) can be narrowed by providing central refuge islands to limit the amount of time pedestrians are exposed to traffic.
- Pedestrians and drivers need to maintain alertness where pedestrians are crossing multilane roads, as they are often hidden from drivers' view, and vice-versa, by vehicles in adjacent lanes.
- Pedestrian refuges are raised median islands in the middle of the road that provide an area for pedestrians to safely wait until an appropriate gap allows them to cross (figures 4.23 and 4.24).
- Islands need to be wide enough to protect pedestrians with strollers (and cyclists) from passing traffic (1.8 m) (figures 4.25 and 4.26).
- This simplifies the crossing maneuver for pedestrians by creating the equivalent of two narrower one-way streets instead of one wide two-way street.
- Refuges are particularly useful for those who are wheelchair-bound, elderly, or otherwise unable to completely cross the road in one movement.
- Islands can also have additional benefits, including

acting to separate traffic moving in opposite directions, controlling vehicle speeds by narrowing the roadway, and providing motorists with an indication of where pedestrians might cross a roadway.

- Footway ramps with tactile paving need to be included to make them appropriate for all mobility conditions.
- Refuges alone do not give any priority for pedestrians to cross.

Case Study

Figures 4.27 through 4.29 illustrate the installation of pedestrian crossing facilities.

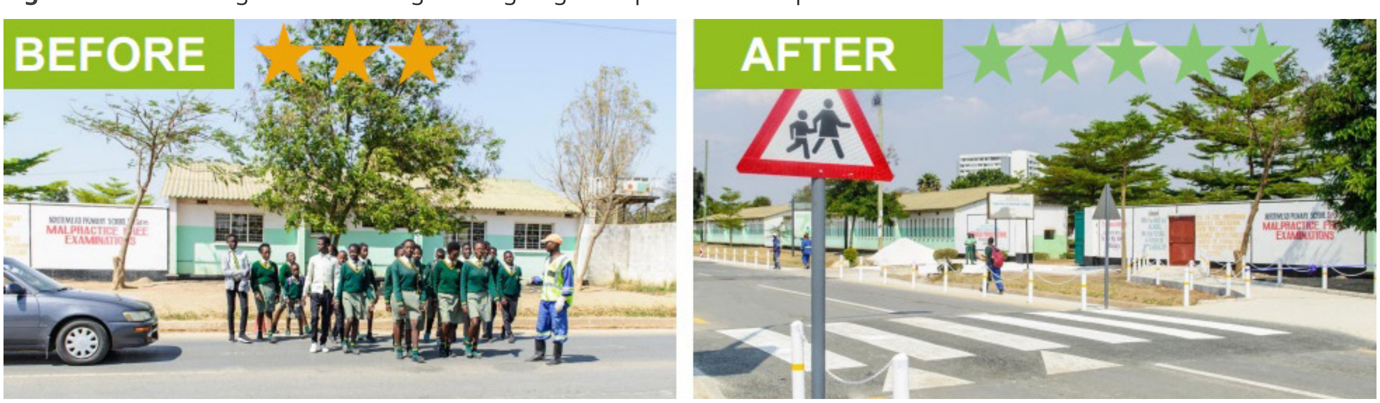
Figure 4.27: Transformation from no crossings to well defined raised crossing with signing.

Source: Prefeitura Municipal de Fortaleza and Bloomberg Philanthropies, PIARC.

Figure 4.28: Installing pedestrian refuge—Vietnam.

Source: iRAP

Figure 4.29: Installing raised crossing with signings and protected footpath—Zambia



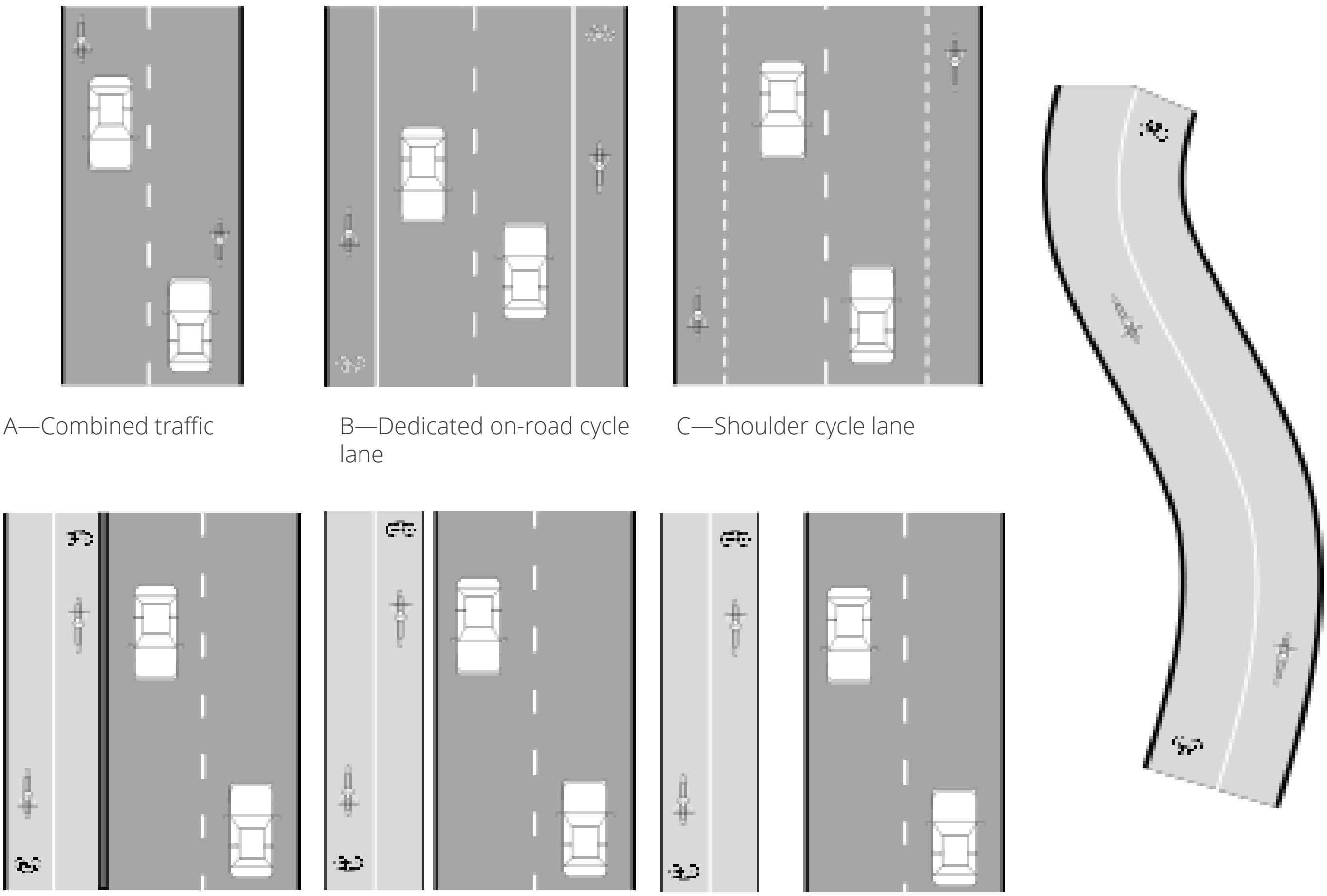
Source: iRAP.

4.3. Cyclist Facilities Design

Safe cycle provision can be achieved in a number of different ways, from separate cycle networks to on-road painted cycle lanes (figure 4.30).

Cycle highways are separate paths for cyclists (and pedestrians) away from motorized traffic (see figure 4.30- G above and figure 4.31). They can facilitate daily, long distance cycle journeys. This may be as a regional connection, a commuter route into a business district, or between residential areas.

Figure 4.30: Examples of cycle paths



A—Combined traffic

B—Dedicated on-road cycle lane

C—Shoulder cycle lane

D—Separate curbed cycle path

E—Separate cycle lane with narrow separation

F—Separate path for pedestrians and cyclists

G—Pedestrian and cycle route independent of roadway

Source: © Milly Lumumba/GRSF/World Bank.

Cycle highways are separate paths for cyclists (and pedestrians) away from motorized traffic (see G above and figure 4.31). They can facilitate daily, long distance cycle journeys. This may be as a regional connection, a commuter route into a business district, or between residential areas.

They have been described as the backbone of the wider cycling network, as the cycle highways often connect multiple local networks. The UK has a national cycle network that has been developed over many years, utilizing old rail corridors, canal towpaths, and quiet low volume roads. The most recent development has been the Barclays Cycle Superhighways in London, all of which are to encourage safe and comfortable cycle journeys. Cycle highways provide direct, flat, and continuous tracks that often link popular origins and destinations.

Figure 4.31: Green Corridor—La Rochelle France.

Source: European Committee. Accessed at https://ec.europa.eu/transport/themes/urban/cycling/guidance-cycling-projects-eu/cycling-measures/cycle-highways_en.

They have been described as the backbone of the wider cycling network, as the cycle highways often connect multiple local networks. The UK has a national cycle network that has been developed over many years, utilizing old rail corridors, canal towpaths, and quiet low volume roads. The most recent development has been the Barclays Cycle Superhighways in London, all of which are to encourage safe and comfortable cycle journeys. Cycle highways provide direct, flat, and continuous tracks that often link popular origins and destinations.

Cycle streets (also known as "boulevards") are a form of mixed-traffic street where the needs of cyclists (and possibly pedestrians) are prioritized over motor vehicles. Cycle tracks provide a physically separated space in which people who cycle can travel without mixing with motor vehicles—through either a physical barrier or raising the track to a higher level (or both), incorporating appropriate side clearance (see E or F in figure 4.30). Cycle lanes can be relatively quick and inexpensive to implement, making them one of the most common forms of cycle paths implemented in cities. They can be either on-road (see B or C in figure 4.30) or off-road or shared footways (see D in figure 4.30), and allow people who cycle to take advantage of the accessibility that the existing road network provides.

Good design practice/ treatments/solutions

Cyclists consist of a wide range of abilities and uses, from occasional recreational use to regular commuters and sports cyclists. The needs of each group are different and need to be accommodated in any specific provision.

Basic quality design principles aim to increase actual and perceived safety, and include:

- Limiting conflict between cyclists and other cyclists, pedestrians, or motorists.
- Ensuring low-stress environments where mixing with other users is limited and controlled.
- Separating main routes for cyclists from pedestrian routes.
- Reducing motor vehicle traffic volumes and speeds around cyclists, especially when road users mix.
- Separating cyclists from fast/heavy motorized traffic, reducing the number of dangerous encounters—including separation on routes and/or at intersections and on-street parking.
- Ensuring conflict points at intersections and crossings are clearly presented so that users are aware of the risks and can adapt behavior appropriately.
- Visibility of cyclists to motorists should be maximized at the approach to intersections.
- Ensure cycling infrastructure is well maintained—especially quality of pavement and continuity through intersections. Wide shoulders may be provided to allow for cyclists' use, along with protection from vehicular traffic using shoulder rumble strips or physical barriers (figures 4.32 and 4.33).

Cycle tracks

- For cyclists, the use of segregated cycle tracks (figures 4.34 through 4.37) is the ideal solution; the use of such lanes by motorcycles/ three wheelers needs to be taken into account, which can make

Figure 4.32: Cyclists using a narrow shoulder—Rwanda.

Source: © John Barrell.

Figure 4.33: Cyclists on sealed shoulder with overlay to roadway causing level difference—Rwanda.

Source: © John Barrell.

Figure 4.34: Urban cycle track in China.

Source: © John Barrell.

Figure 4.35: Cycle track in Beijing, China.

Source: © Blair Turner/GRSF/World Bank.

Figure 4.36: On-road segregated cycle path on a highway in Ethiopia.

Source: Dipan Bose/World Bank

Figure 4.37: Well designed cycle lane—Shanghai.

Source: © Alina F. Burlacu/GRSF/World Bank.

the situation more difficult for pedestrians (and cyclists).

- To be effective, they require parking enforcement to avoid vehicles blocking them, and careful treatment at junctions.
- Along straight sections of the carriageway, cycle tracks provide greater protection for people who cycle compared with cycle lanes, as they are physically separated from the traffic lanes.
- Buffer zones between cycle tracks and parked vehicles or moving car traffic are strongly recommended.
- At intersections designs must ensure that the visibility of people cycling to motorists is maximized.
- Where possible, priority should be awarded to people who cycle at intersections on cycle tracks (especially where it is given to traffic on the adjacent carriageway).
- Clear markings and accompanying signage should be in place to increase the visibility of the cycle tracks.
- They should be wide enough for people who cycle to feel comfortable and safe (minimum 3 m) and allow overtaking between cyclists moving in the same or opposite directions.
- Overall width will depend on the volume of cyclists.
- Where they allow two-way cycling, centerline marking should be used along the track and at intersections to raise awareness.
- The surface of cycle tracks should be smooth (closed surface paving) and level and well maintained.
- Roadside objects can present a hazard to cyclists, especially at higher speeds, and so should be removed or protected where possible.
- Preferably the surface should be colored and cycling symbols used to improve awareness and understanding.

Cycle lanes

- When the design of the cycle lane follows best practice and implementation is part of a coherent network, cycle lanes offer a safe and convenient route for people who cycle to travel around a city.
- In rural areas, cycle lanes can also be provided on the paved shoulders (caveats as for pedestrians use discussed above apply).
- They should only be applied on streets with medium or low motor vehicle volumes and speeds.
- Where vehicle speed and/or volume are high, then separate cycle lanes should be used (figure 4.38 and 4.39).
- Cycle lanes should be wide enough for people who cycle to feel comfortable and safe, allowing for comfortable clearance of other users, with surfaces smooth and level.

Figure 4.38: Shared footway/cycleway Tanzania.

Source: © John Barrell.

Figure 4.39: Cycle lane separated from main road vehicle traffic—Bucharest, Romania.

Source: © Alina F. Burlacu/GRSF/World Bank.

Figure 4.40: Unsuccessful cycle lane separated from vehicle traffic/parking—Bucharest, Romania.

Source: © Alina F. Burlacu/GRSF/World Bank.

- Minimum recommended width is 2.5 m for a single direction.
- Clear markings and accompanying signage should be in place to increase the visibility of the cycle lanes.
- Buffer zones may be considered between the cycle lane and motorized traffic where safety is of concern, particularly where there is heavy freight traffic.
- Buffer zones between the cycle lane and parked vehicles are strongly recommended.
- Cycle lanes separated from motorized traffic simply by painted road markings lead to parking and moving traffic encroachment (figure 4.40).

Contraflow cycle lanes

- Contraflow refers to cycles travelling in both direction on the same facility.
- This can contribute to improving conditions for cycling, including increased accessibility, coherence, and convenience, especially in urban one-way networks.[43]
- Contraflow cycling can also contribute to improving conditions for cycling more generally within a city, improving the convenience to travel. This can be implemented through:
    - Unsegregated two-way cycling on an unmarked road (quieter roads), which can be implemented through the use of signage.
    - The use of designated contraflow lanes on one-way roads with a high traffic volume.
- Since almost all conflicts take place at road crossings, it is often considered sufficient to mark contraflow lanes at the crossings only (10 m length).
- Usually, on straight stretches, no markings are required.
- This lower cost allows the cyclist to ride centrally in the road when there is no traffic ahead, reducing the risk of dooring or vehicles parking out, and makeing it easier to change the direction of the one-way road.
- Implementation of contraflow lanes may involve segregated lanes and pavement build-outs and should be decided based on factors such as the traffic volume and speed, and road width.

Cycle streets

Cycling should be the dominant mode, while the number of motor vehicles should be minimized, and so cycle streets are most likely to be implemented on through or main cycle routes where motorized traffic requires access to local destinations (figure 4.41). Design and signage should clearly assign priority to cyclists, and the route should be attractive to cyclists due to its comfort and directness.

Figure 4.41: Cycle street—UK.

Source: Gear Change A bold vision for cycling and walking

43 https://ec.europa.eu/transport/themes/urban/cycling/guidance-cycling-projects-eu/cycling-measure/contra-flow-cycling_en.

Figure 4.42: Advance cycle stopline (bike box) with contraflow cycle lane.

Source: Brighton & Hove City Council.

Figure 4.43: Right-of-way intersection (for cyclists)—Holland.

Source: Dutch Cycling Embassy

Intersections

The traffic intensity, speed and number of traffic lanes should guide the choice of the most appropriate intersection design. At any intersection, there will be conflict points between transport modes, but effective intersection design can reduce possible conflicts and increase safety and comfort for cyclists.

Knowledge is increasing about types of infrastructure that can be provided at intersections to improve safety for cyclists. Good design will generally include the following principles:

- Avoid mixing motor traffic with cyclists where the traffic flow and/or speed is typically high.
- On carriageways with low traffic volumes and low traffic speeds (typically 30 km/h or less), cyclists usually mix with other road traffic, and cycling specific infrastructure is typically not necessary at intersections.
- Maximize separation of cyclists from dangerous traffic movements.
- Separate traffic light phases for people cycling and people motoring or separate routes by over/underpasses.
- Maximize the visibility of cyclists.
- Make drivers aware of cyclists on the approach to an intersection.
- Use bike boxes (figure 4.42) and advanced green lights to allow cyclists to proceed through an intersection ahead of other road traffic.
- Intersections should be easy to identify, understand, and safe to use by all transport users. This requires specific designs to underline the priority status of cyclists.
- For any type of intersection, the primary consideration for safety is visibility of cyclists.
- In situations where cyclists and motor traffic are approaching the intersection in close vicinity (i.e. cycle lanes or mixed traffic), it is assumed that drivers are aware of cyclists.
- In situations where cyclists are separated from the carriageway, it is advised that the cycle path should be designed alongside the carriageway on the approach to the intersection to increase drivers' awareness of cyclists.
- Advanced cycle stop line/bike box gives cyclists advantage away from signal stop lines.
- Turning provisions may be needed at intersections for motorized vehicles cutting through cycle lanes to ensure cyclists are highly visible. This includes colored road surfacing for the cycle lane and additional signage.

Figure 4.44: Roundabout for cyclists—Netherlands.

Source: Bicycle Dutch.

Single lane roundabouts are considered the safest intersection design for all users on moderately busy roads if designed correctly. They reduce the speed of approaching traffic and allow the smooth flow of traffic through the intersection. Two-lane roundabouts can be particularly dangerous for cyclists due to the movement of motor traffic between lanes.

- Right-of-way intersections (figure 4.43) are the simplest intersection solution on roads with low traffic intensities, while signalized intersections are recommended when a cycling route crosses a main road with high traffic volumes, and particularly if there are multiple lanes.
- Single lane roundabouts (figure 4.44) are usually a safer alternative to signalized intersections due to the lower speed environment these create and reduced conflict points, although they cannot handle as many vehicles.
- When a busy cycle route crosses a main road with high traffic volumes, a grade-separated crossing is preferred (figure 4.45).

General Cycle Case Study/Example

Nairobi, Kenya: Nairobi was the first pilot country for a "Share the Road" design. A showcase road has been constructed that was entirely financed by the government. The adaptation of the 1.70 km UN Avenue included the construction of a three-meter-wide sidewalk on both sides, and a three-meter two-way segregated cycle lane (figure 4.46). The rehabilitation also included redesigning the intersection on Limuru Road and adding a slip-turn lane with a corner island to facilitate pedestrian crossing. The bus stop was relocated a few meters to avoid conflict with turning vehicles. The road was selected because there were recurrent severe crashes over a short period of time, which highlighted the need to improve road conditions.

Separating pedestrians and cyclists from vehicles through NMT infrastructure has reduced the severity and number of crashes. However, improved driving conditions have actually increased vehicle speeds as well as their number. Traffic calming measures, such as raised zebra crossings and refuge median islands, improve crossing conditions. But in sections where vehicles continue to circulate at high speeds, the painted-only pedestrian crossings have little effect on traffic.

Despite changes in the bike pathway to facilitate NMT,

Figure 4.45: Floating roundabout for cyclists—Netherlands.

Source: Ronald Otten/Bicycle Dutch.

Figure 4.46: Bicycle lanes separated from pedestrians.

Source: Share the Road Design Guide UNEP/FIA.

Figure 4.47: Installing crossings with advance cycle stopline—India.

Source: iRAP.

after six months of operation, the number of cyclists remained steady on the road section. Surveys show that most cyclists use the avenue as an access route, while pedestrians generally start or finish their trip in the neighborhood. Cycling trips tend to be longer than the intervention area.

As an additional case study, figure 4.47 illustrates the installation of crossing facilities including an advance cycle stopline in India.

Further Reading

- WHO. 2013. Pedestrian safety: a road safety manual for decision-makers and practitioners, https://www.who.int/publications/i/item/pedestrian-safety-a-road-safety-manual-for-decision-makers-and-practitioners. Must read chapter 2, Pedestrian safety in roadway design and land-use planning,
- UN-Habitat & Institute for Transportation and Development Policy. July 2018. Streets for walking & cycling—Designing for safety, accessibility, and comfort in African cities: Must read the section for foot path, cycle track, intersection, and design process.
- ARRB Project Report No: PRS17017. 2017. Road safety measures to achieve Safe System outcomes for pedestrians.
- FHWA. 2007. Pedestrian Road Safety Audit Guidelines and Prompt Lists FWHA-SA-07-007. Must read chapter 4, Using the guidelines and RSA prompt lists and chapter 5, Guidelines—detailed descriptions of prompts.
- United Nations Environment Programme. 2013. Share the Road—Design Guidelines for NonMotorised Transport in Africa. Must read chapter 1, Policy for Walking and Cycling, chapter 2, Improving Pedestrian Facilities, and chapter 3, Cycling Infrastructure.

4.4. Motorcyclist Facilities Design

General description

Motorcycle and moped use is on the increase and offers a solution to growing traffic congestion, parking problems, and the high cost of private car ownership. Users range from leisure bikers on high-powered machines to young people, professionals commuting by moped, and transporters of goods, and public transport users (figures 4.48 and 4.49). They are a popular form of transport because they are relatively cheap compared to other forms of motorized vehicles, provide mobility to millions of people worldwide, and

Figure 4.48: Motorcycle goods transport—Kenya.

Source: © John Barrell.

Figure 4.49: "Boda Boda" motorcycles Kenya.

Source: © John Barrell.

their requirements should be reflected in road design and traffic management measures.

Although few physical engineering facilities to improve motorcycle safety exist, some measures have been identified and are considered important. Furthermore, motorcyclists will benefit from speed reduction measures where there is mixed traffic, as they are less visible to drivers (having a smaller profile) and often appear where least expected.

Particular care needs to be given to the design of road and traffic engineering facilities where a large number of motorcyclists can be expected in the traffic stream. Although such measures will not completely eliminate motorcycle crashes, they will minimize their occurrence and reduce their severity when they do occur.

Safety implications

- Unlike other forms of motorized transport, there is very little protection for motorcycle riders and passengers due to their size, lack of stability, and maneuverability.
- A recent iRAP assessment of 1,400 km of highways in Bangladesh indicated the severity of road safety hazards for motorcyclists as the assessment revealed that 71 percent of assessed highways are 2-star or less (out of a possible 5-star) indicating a relatively high level of risk of deaths and injuries. Addressing the safety of motorcycles and the riders is therefore an enormous challenge to transport engineering professionals.
- When crashes do occur, they often have very severe consequences, especially at higher speeds or in situations where larger vehicles are involved.
- The chance of a motorcycle rider or passenger surviving a collision with a car is greatly reduced at speeds over 30 km/h.
- While many motorcycle crashes involve collisions with other vehicles, a significant number are single vehicle crashes. These crashes include a rider:
    - Losing control and running off the road;
    - Overtaking or crossing the centerline (usually on curves);
    - Hitting another vehicle (or other obstruction) from behind; or
    - Being thrown from the motorcycle and hitting the road surface.
- The road environment has a significant influence on the risk of crashes involving motorcyclists. Contributing factors include:
    - Interaction with larger vehicles (cars, trucks);
    - Road surface issues (such as roughness,

  - potholes or debris on the road) and poor skid resistance;
  - Water, oil, or moisture on the road;
  - Excessive line marking or use of raised pavement markers;
  - Poor road horizontal and vertical alignment;
  - Presence of roadside hazards; and
- Number of vehicles and other motorcyclists using the route.
- Motorcycles also have very different road performance characteristics than other types of vehicles. They:
  - Are less stable;
  - Can accelerate much more rapidly than other vehicles;
  - May appear in positions where other road users do not expect them;
  - May also suddenly change their lane position to avoid a surface hazard or irregularity;
  - Are much more maneuverable than cars or heavier vehicles; and
  - Can negotiate constraining alignments much more easily.
- This latter characteristic poses major challenges for road designers and is a significant influence on the risk of crashes involving motorcyclists, as is the quality of the road surfacing and maintenance with potholes and utility covers.
- Where drivers emerge from side roads—or come to the end of segregated lanes—their view can be obscured, making it more likely they will fail to see motorcyclists.
- Wide entries to priority intersections can encourage drivers to pull up on the offside of the rider, especially if the latter is on a low-powered machine. This increases the potential for injury when moving off and competing for the same forward lane space.
- Excessive entry width of the entry can also encourage two cars to pull up side by side, obscuring the adjacent driver's view of oncoming traffic on the main road and increasing risk for motorcyclists.
- The positioning of street furniture and vegetation affects clear visibility, which is critical for safety at intersections.

Good design practice/ treatments/solutions

Increased safety can be achieved by the separation of motorcycles from other motor vehicles. This segregation can take one of two forms. Either exclusive motorcycle lanes or inclusive lanes can be provided. These joint lanes provide routes that pedal cyclists and other nonmotorized vehicles can also use. Motorcycles can also share bus priority lanes in certain countries.

Exclusive motorcycle lanes

Exclusive motorcycle lanes require a carriageway separate from that used by other vehicles.

- They can minimize crashes at intersections by providing segregated routes or control.
- Their width and appropriateness will depend on specific usage—the higher the use, the greater the width and junction control.

Inclusive motorcycle lanes

- Inclusive motorcycle lanes are installed on the existing road and are usually located on the driver nearside of the main carriageway (next to footways or shoulders) for each direction of traffic flow.
- Motorcycle lanes may be separated from the rest of the road by painted lines or physical barriers.
- Some motorcycle and motor vehicle separation can be achieved by allowing the shared use of bus lanes. However, full consideration of the traffic

flows of both types of vehicle is important—shared use at specified times of the day could be a possible acceptable measure.

- Alternative measures may be needed on shared links to prevent four-wheeled vehicle access, i.e., by using posts at the entry/exit points.
- Care is needed to not encourage the sharing of all facilities such as pedal cycle measures at intersections or even on footbridges, due to the differences in respective vehicle speeds.

Despite the provision of separate small moving vehicle (SMV) lanes, the shared use by nonmotorized vehicles (NMUs) and motorcycles is generally not allowed, and motorcycles must usually use the main carriageway.

Alignment

To cater fully for the needs of motorcyclists, road design needs to consider:

- Consistent horizontal alignment such as avoiding bends that tighten after entry.
- Smooth transitions in vertical alignment to minimize loss of tire adhesion and to prevent water collection. This has a greater effect on motorcycles than on twin-track vehicles (i.e., traffic calming ramps at junctions).
- Cross-sectional designs consistent with the speed of the road and the radius of the bends where adverse camber or inadequate superelevation can have graver consequences for motorcyclists than other vehicles.
- Specification and positioning of street furniture, including impact characteristics when struck by a fallen or sliding body, are crucial to minimize the number of obstacles, especially on higher speed bends, and to use supports that do not shear off leaving sharp remains or protrusions that could snag a fallen rider.
- On higher-speed roads consideration must also be given to the "swept path" of the rider leaning into bends to avoid roadside features and oncoming traffic.
- Compared to all other single-vehicle motorcycle crashes, motorcycle impacts with barriers were found to be significantly more likely on smaller radius horizontal curves and sections with grades in excess of 3 percent. With regard to the sole quantitative recommendation of placing countermeasures on horizontal curves with radii fewer than 820 feet (250 meters), designers should carefully consider whether direct application of this criterion is prudent given the available data.[44]

Intersections

At intersections inclusive motorcycle lanes rejoin the general traffic lanes to allow motorcyclists to change direction or route.

- A significant proportion of collisions between motorcycles and cars in urban areas are caused by drivers failing to see the approaching or adjacent motorcycle. This can be helped by advanced stop lines for motorcyclists similar to those common for pedal cyclists (figures 4.50 and 4.51).
- It is important to optimize sight lines and to provide good braking surfaces for all users.
- Motorcyclists should be able to brake and stop while upright, travelling in a straight line, and on a surface which offers consistent grip. High friction surfacing at intersections can maximize the rider's chances of braking safely.
- Ensure consistent and appropriate skid resistance including that of extra surface features such as colored patches and thermoplastic markings. Clear advance warning and direction signs should minimize the need for such surface signing. The requirement to lean when cornering increases the likelihood of loss of control when there is a substantial variation in the skidding resistance between two

44 Gabauer, D. J. 2016. Characterization of roadway geometry associated with motorcycle crashes into longitudinal barriers. Journal of Transportation Safety & Security, 8(1), 75–96.

Figure 4.50: Motorcyclists at intersection—Thailand.

Source: Bangkok post.

Figure 4.51: Advance motorcycle stop line.

Source: Westminster cycling campaign. http://www.westminstercyclists.org.uk/asl.htm.

different types of material. The following should be kept in mind:

- ◦ Avoidance of different surface materials, for example granite blocks, to emphasize a change in circumstances at turning points.
- ◦ Thermoplastic road markings, some types of block paving, and metal utility covers can be particular problems for motorcyclists in these situations.
- ◦ Careful thought should be given before using large areas of hatching.
- ◦ The use of a high quality, cold-applied, colored antiskid material provides the required visual effect without presenting a hazard for motorcyclists.
- ◦ Roundabouts also need to be designed with the correct entry path curvature and width to help reduce the speed of vehicles and ensure that approaching vehicles are not positioned at an excessively oblique angle.
- ◦ Concentric overrun areas feature on roundabouts to increase the deflection, reduce speeds, and be more conspicuous to approaching vehicles.
- ◦ Care needs to be taken with this kind of treatment to ensure that it does not introduce an additional hazard for circulating motorcyclists. For example, where overrun areas have a slight curb up-stand (10–20 mm) between the extended area and the remaining carriageway, as a motorcycle must lean over to negotiate a roundabout, crossing the up-stand can cause a rider to lose control.

- Single lane roundabouts are considered the safest intersection design for all users on moderately busy roads. They reduce the speed of approaching traffic and allow the smooth flow of traffic through the intersection. Two-lane roundabouts are particularly dangerous for motorcyclists due to the movement of motor traffic between lanes.

Roadside barriers

- Roadside crash barriers are designed to contain an impacting twin-track vehicle and prevent it from crossing the path of oncoming traffic or leaving the running lane and colliding with a severe hazard.
- The majority of the roadside safety barrier systems in use today are designed to bring passenger cars and/or heavy vehicles to a controlled and safe stop. However, when struck by errant motorcyclists,

Figure 4.52: Motorcyclist impact with wire rope barrie.

Source:FEMA.

Figure 4.53: Typical metal barrier.

Source: John Barrell.

these systems may fail to provide this same level of protection.

- Research shows that there are two dominant types of motorcycle-to-barrier crashes.[45] In the first type, motorcyclists hit the barrier while sliding on the ground, having fallen from their motorcycle. In this type of crash, the impact mainly occurs with the lower section of the barrier. In the second type, motorcyclists hit the barrier at an upright position while they are still on the motorbike. In this type of event, the impact mainly occurs with the upper section of the barrier.
- For riders who hit the barrier at an upright position, the sharp corners located at the top of the posts also pose a significant danger. The Norwegian Public Roads Administration's Handbook 231[46] has identified the top of the posts as being particularly hazardous for motorcyclists if they become dismounted from their motorcycle during an impact and fall on top of these, which is a view shared by Gibson and Benetatos (2000)[47] and Duncan et al. (2000).[48]
- Wire rope (figure 4.52) is another common barrier type which poses similar dangers to errant motorcyclists like steel systems (such as W-beams) do. Contrary to popular belief among motorcyclists, research shows that it is the exposed posts which pose the biggest danger, not the wire ropes. For example a study comparing W-beam barriers and wire rope barriers in motorcycle safety carried out in India found that wire rope barriers can restrain the rider on the road in all cases. Although injuries to lower extremities increased in some cases, potentially fatal injuries to the rider's head were reduced by the wire rope barrier.[49] Duncan et al. (2000) have stated that there is no substantial evidence to show that wire rope barriers pose a greater risk to motorcyclists than the objects from which they are designed to shield the road user, such as trees, posts, or oncoming traffic. Duncan et al. (2000) also added that there is no evidence of the "cheese cutter effect" during injury events.
- The gap beneath the main panel of continuous barrier designs can allow motorcyclists to slide through and collide with the fixing posts (figure

45 C. Erginbas, and G. Williams. 2015. "Motorcyclists and Barriers on the Highways Agency Road Network," TRL (Unpublished).

46 Norwegian Public Roads Administration, "MC Safety Design and Operation of Roads and Traffic Systems," Directorate of Public Roads, Norway, 2004.

47 T. Gibson, and E. Benetatos. 2000. "Motorcycles and Crash Barriers," NSW Motorcycle Council, New South Wales.

48 C. Duncan, B. Corben, N. Truedsson, and C. Tiugvall. 2000. "Motorcycle and Safety Barrier Crash-Testing: Feasibility Study," Crash Research Centre, Monash University.

49 Patel, H., Jani, D., and Joshi, A. 2018. Comparison of potential injuries to the head and lower extremities of a motorcyclist during impact with W-beam and wire rope barriers using FE simulations. International Journal of Crashworthiness, 23(1), 11–17.

Figure 4.54: Motorcycle skirt added to metal barrier in Vietnam.

Source: iRAP.

Figure 4.55: Concrete barrier-separated motorcycle lane in Indonesia.

Source: The World Bank.

Figure 4.56 Modified U-shaped posts and attached to a curved concrete barrier

Source: © Texas A&M Transportation Institute/FHWA

4.53).

- Rails that protect riders from the posts and present a continuous surface (figure 4.54), impact attenuators that cover the support posts themselves, or continuous concrete barriers (figure 4.55) are being increasingly implemented to reduce concerns for motorcyclists.
- A study carried out in the US identified that a new chain link fence containment system supported by modified U-shaped posts and attached to a curved concrete barrier would prevent riders from ejecting over the barrier, thus reducing injury severity to the rider during the impact event (figure 4.56). This finding was confirmed by conducting finite element computer simulations and a full-scale crash test.[50]

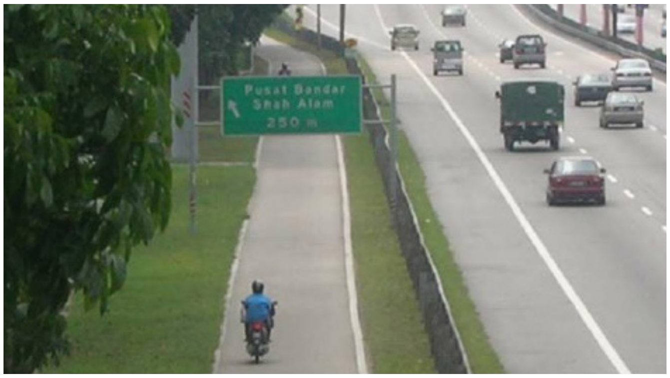
Case Study

The exclusive motorcycle lane in Malaysia (figure 4.57) is 14 km long and has led to a recorded reduction in crashes of 27 percent with a benefit to cost ratio of constructing the lane valued at about three. A subsequent extension constructed in 1992 is estimated to have reduced motorcycle crashes by 34 percent along the section of road concerned.

As an additional example, motorcycle lanes may also be inclusive as illustrated in figure 4.58.

50 Silvestri Dobrovolny, C., Shi, S., Kovar, J., and Bligh, R. P. 2019. Development and evaluation of concrete barrier containment options for errant motorcycle riders. Transportation research record, 2673(10), 14–24.

Figure 4.57: Exclusive motorcycle lane—Malaysia.



Source: © Hussain Hamid

Figure 4.58: Inclusive motorcycle lane—Malaysia.

Source: iRAP.

Further Reading

- Austroads guide on motorcycle and infrastructure. Accessed at https://austroads.com.au/publications/road-safety/ap-r515-16.
- WHO guide for powered 2 and 3 wheeled vehicles. Accessed at https://apps.who.int/iris/rest/bitstreams/1081388/retrieve.
- iRAP Road Safety Toolkit. http://www.toolkit.irap.org/.
- FHWA. 2016. Motorcycle Road Safety Audit Case Studies and Checklists. Accessed at https://safety.fhwa.dot.gov/rsa/resources/docs/fhwasa16026.pdf.
- IHE Guidelines for Motorcycling Road Design and Traffic Engineering. Accessed at http://www.motorcycleguidelines.org.uk. Must read chapter 3.
- Asian Development Bank. 2003. Vulnerable Road Users in the Asia and Pacific Region. Must read chapter 5, Motorcycles.
- EuroRAP. 2008. Barriers to Change—Designing Safe Roads for Motorcyclists. Accessed at https://roadsafetyfoundation.org/project/barriers-change-designing-safe-roads-motorcyclists/.
- Phathai Singkham. 2016. Separate lane for motorcycle to reduce severity of road traffic injury among motorcyclist in Thailand. A thesis submitted in partial fulfillment of the requirement for the degree of Master in Public Health. Accessed at https://bibalex.org/baifa/Attachment/Documents/ntpjD1a5OV_20170507113930220.pdf.
- To Quyen Le, and Zuni Asih Nurhidayiti. 2016. A Study of Motorcycle Lane Design in Some Asian Countries.
- VicRoads. 2014. Making Roads Motorcycle Friendly.
- World Bank. 2013. Improving Accessibility to Transport for People with Limited Mobility: A Practical Guidance Note. Washington, DC. https://openknowledge.worldbank.org/handle/10986/17592 License: CC BY 3.0 IGO

4.5. Public Transport—Bus Stops; Bus Rapid Transport and Other Modes

General description

Public transport is generally thought of as referring to buses, coaches, and possibly trams (figure 4.59) that run regular and advertised schedules both in rural and urban areas wholly within the confines of the public right-of-way. In urban areas, public transport provides an efficient form of transport for large numbers of people and reduces congestion in busy cities.

However, buses and coaches are just a small part of the overall public transportation, public transit, or mass transit network. Public transport is a system of transport that is available for use by the general public, typically managed on a schedule, operated on established routes, and that charges a fixed fee for each trip dependent on journey length. Trips can be undertaken in vehicles of different size and different control conditions. In LMICs the variety of public transport is extensive, from formal Bus Rapid Transport (BRT) (see figure 4.60) running in defined and protected corridors to poorly regulated shared taxi or motorcycle/cycle taxis (see figures 4.61 and 4.62).

There are a wide variety of vehicles used for the transportation of passengers and their goods on

Figure 4.59: Tram system—Ukraine.

Source: © John Barrell.

Figure 4.60: BRT Lane—Bolivia.

Source: World Bank.

Figure 4.61: Matatu bus service—Kenya.

Source: © John Barrell.

Figure 4.62: Rickshaw taxi—India.

Source: World Bank.

roads such as cycle rickshaws, motorized rickshaws, cars (including taxis), minivans, buses, and trucks. These types of services are prevalent in Africa and Asia.

The degree of regulation and control on public transport services varies from country to country, and particularly in LMICs, this level of control may be very limited. While public transport is considered to be a safer form of transport, when services are poorly regulated, vehicles poorly maintained, and often overcrowded, when crashes do happen, they can result in a large number of fatalities. This is often the case in LMICs where overcrowding, speeding, and poor vehicle maintenance can result in frequent multiple fatality collisions.

Well-regulated public transport systems run along fixed routes with set embarkation/disembarkation points to a prearranged timetable, with the most frequent services running to a headway (e.g., "every 15 minutes" as opposed to being scheduled for any specific time of the day).

Paratransit is the term used for transportation services that supplement fixed-route mass transit by providing individualized rides without fixed routes or timetables. Paratransit services may vary considerably on the degree of flexibility they provide their customers. At their simplest they may consist of a taxi or small bus that will run along a more or less defined route and then stop to pick up or discharge passengers on request. At the other end of the spectrum—fully demand responsive transport—the most flexible paratransit systems offer on-demand, call-up, and door-to-door service from any origin to any destination in a service area. In addition to public transit agencies, paratransit services may be operated by community groups or not-for-profit organizations, and for-profit private companies or operators. Control and regulation of setting down and picking up points for these are difficult and can lead to the use of inappropriate and unsafe locations.

Shared taxis offer on-demand services in many parts of the world, which may compete with fixed public transport lines, or complement them by bringing passengers to interchanges. These less formal transit services are sometimes used in areas of low demand and for people who need a door-to-door service.

Safety implications

- Travel by formalized public transport is very safe and perceived to be so.[51] Estimates for Norway for 1998–2002 indicated 0.93 fatalities in road crashes per billion passenger kilometers for bus, versus 3.82 fatalities per billion kilometers for car occupants (driver and passenger) approximately a quarter that of automobiles.[52] Less well-regulated and overcrowded services in LMICs have a high incidence of fatalities when crashes occur.
- Being a large vehicle, a bus protects its occupants well. The smaller and less stable vehicles are more risky.
- Most injuries in collisions where regulated buses are involved are sustained by other road users.[53]
- Each vehicle type has its own specific safety problems, but one issue in common is that crashes involving such vehicles often result in multiple injuries and deaths (up to 80 or more in some regions with overloaded buses).[54]
- Another common issue is that there is danger, not only when moving around the road network, but also when picking up or dropping off passengers, and extra care needs to be taken at such locations.

51 Elvik, R., and Bjørnskau, T. 2005. How accurately does the public perceive differences in transport risks? An exploratory analysis of scales representing perceived risk. Accid. Anal. Prev. 37, 1005–1011.

52 Litman, T. 2020. Terrorism, Transit and Public Safety: Evaluating the Risks by Victoria Transport Policy Institute. March 20, 2020

53 Elvik, R. 2019. Risk of non-collision injuries to public transport passengers: Synthesis of evidence from eleven studies Journal of Transport and Health Vol. 13, pp. 128–136.

54 iRAP Road Safety Toolkit.

- Buses may also block the view of pedestrians attempting to cross at the signals. There is therefore an increased risk of crashes associated with unintentional noncompliance with the signals.
- Fares are often low, so operators of public transport often work long hours to stay in business.
- They might also drive at fast speeds to compete with other operators and may make sudden and frequent stops to pick up passengers.
- Public transport vehicles produce dangers for those who ride in (or on) them, but also may be of risk to other road users. This is particularly so as the size of the vehicle increases.
- Siting of bus stops that obscure intersections or signs, or obstruct traffic movements present particular safety problems for all users.
- Falls when walking to or from public transport stops contribute substantially to the total risk of door-to-door journeys using public transport.
- Better road maintenance, especially during the winter, can also reduce the number of falls.
- Bus lanes appear to lead to an increased number of crashes, at least injury crashes. The increase is greatest for American-style bus lanes, where share-a-ride schemes with private cars are also allowed. There may be several reasons why this type of bus lane leads to more crashes including:
    - Such bus lanes are often constructed in the central reservation or in the left lane of motorways, i.e., where the traffic is fastest.
    - In order to move in or out of such bus lanes, several lane changes may be necessary (large motorways in the US often have three, four, or five traffic lanes in the same direction).[55]
    - There may be major differences in speed between a bus lane and the other traffic lanes. Furthermore, buses and light cars both use the bus lane. This type of bus lane also appears to increase the number of crashes. In Norway, bicycles, mopeds, and motorcycles are also permitted in the bus lane. This means that the heaviest and the lightest vehicles use the same traffic lane.
    - When turning at an intersection, it may be necessary to cross the bus lane. In dense traffic, the differences in speed between a bus lane and the other traffic lanes may be relatively large.

Good design practice/ treatments/solutions

Bus Rapid Transit

- Bus Rapid Transit (BRT) (see figure 4.63) is a high-quality, efficient mass transport mode providing capacity and speed comparable with urban rail (light and heavy rail).
- In cities of the developing world, the implementation of median-running BRT systems has generally proven to have a positive impact on safety. Research from Australia indicates that bus priority systems (including signal priority and dedicated lanes) also had a positive safety impact.[56]
- On average, BRTs in the Latin American context have contributed to a reduction in fatalities and injuries of over 40 percent, and a reduction in Property-Damage Only (PDO) crashes of 33 percent on the streets where they were implemented. The mean effect is quite consistent across different regions of the world, as evidenced by the similar impacts of the Janmarg BRT in Ahmedabad, India.[57]
- The main reason that BRT systems have had

55 Elvik, R. et al. 2009. Handbook of Road Safety Measures, 2nd ed.

56 Duduta, N. et al. 2015. Traffic Safety on Bus Priority Systems, EMBARQ WRI.

57 Carrigan, A. et al. 2013. Social, Environmental and Economic Impacts of Bus Rapid Transit, EMBARQ WRI.

Figure 4.63: Dedicated bus lanes for bus rapid transit system.

Source: Dubuta, N. et al. 2015.

positive safety impacts in Latin America is because in order to accommodate the BRT infrastructure, the city removed lanes, introduced central medians, shortened and provided improved crosswalks, and prohibited crossing turns by general traffic at most intersections.

- In bus rapid transit systems, bus stops may be more elaborate than street bus stops, and can be termed “stations” to reflect this difference. They may have enclosed areas to allow off-bus fare collection for rapid boarding and be spaced further apart like tram stops. Bus stops on a bus rapid transit line may also have a more complex construction allowing level boarding platforms and doors separating the enclosure from the bus until ready to board.

Bus lanes

- These are dedicated lanes within the main carriageway to allow buses to bypass traffic congestion (figure 4.64). They are usually located at the nearside of the carriageway to allow easy access for passengers from an adjacent footway. They are often separated from main traffic by a single solid white line, although in some instances they can be separated by a median.
- Provision of dedicated bus lanes prevents use by general traffic and restricts parking and loading for adjacent properties. Obstruction of the bus lane by other vehicles negates the advantages of a dedicated lane and requires a dangerous maneuver for both vehicles to enter and leave the general traffic stream.
- Particular care is needed at intersections where the bus lane ends to allow all traffic to queue or buses to make turns across the main traffic flow.
- Additional benefit can be given to buses at signal-controlled intersections with specific stop lines and call stages.

Figure 4.64: Bus lane and priority signal—UK.

Source: Google Streetview.

Bus stops

- Bus stops are the places where passengers enter and leave the bus and change from being passengers to pedestrians (figure 4.65). Depending on the number, size, and frequency of vehicles using stops, their complexity can vary.
- Pedestrians must be able to access bus stops safely. If pedestrians have to cross busy roads where complex maneuvering occurs in order to access or leave buses, pedestrians will be at risk of crashes.
- In rural areas where services are less frequent, clear identification of formal stopping places is needed to prevent unsafe maneuvers and deterioration of the highway shoulder (see figure 4.66).
- Bus stops need to be clearly identified and safely accessed whatever form of vehicle uses them and wherever they are located.
- Bus stop infrastructure ranges from a simple pole and sign, to a rudimentary shelter, to sophisticated structures. The usual minimum is a pole-mounted flag with suitable name/symbol.
- Bus stop shelters may have a full or partial roof, supported by a two-, three-, or four-sided construction. Modern stops are mere steel and glass/ Perspex constructions, although in other places, stops may be wooden, brick, or concrete built.
- Individual bus stops may simply be placed next to the roadway (often with no footway provision in rural areas), although they can also be placed to facilitate use of a busway. More complex installations can include construction of a bus lay-by or a bus bulb, for traffic management reasons, although use of a bus lane can make these unnecessary.
- Bus stops must not be located such that stopped buses will obstruct the sightline to the traffic signal.
- Where lay-bys do exist (see figure 4.67), they can be crowded with waiting passengers, and bus drivers tend not to use them. This behavior is frequently observed on heavily trafficked roads where the driver is more likely to experience difficulty in merging with the main road flow again.
- Several bus stops may be grouped together to facilitate easy transfer between routes. These may be arranged in a simple row along the street, or in parallel or diagonal rows of multiple stops. Groups of bus stops may be integral to transportation hubs. With extra facilities such as a waiting room or ticket office, outside groupings of bus stops can be classed as a rudimentary bus station. The stop may include separate street furniture such as a bench, lighting, and a trash receptacle.

Figure 4.65: Curbside trolleybus stop—Ukraine, with shelter and kiosk.

Source: © John Barrell.

Figure 4.66: Rural village bus stop—Burundi, no signs or facilities.

Source: © John Barrell.

Figure 4.67: Bus lay-by —Ghana and Romania, used as a garage facility.

Source: © John Barrell and Alina F. Burlacu/GRSF/World Bank.

- At the busiest urban center locations, complex interchanges may be necessary to accommodate both large numbers of vehicles and passengers. They need to segregate both users up to the point of boarding and allow individual bays for separate services.
- Whichever level of provision is made, the key elements are to ensure that:
  - Vehicles should be able to enter, stop, and leave the location safely and smoothly.
  - Lay-bys should be positioned on straight, level sections of road and should be visible from a good distance in both directions.
  - Access to a lay-by should be convenient and safe for vehicles and, also for pedestrians in the case of bus stops.
  - Advance warning signs should be erected to alert drivers of the approach to bus stops, and to the possible presence of pedestrians ahead.
  - Passengers are provided with sufficient advance warning (either within the vehicle or by external signage) to allow them to stand safely and comfortably.
  - Adequate queueing areas should be available so that waiting passengers do not use the road or a dedicated bus lay-by.
  - Pedestrian crossing facilities should be placed before the bus stop to aid visibility of crossing pedestrians and ease bus egress from the stop, whether at the curb or within a lay-by
  - Adequate and safe routes are provided to and from the stops to the surrounding pedestrian network.
  - Locations for stopping and waiting are clearly identified and protected.
  - Informal stopping on the highway or shoulder should be prevented.
- Improvements to footways and well-maintained pedestrian routes and short distances between bus stops can reduce walking distances and thus the number of injuries.

Further Reading

- Traffic Safety on Bus Priority Systems. 2105. EMBARQ WRI. Must read chapter 4 and chapter 8, about the case studies of BRT.
- *Bus Stop Design and Safety Guideline Handbook.* 2014. Imperial County Transportation Commission USA. Must read section 5, On street bus stop and section 6, Off street transit transfer stations.
- Public Transport Interchange Design Guidance, Auckland Transport NZ. 2013. Must read chapter 3, Design principles and chapter 4, Auckland interchange hierarchy.
- Interchange Best Practice Guidance. 2009. Transport for London, UK. Must read design themes and principles.

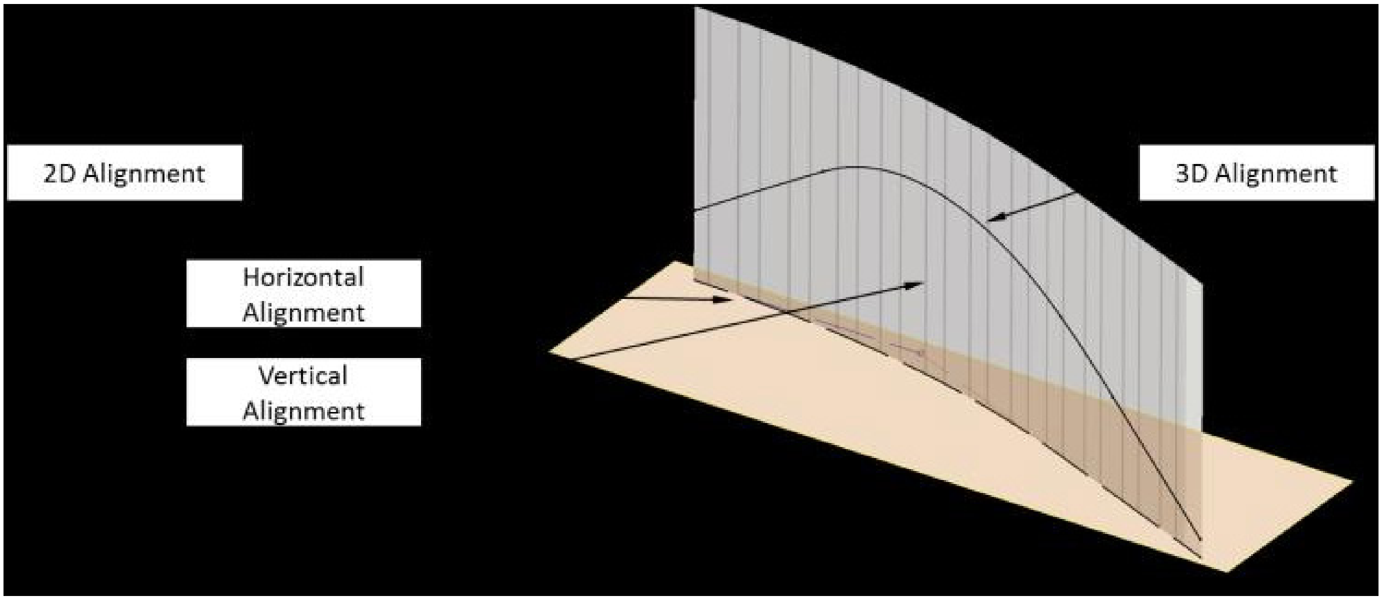
5. CROSS SECTION AND ALIGNMENT

Road design can be broken into three main parts: horizontal alignment, profile/vertical alignment, and cross section. Combined, they provide a three-dimensional layout for a roadway (figure 5.1).

- The horizontal alignment is the route of the road, defined as a series of horizontal tangents (straights) and curves (usually circular). This is usually represented in plan form as centerline geometry with lane and edge lines.
- The profile/vertical alignment is the vertical aspect of the road, including crest and sag curves, and the straight grade lines connecting them. This is usually represented in profile form and includes a section cut through the existing terrain along the line of the road centerline.
- The cross section shows the position and number of travel lanes, including cycle lanes and sidewalks, along with their cross slope or banking. Cross sections also show drainage features, pavement structure, and other items outside the category of geometric design. This could be a "typical section" showing the standard or recommended widths of design components, or sections at specific locations used to highlight particular features.

Each of these parts are comprised of geometric design elements, including horizontal curves and straights, vertical curves and gradients, lane widths, shoulder widths, median widths, superelevation, and crossfalls, among others. The design of these elements influences safety and very restrictive designs, such as sharp horizontal curves or very narrow lanes, relative to the

Figure 5.1: Three-dimensional layout combined with horizontal and vertical alignments.



Source: © Julian Amann

travel speeds, and often results in considerably higher crash rates. Certain combinations of these elements may also result in severe crash consequences. It is important to keep in mind the principles to good geometric design as discussed in section2.1. The design should result in a road environment that is consistent with the road users' expectations or "non-surprising," as well as "forgiving" in the sense that road users' mistakes can, as far as practicable, be corrected, if not avoided. The selected design speed on which road alignment and cross-section characteristics are determined needs to be realistic and compatible to the expected operational speed (see section 3.1). It should also be in accordance to the type and functional requirements of the road and compatible to the roadway environment (see chapters 2 and 1).

The key principles when designing a road are to provide consistency, readability, and predictability. As such, elements of the alignment that are inconsistent or out of context with the rest of the alignment should either be avoided or clearly signaled to the driver with additional signing, delineation, and other visual cues. Context is also important when considering the form, function, and primary purpose of the road. This will influence the width of the road, its look and feel, and also how drivers are likely to read it and select their driving speed.

In the following sections, the safety implications (i.e., the relationship between the design element and safety) as well as good design practice of various cross-section elements, and the horizontal and vertical alignment are discussed in detail. The combination of horizontal and vertical curves is discussed in section 5.3. Various case studies/ examples of both good and bad practice are also provided in each section. Design elements for vulnerable road users including footpaths, and cycle and motorcycle facilities, though part of the cross section, are discussed separately in chapter 4.

5.1. Road Width

General description

Road width is the total width of the portion of the roadway that allows for the movement of through vehicular traffic, including shoulders but excluding facilities such as curbs, separated cycle facilities, sidewalks, or parking lanes.[58] It is the full width of the carriageway, including all the travel lanes and adjacent shoulders (if present).

A lane width is the cross-sectional dimension of a traffic lane, perpendicular to the direction of travel, measured between the center of lane markings and the faces of curbs or edge line at the shoulder, as applicable.

Road width affects safety through its influence on speeds and a vehicle's ability to remain within its assigned traffic lane. Generally, higher-speed facilities require wider roads/lanes compared to lower-speed facilities. The environment (whether urban or rural context) and the road function also play critical roles in the selection of road widths.

Safety implications

It is important that the assignment of available space on the road is consistent and well considered to achieve a high level of readability and predictability. This means that all modes sharing the road corridor understand where they each should be and their position relative to each other, whether in adjacent lanes and shoulders or opposing lanes.

Wider roads/lanes generally encourage, and are associated with, higher operating speeds than narrower roads/lanes. As such, the use of wide roads/lanes can pose significant safety risks, especially within the urban traffic environment where pedestrians, cyclists,

58 These facilities (curbs, bicycle facilities, sidewalks, parking lanes) are also essential elements of the road cross section within the right-of-way (total land area acquired for the construction of a roadway) and are covered in detail in separate sections. Shoulders are also discussed in detail in the following section.

Figure 5.2: Use of wide lanes in an urban area at the expense of vulnerable users (pedestrians and cyclists).

Source: Global Designing Cities Initiative, & National Association of City Transportation Officials (NACTO).

Figure 5.3: Appropriate use of wide lanes on freeway.

Source: iRAP.

and crossing vehicles are embedded in the traffic mix (figure 5.2; see also figure 5.3 for appropriate use of wide lanes). Higher operating speeds and associated greater stopping sight distances can make it more difficult for motorists to bring their vehicles to a quick stop to avoid crashes. This is because the following distances at higher speeds may appear excessive, leading to vehicles cutting across on multilane roads and a tendency for drivers to drive closer to the car in front of them. The severity of crashes may also be increased.

- Wider road/lane widths in urban areas increase exposure and crossing distance for pedestrians at intersections and midblock crossings.
- Lanes that are too narrow (typically less than 2.8~3.0 m) have increased risks of poor lane discipline at high speeds, such as single vehicle run-off-the-road crashes and multiple-vehicle head-on, opposite-direction sideswipe, and same-direction sideswipe collisions. This may be due to encroachments onto adjacent lanes, insufficient space for overtaking wide vehicles, or reduced sightlines to other vehicles in congested conditions. Within urban areas, narrowing of lanes can be used to control speed.
- Lanes that are excessively wide have increased crash frequencies. Studies report that the safety benefit of widening lanes stops once lanes reach a width of roughly 3.4 m, with crash frequencies increasing as lanes approach or exceed 3.7 m.[59], [60] The use of lanes greater than 3.6 m may in fact be used as two lanes, which can lead to increases in sideswipe crashes. Higher speeds may also be expected, which increases the likelihood and severity of crashes.
- Narrow lanes at curves may not provide an adequate tracking width or swept path for wide vehicles or room for driver error and may result in head-on crashes, sideswipes (particularly with vulnerable users in shoulders), or run-off-the-road crashes. Superelevation around curves can be applied to help maintain good lane tracking.
- Narrow turning lanes at intersections may not accommodate the swept path of larger vehicles such as trucks and buses, which may lead to encroachments onto adjacent lanes increasing the risk of sideswipes (particularly with vulnerable users), and head-on and run-off-the-road crashes.

59 Dumbaugh, E., and Rae, R. 2009. Safe urban form: revisiting the relationship between community design and traffic safety. Journal of the American Planning Association, 75(3), 309–329.

60 Noland, R. B. 2003. Traffic fatalities and injuries: the effect of changes in infrastructure and other trends. Accident Analysis & Prevention, 35(4), 599–611.

Good design practice/treatments/solutions

- The selection of the lane width and the number of lanes will depend on various factors including:
    - Target vehicle speed (design speed, average speed, and posted limits) and lateral displacement.
    - Context (existing or future function of streets and land uses).
    - Level of pedestrian and cycle activities and facilities.
    - Vehicle volumes and capacity.
    - Vehicle type (large vehicles, transit vehicles, trucks) and the degree of truck proportion in total traffic.
    - Provisions for other users.
    - Nature, direction, and number of lane uses (turning lanes, through lanes, curbside lanes).
    - Situation adjacent to the lane (delivery, on-street parking, boulevards).
    - Emergency vehicle operations. Travel lanes should not be too narrow (less than 2.8~3.0 m) for vehicles pulling out from emergency vehicles' paths, and long uninterrupted medians should be avoided. Multiple lanes leave sufficient space for drivers to pull out of the way of emergency vehicles.
    - Topography and geometry (continuous median, horizontal alignment, crossfall, or slope of the road).
    - Other considerations (snow cleaning and storage, topography and road camber or curvature, maintenance, bridges and crossing points, planned changes of streets).
- Narrowing lanes is an effective tool for speed management since narrower lanes generally bring down operating speeds closer to safer speed limits, while maintaining consistent speed and minimum impact on corridor travel time.
- In urban areas, the use of narrower lanes has numerous benefits when considered within the assemblage of a given street, and urban streets can be redesigned to accommodate the needs of all road users through a road diet (figure 5.4). A road diet is generally described as reducing the number of travel lanes and/or narrowing travel lanes in a roadway and utilizing the space for other uses and travel modes. The benefits include:
    - Reclaimed space to serve other modes, including cycle lanes and sidewalks, which improves mobility and access for all road users.
    - Reclaimed space for geometric features that enhance safety, such as medians, pedestrian refuge islands, and turn lanes.
    - Allow greater and more attractive space for pedestrians to relax and linger.
    - Shorter pedestrian crossing times because of reduced crossing distances.

Figure 5.4: Example of a road diet in Brazil showing reduction in the number of lanes from three each way in 2009 to two each way in 2014, with the addition of a wide median footpath and cycle lanes.

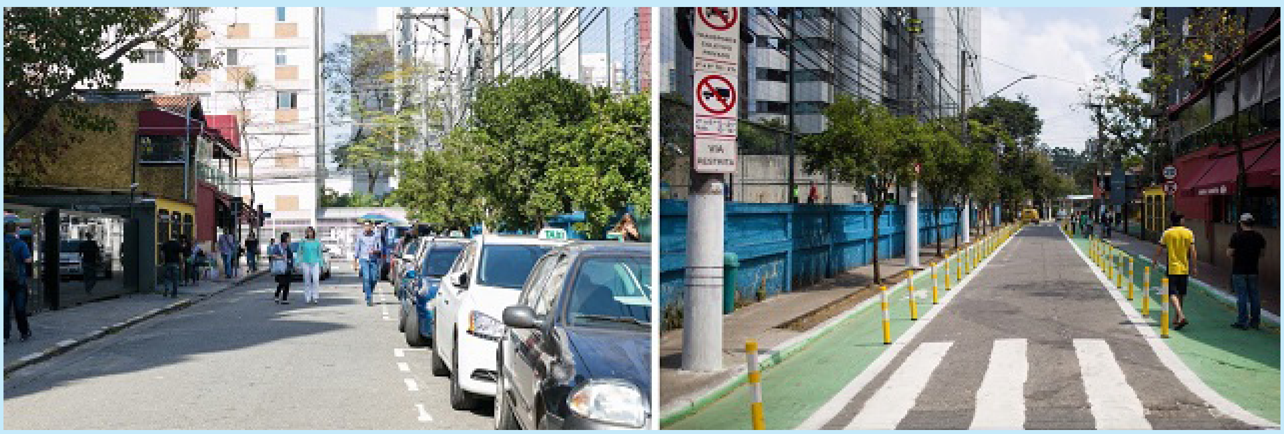
Source: Urban ideas. Accessed at https://www.urb-i.com/before-after-gallery.

    - Reduced interference with surrounding development.
    - More economical to construct.
    - Less stormwater runoff as more space can be left as vegetation.
- Wider lanes may be necessary at turning locations, including curves, turning lanes, and roundabouts, especially when designed to accommodate larger vehicles. This allows more space for drivers to get around a curve/turn without encroaching onto the adjacent lane, shoulder, or even footpath. The amount of widening per lane will depend on the radius of the curve, the type/size of vehicle operating on the road, and some allowance for steering variations by different drivers.

Case Study

São Paulo, Brazil

Figure 5.5: Before and after of Joel Carlos Borges Street, São Paulo, Brazil, September 2017.



Source: © Daniel Hunter/WRI Brasil.

São Paulo's Berrini Train Station is connected to the city's central business district by Joel Carlos Borges Street that accommodates thousands of daily users. Before September 2017, the street had narrow sidewalks that were unable to safely accommodate the heavy pedestrian flow of approximately 4,700 pedestrians during the morning peak (between 7:00 am and 9:30 am). In contrast, only 170 vehicles travelled on the street at the same peak, translating to an average of 28 pedestrians for each car. Since the narrow obstacle-filled sidewalks could not meet this demand, people walked unsafely in the middle of the street and between parked and moving cars.

The city decided to increase the pedestrian area on the road by 70 percent by removing the parking lane and narrowing the vehicle travel lane (see figure 5.5). The narrow and rundown sidewalks gained an additional 3.5 m in width, providing ample space for pedestrian traffic. The city also improved signages, lowered speed limits, and added street furniture and green infrastructure.

This was the first temporary road intervention in the city that aimed to test low-cost transformation measures before performing expensive and more complex works. The project was well received by the public, and the city is now considering similar efforts in other high pedestrian areas such as schools and hospitals.

- Narrowing lanes on the approaches of signalized urban intersections can help manage the speeds and reduce pedestrian crossing times due to reduced crossing distances.
- Advance warning is needed whenever there is a change in the cross section, for example on approaching narrow bridges and culverts. This is in line with the principle of predictability and a "no surprises" approach in which road users are provided with appropriate and relevant information in a timely fashion to facilitate their decision-making.
- Since vehicle speeds increase when roads are widened and reduce when a lane is narrowed (to a reasonable degree), a safety assessment is needed to determine the appropriate lane width and the suitability of a lane widening/narrowing treatment at a given hazardous location or intersection.

Further Reading

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- Global Designing Cities Initiative, & National Association of City Transportation Officials. 2016. Global street design guide. Island Press. Accessed at https://globaldesigningcities.org/publication/global-street-design-guide/.
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- Welle, B., Liu, Q., Li, W., Adriazola-Steil, C., King, R., Sarmiento, C., and Obelheiro, M. 2015. Cities safer by design: guidance and examples to promote traffic safety through urban and street design. Must read chapter, Kenya Urban Design Elements and chapter 5, Pedestrian Spaces and Access to Public Space.

5.2. Shoulder Width and Type

General description

A shoulder is the portion of the roadway contiguous with the travelled way that, depending on the width, design, and maintenance, performs several functions. The benefits include:

- Accommodation of stopped vehicles for emergency use;
- The provision of a controlled recovery area for drivers who inadvertently stray from their lane, thus reducing the risk of run-off-the-road crashes (especially in high-speed locations);
- Provision of space for evasive maneuvers to avoid potential crashes or reduce their severity;
- Provision of a defined space for cyclists or pedestrians where designed safely, in the absence of separated facilities;
- The provision of structural support to the pavement;
- Reduction of pavement breakup by allowing storm water to be discharged farther from the travelled way, and therefore have both safety and asset management benefits;
- Provision of lateral clearance to roadside objects, e.g., curbs, signs, and guardrails; and

Figure 5.6: Paved shoulder.

Source: © John Barrell.

Figure 5.7: Unpaved gravel shoulder.

Source: Zeng, H., Schrock, S. D., and Mulinazzi, T. E. 2013. *Evaluation of safety effectiveness of composite shoulders, wide unpaved shoulders, and wide paved shoulders in Kansas* (No. K-TRAN: KU-11-1). Kansas Dept. of Transportation. Bureau of Materials & Research.

Figure 5.8: Partially-paved or composite shoulder

Source: Zeng, Schrock, and Mulinazzi, 2013.

- Improvement of sight distance in cut sections and enhancement of highway capacity and efficiency by encouraging uniform speeds.

Shoulders can be paved (figure 5.6), unpaved (i.e., granular or earthen shoulders; figure 5.7), or partially paved (i.e., shoulders comprising of a paved section and unpaved section; figure 5.8). These are also known as composite shoulders.

Safety implications

- Shoulders that are too narrow do not provide an adequate recovery width for stray vehicles and enough through traffic clearance to vehicles stopped on the shoulder. These vehicles actually create roadside hazards and result in increased risks for run-off-the-road crashes, head-on and nose-to-tail collisions, and sideswipes.
- Shoulders with inadequate skid resistance may cause a vehicle that leaves the travelled way, especially one travelling at high speeds, to lose traction and control resulting in run-off-the-road crashes, with severe consequences upon impact with roadside objects or other vehicles.
- In the absence of other facilities with more separation, a shoulder that is too narrow or in poor condition inevitably displaces nonmotorized traffic onto the carriageway where they face increased

Figure 5.9: Narrow shoulders resulting in increased risks for cyclists on the travelled way

Source: iRAP.

Figure 5.10: Pavement edge drop.

Source: © Watetu Mbugua/World Bank.

Figure 5.11: Illegally parked trucks on shoulder.

Source: Indian Institute of Technology, Kharagpur. 2019. Report on Road Safety Audit of SH-11 During Operation Stage.

safety risks due to exposure to high-speed traffic (figure 5.9).

- Unpaved shoulders, especially on roads with high heavy-vehicle volumes in areas with heavy rainfall or abundant water runoff such as sag curves, may be eroded with time, resulting in pavement edge drop-offs (figure 5.10), i.e., where there is a difference between the height of the road surface and the height of the shoulder. Edge drops may cause a driver who drifts out of the travelled way to lose control of the vehicle and either veer off the road or overcorrect and veer into the oncoming traffic.
- Roadways with no clear distinction between the carriageway and the shoulder (due to lack of signs, pavement markings, or low curbs) may encourage the use of shoulders by motorized traffic, even when the shoulder is of a different surface material and intended to serve a separate purpose to the carriageway (figure 5.11).

Figure 5.12: 2.5 m shoulder people wrongly using as a traffic lane—Romania.

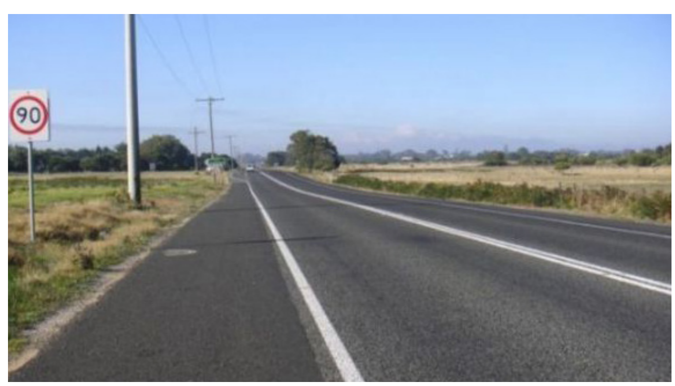
Source: © Alina F. Burlacu/GRSF/World Bank.

- Excessively wide shoulders, especially when paved, can pose some safety risks including:
  - Wide, paved shoulders result in higher operating speeds which, in turn, may impact the severity of crashes,
  - Paved shoulders greater than 2.5 m may be interpreted as a travel lane by drivers, or even as temporary places for commercial activity (such as selling items to passing motorists),
  - Wide shoulders may generate voluntary stopping on the shoulders, and
  - Wide roadway widths, resulting from wide shoulders and wide lanes, combined with limited right-of-way, may result in steeper side slopes or backslopes.
- Objects such as electricity posts, cable ducts, and raised drainage covers that are located along the shoulders are hazardous to all road users.

Good design practice/ treatments/solutions

- It is recommended that the shoulder be constructed of the same materials as the carriageway in order to facilitate construction, improve pavement performance, and reduce maintenance costs.

Figure 5.13: Wide sealed shoulder.



Source: iRAP.

Figure 5.14: Wide, paved shoulder on curve.

Source: iRAP.

Figure 5.15: Paved shoulder with rumble strips used by cyclists.

Source: Bob Boyce/Ped Bike.

- The ideal width of shoulder depends on the usage of the road. A wide enough shoulder is recommended to provide an adequate refuge for vehicles to pull over and a recovery area in case of a roadway departure but not too wide to encourage the use of the shoulder as an additional lane (figures 5.12 and 5.13).
- The shoulder surface should provide sufficient skid resistance to prevent the loss of traction and control for stray vehicles. A sealed surface will provide the best grip for tires.
- Shoulders should be continuous regardless of the width to avoid intermittent stopping on the travelled way. This also provides a continuous path for cyclists and pedestrians when shoulders are used as cycle lanes or footpaths.
- The shoulder surface should connect to the pavement at approximately the same level to prevent loss of control for vehicles that erroneously leave the travelled way.
- Sealing shoulders (full width or partially) on otherwise gravel shoulders can reduce the amount of erosion on the gravel shoulder and provide a safe recovery zone for shoulder encroachments.
- The quality of shoulders, on low radius curves in particular, requires special attention given the higher probability of encroachment at these locations. This may be due to intentional driver behavior or inadvertent "off-tracking" of an articulated trailer. Wide, paved shoulders improve the safety of curves (figure 5.14), particularly on the inside edge (also see section 5.3).
- In the absence of other facilities with greater separation, wide, paved shoulders provide space for pedestrians and cyclists, thereby potentially improving the safety of vulnerable users. Noting that pedestrians and cyclists may be at risk when drivers inadvertently drift off the road, shoulder rumble strips or edge-line rumble strips could be installed to mitigate against this risk (figure 5.15).
- Rumble strips or textured edge markings, which can be produced either by cutting grooves or adding ribs to the road, may be placed on the shoulders (near the edge of the travel lane) to alert drivers when they are leaving the roadway. These are highly effective and significantly reduce run-off-the-road crashes due to inattention, distraction, and fatigue.
- Signs, pavement markings, and textured edge markings provide the necessary distinction between the shoulders and the carriageway and should be used to deter the use of shoulders by motorized traffic except in emergencies. In urban areas, curbs along the edge of the carriageway may be used.
- Objects that are located along the shoulders should be moved and/or buried beyond the shoulders, and where possible, beyond the clear zone (see section 5.7). It is essential that shoulders remain traversable to serve their function.
- The management and maintenance of the road and shoulder should be routine and simple.

Further Reading

- American Association of State Highway and Transportation Officials. 2010. Highway Safety Manual (2010). Must read Highway Safety Manual Overview and chapter 3, Integrating the HSM in the Project Development Process.
- FHWA. Small Town and Rural Design Guide: Facilities for Walking and Cycling. Accessed at https://ruraldesignguide.com. Must read Visually separated part.
- PIARC. 2009. Catalogue of Design Safety Problems and Potential Countermeasures. Must read section 2, Cross-section and section 3, Alignment.
- PIARC. 2019. Road Safety Manual. Accessed at https://www.piarc.org/en/PIARC-knowledge-base-Roads-and-Road-Transportation/Road-Safety-Sustainability/Road-Safety/safety-manual.
- World Bank. 2005. Sustainable safe road design: A practical manual. Must read chapter 3, Sustainable safe road design: theory, and chapter 4, Sustainable safe road design: cross sections.

5.3. Horizontal Curvature

General description

Horizontal curves are associated with higher safety risks compared to tangent sections. This difference becomes particularly apparent at radii less than 1,000 m and becomes increasingly significant as curve radii reduce further (< 200 m).[61] This is often the result of a mismatch between the radius, superelevation, and negotiation speed chosen by the driver. This creates an imbalance in the forces exerted on the vehicle and does not match driver expectations, among other factors.[62] It should be noted, however, that while short horizontal curves of low radius may increase the crash risk in high-speed environments, the same curve length and radius may be appropriate in low-speed residential environments to help facilitate slower speeds,[63] or as part of a series of curves. In addition, high radius curves may be introduced into rural designs to manage vehicle speeds and reduce monotony.

Horizontal curves are associated with run-off-the-road crashes, head-on collisions, and side crashes. The severity of crashes has also been found to be high at horizontal curves. Studies in high-income countries (HICs) show that 25 percent to 30 percent of fatal crashes occur in curves and that 60 percent of the fatal crashes are single vehicle off-the-road crashes.[64]

The key objective while designing horizontal alignment is to ensure there is consistency and uniformity of alignment along the road corridor, thereby providing predictability that maximizes the overall safety of the road. This philosophy of "no surprises" provides a driver with visual cues in the form of a clear view of the curve ahead, with sufficient time to adjust their speed accordingly. Drivers are strongly influenced by their interpretation of the curve radius, and many assume that the combination of radius and applied superelevation is appropriate for the speed limit. If the road has been designed and well maintained, then this assumption is a reasonable one. However, if the road network has evolved over time, there may well be a mismatch between the shape of the road surface and posted speed limit. Without appropriate superelevation, the forces on the driver are not balanced and the driver might feel uncomfortable or potentially lose control.

61 Hauer, E. 2000. Safety of horizontal curves. Draft prepared in the course of project for UMA Engineering (for the new Canadian Geometric Design Guide) and for DELCAN.

62 Hummer, J. E., Rasdorf, W., Findley, D. J., Zegeer, C. V., and Sundstrom, C. A. 2010. Curve collisions: road and collision characteristics and countermeasures. Journal of Transportation Safety & Security, 2(3), 203–220.

63 American Association of State Highway and Transportation Officials (AASHTO). 2010. Highway Safety Manual.

64 Lamm, R., Psarianos, B., and Mailaender, T. 1999. Highway design and traffic safety engineering handbook.

Safety implications

- Unexpectedly sharp curves often result in loss of control, skidding, or crashes onto roadside objects or oncoming vehicles when drivers mismatch their speed to the geometry and are forced to perform sudden corrective actions. This is made worse when the sharp curve is "out of context" or does not match with the alignment conditions adjacent to the sharp curve section that mislead or encourage high speeds, for example, a sharp curve after a series of gentler curves or after a long straight section.
- Obstructions located too close to the carriageway on the inside of the curve without the necessary horizontal sightline offset, limit the sight distance and the driver's ability to see and anticipate road features ahead of the curve (figures 5.16 and 5.17).
- Sharp curves increase the width of a vehicle's swept path, which may cause a vehicle to cross into the path of an approaching vehicle on narrow carriageways, or onto the shoulders and pedestrian areas, increasing the crash likelihood for other road users. This is worse for wide or long vehicles/trucks.
- Drivers may overtake on curves when it is unsafe despite the "no-overtaking" provision.
- The road surface on curves tends to polish more quickly than straight sections due to the higher forces exerted by the side thrust of the tire, resulting in reduced skid resistance with time.
- The loss of superelevation (positive camber), particularly on gravel roads, through the lack of maintenance increases the safety risk of curves.
- Other factors that influence the safety on curves include the roadside profile (whether level or drop-off if a vehicle leaves the road), the presence of unshielded roadside hazards, poor visibility, poor delineation (figure 5.18), poor drainage, inadequate or reverse superelevation, inadequate lane widths or lack of extra widening on curves.
- Poor coordination of horizontal and vertical curvature can result in visual effects that may mislead drivers thus contributing to crashes (figures 5.19 and 5.20). This usually occurs when horizontal and vertical curves of different lengths occur at the same location.
- The presence of crest curves immediately preceding sharp curves can hide the sharp curves from the drivers view, creating a lack of readability (figure 5.21).

Figure 5.16: Tree located too close to the carriageway on inside of curve. It obstructs line of sight and is a safety hazard. It also has the potential to push road users toward or even across the centerline at a curve, making it very unsafe.

Source: Indian Institute of Technology. 2019. Report on Road Safety Audit of SH-11 during operation stage.

Figure 5.17: Mountainous curve with tree obstructs where a road crash occurred.

Source: Nepali Times, 2021. Nepal's other pandemic: road fatalities. 2021. Accessed at https://www.nepalitimes.com/here-now/nepals-other-pandemic-road-fatalities/.

Figure 5.18: Insufficient delineation at curve.

Source: ChinaRAP.

Figure 5.19: Hazardous combination of horizontal curve at the base of a steep upgrade.

Source: Federal Highway Administration. 2007. Mitigation Strategies for Design Exceptions, US. https://safety.fhwa.dot.gov/geometric/pubs/mitigationstrategies/.

Figure 5.20: Poor alignment combination showing optical breaks caused by steep sag curves along horizontal tangent.

Source: Barnaby Green.

Figure 5.21: Hazardous combination: crest curve preceding sharp horizontal curve, with intersections and accesses.

Source: PIARC. 2003. *Road Safety Manual, First edition*.

Good design practice/ treatments/solutions

- It is important that a road is designed for a speed that exceeds, as a minimum, the speed often referred to as the operating speed or at which it is anticipated (or intended) drivers will travel.
- At the design stage, consistency and predictability of the driver experience are very important, and unexpectedly tight curves should be avoided. This can be done by either increasing the radius of the curve or ensuring the transition to sharper curves is carried out through gradual and progressive reduction of the radii along sequential curves.
- For tight horizontal curves, which are out of context compared to the rest of the design and cannot be re-aligned for financial or environmental reasons, special treatments at these curves should be specified and carried forward to the design and construction phases. These special treatments can be in the form of specific signs or markings that alert the driver to the change in conditions.
- Forward visibility and sight distances are important to help the driver assess the road ahead and adjust their speed in anticipation of the road condition. Sight obstructions on the inside of curves or the inside of the median lane in divided highways need to be removed to provide appropriate sight distance. In situations where it is impractical

to remove such obstructions (such as retaining walls, cut slopes, concrete barriers, buildings, and longitudinal barriers), the sight distance should still be optimized, but the design needs to evaluate the risk associated with the deficiency and assess the options for mitigating that risk. Because of the many variables in the design of curves, i.e., the alignment and cross section, and the number, type, and location of potential obstructions, it is necessary to conduct a specific study for each individual curve. Using sight distance for the design speed as a control, the designer can then check the actual conditions on each curve and make the necessary adjustments to provide adequate sight distance. These adjustments should take into account the extent or duration of the obstruction. For example, a retaining wall may represent a significant length of deficiency, thereby requiring some adjustment of design or speed, whereas a single building or clump of trees represents only a momentary reduction and therefore the risk is much lower.

- Curves should be superelevated in proportion to their radius and speed.
- Superelevation should be changed gradually and equally between curves of a different radius; between straights and curves it is normal to change two thirds of the superelevation on the straight and a third on the curve. The superelevation should always be changed at the same rate along an alignment. This is usually expressed as a percentage per second of travel time and is normally between 2.5 percent/s and 3.5 percent/s. This provides a consistent balance in the forces on the vehicle as its direction transitions from one curve to the next.[65]
- Transition curves may be provided between a tangent and a circular curve or between two circular curves, allowing the gradual introduction of superelevation. The length of the transition curves should be equal to the distance over which the superelevation changes. The full nature of approaching curves should be evident to the driver. Long transition curves that mask a sharp final radius should be avoided.
- While simple curves are preferred, compound curves can be used to satisfy topographical constraints that cannot be as effectively balanced with simple curves. For compound curves on open highways, it is generally accepted that the ratio of the flatter radius to the sharper radius should not exceed 1.5:1.
- Higher skid resistance materials can be used on critical bends, particularly in wet environments.
- Large radius horizontal curves may be introduced on straight alignments to break driver monotony and enable drivers to make better judgements of the speeds of approaching vehicles.
- It is worth noting that there is a difference between the European and US/Australian design philosophy regarding adopting long straight roads and more sinuous or curved alignments, which may be a result of the characteristics of the general terrain. In Germany, the condition for the alignment is to have over 70 percent curves with high radii. Straight roads should be avoided. In US/Australia the reverse is true. Either approach can result in unsafe conditions, but needs to be applied consistently, and mixing approaches can lead to greater risk.
- Lane (or curve) widening is normally applied to the inside edge of curves and is often necessary on lower radius curves to provide room for "off-tracking" of articulated vehicles. Especially relevant where radii are <500 m, this allows for the difference between the path of the rear axles of the trailer compared to the truck (tractor) unit.
- Adequate maintenance should be provided, especially on gravel roads, to maintain an acceptable cross-sectional profile with appropriate camber. When it is anticipated that such maintenance is

65 For more details refer to design guidelines including Austroads. 2009. Guide to Road Design Part 3: Geometric Design and AASHTO (2018). Policy on geometric design of highways and streets (chapter 3). American Association of State Highway and Transportation Officials, Washington, DC.

unlikely, the design of the road and in particular the operating speed, should be based on the assumption of a level cross section.

- On surfaced roads, there is also a requirement for maintenance, including to ensure that debris is removed, as this will have a significant impact on surface friction and the potential loss of vehicle control. This is an issue for all vehicles, but particularly for motorcyclists.
- Where it is not possible to entirely separate horizontal and vertical curves, they should be combined with common changes for intersection points (where the ends and center of the vertical curve are coincident with the corresponding ends and center of the horizontal curve) to avoid the presentation of misleading information to drivers. Where possible, they should be of the same or similar length, and where this is not achievable, the preference is for the extent of vertical curves to lie wholly within a single horizontal curve. This arrangement should produce the most pleasing, flowing, three-dimensional result, which is more likely to be in harmony with the natural landform (figure 5.22). In addition, the following should be kept in mind:
    - Sharp horizontal curves in combination with a pronounced crest vertical curve should be avoided since drivers may not perceive the horizontal change in alignment, especially at night.
    - Sharp horizontal curves at or near the low point of a pronounced sag vertical curve should be avoided since the view of the road ahead would be foreshortened, and curves in these locations tend to be sharper than they appear.
    - The radius of horizontal curves or the camber applied to those curves may be increased in the order of 15 percent at the bottom of steep grades to improve perception and allow for vehicles running out of control. Alternatively, escape lanes may be provided to allow vehicles that are traveling too fast for the turn to safely stop.
    - The horizontal and vertical alignment should be made as flat as possible at intersections and interchanges to allow the provision of sufficient sight distance.
    - On two-lane roads where combinations of curves are likely, tangent sections may be provided with good passing sight distance to provide opportunities for safe overtaking.

Figure 5.22: Example of good combination of horizontal and vertical curvature providing good visibility.

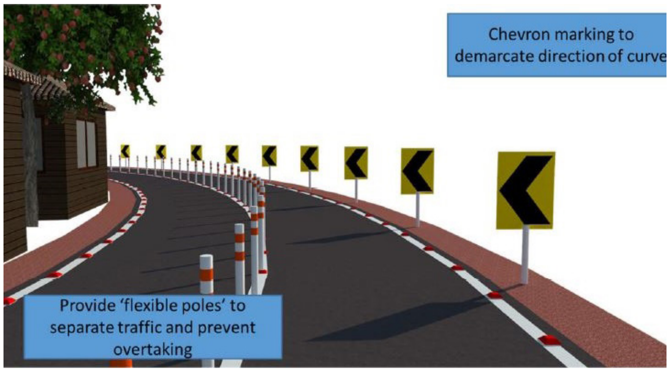
Source: TRL & Department for International Development. 2001. Horizontal curves, highway design note 2/01, TRL Ltd, Crowthorne, UK.

Below is a summary of treatments for horizontal curves:

Markings and signs

- Pavement markings are important in providing continuous information to help drivers navigate roadways successfully. These include:
- Longitudinal pavement markings (centerlines and edge lines). Wider centerline markings can be used where space allows to increase separation between vehicles travelling in opposite directions.
- Guideposts/delineators along the side of the road. They can be used for both unpaved and paved roads.
- Flexible posts along the centerline of curves with limited sight distance to prevent overtaking. The flexible posts or poles should be at least 1 m high with retroreflective marking to ensure nighttime visibility (figure 5.23).
- Advance pavement markings for curves including

Figure 5.23: Illustration on provision of flexible poles and chevron signs at curves with limited sight distance.

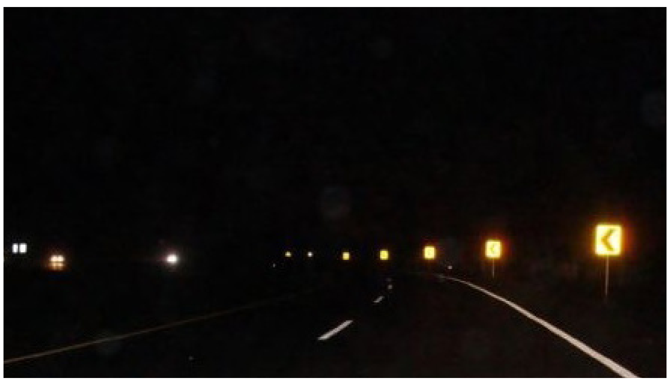


Source: Indian Institute of Technology. 2018. Road Safety Audit of NH 60 and NH 117 and Capacity Building on Road Safety Issues in the State of West Bengal: Final Report on NH 117.

Figure 5.24: Transverse lines at the entrance of curve in China.

Source: iRAP.

Figure 5.25: Chevron alignment signs providing good night-time visibility.



Source: iRAP

Figure 5.26: Advance curve warning and speed sign.

Source: World Bank

speed advisory markings and speed reduction markings/optical speed bSource: FHWA.ars (figure 5.24).

- Retroreflective raised pavement markers (RRPMs). Usually used in conjunction with painted line marking to warn drivers of changes in alignment in road ahead.

Signs may include chevron alignment signs (figure 5.25), advance warning signs (figures 5.26 and 5.27), and advisory speed plaques. Signage can be enhanced using larger devices, retroreflective strips on signposts, highly retroreflective and fluorescent sheeting, flashing beacons, and dynamic curve warning systems.

Figure 5.28 shows a set of treatments applied to a high-risk curve in Malaysia.

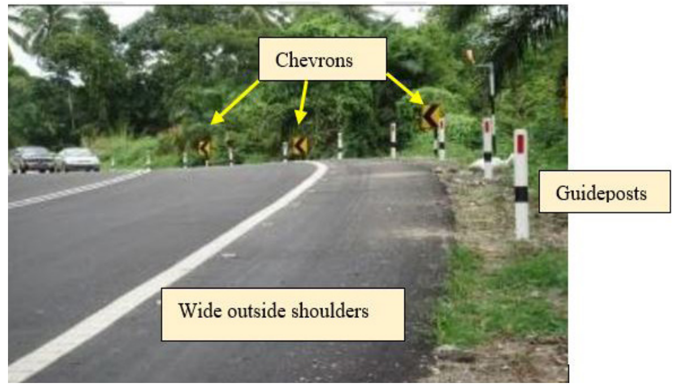
- Route-based curve treatments

Route-based treatments are a method of ensuring consistency of signing of curves along a section of road. Each curve is classified based on risk factors, such as design speed, tangent speed, sight distances, and so forth. Once the risk of the curve has been identified, signs and markings for that curve are installed according to this risk category. The higher the risk category, the more treatments are installed. To avoid confusion and maintain driver confidence and compliance, treatments should be applied consistently where curves of similar risk categories receive similar treatments. Since it is applied along a route/network, this method is consistent with the self-explaining roads concept.

Figure 5.27: Horizontal curve at the base of a steep downgrade with advance warning sign.

Source: PIARC. 2003. *Road Safety Manual*, First edition.

Figure 5.28: Example of curve improvement in Malaysia.



Source: iRAP.

Figure 5.29: Wide centerline with median rumble strips on curve in Australia.

Source: iRAP.

Figure 5.30: Safety edge. After installing the safety edge, the unpaved material adjacent to the edge should be graded flush with the top of the pavement.

Source: Fitzgerald, 2014.

Pavement countermeasures

The following countermeasures may be applied to improve the pavement's skid resistance:

- High-friction surface treatments (HFSTs),
- Pavement grooving on concrete pavements to increase friction and improve watershedding,
- Provision/correction of superelevation, and
- Widening at curves to allow wide centerline treatment (figure 5.29).

The following treatments are applicable to shoulders:

- Shoulder widening to provide a recovery area for drivers to regain control in case of a roadway departure, especially on the inside of the curve,
- Shoulder paving to replace unstable or narrow shoulders, and
- Safety edge—technique that involves shaping and consolidating the pavement edge into a 300 wedge (figure 5.30). The edge allows for controlled recovery of drivers after straying and also reduces the tendency of the pavement to separate or crumble, thereby improving the durability of the edge.

Rumble strips/stripes may also be installed to warn fatigued, distracted, and inattentive drivers when leaving their travel lane by either milling/cutting grooves or placing ribs/bumps on the road. These can be placed on the shoulders near the edge of the travel

Examples of rumble strips/stripes

Figure 5.31: Shoulder rumble strips.

Source: FHWA, 2015. Rumble strip implementation fact sheet: pavement. Accessed at https://safety.fhwa.dot.gov/roadway_dept/pavement/rumble_strips/media/RumbleStripFactSheet_Pavement/pavement_fs.cfm. September 14, 2021.

Figure 5.32: Edge line rumble stripes by adding ribs.

Source: iRAP.

Figure 5.33: Edge line rumble stripes by milling of road.

Source: FHWA, 2015.

Figure 5.34: Centerline rumble stripes by milling of road.

Source: FHWA, 2015. Rumble strip implementation guide: addressing pavement issues on two-lane roads. Accessed at https://safety.fhwa.dot.gov/roadway_dept/pavement/rumble_strips/media/RumbleStripGuide_Pavement/pavement_bpg.cfm. September 14, 2021.

Figure 5.35: Concrete barrier on curve section with chevron alignment signs.

Source: iRAP.

Figure 5.36: Semi-rigid barrier on horizontal curve in Nepal.

Source: GRSF.

Figure 5.37: Cable barrier on tangent section.

Source: iRAP.

lane (figure 5.31), at the edge of the travel lane in line with the edge line marking (figures 5.32 and 5.33), or at/near the centerline of an undivided highway (figure 5.34). They can be created by milling grooves in the road surface or the addition of intermittent raised edge line markings.

- Roadside improvements (see section 5.7, Roadsides).
- Provision of barriers. Barrier types may include concrete barriers (figure 5.35), guardrails (figure 5.36), and cable barriers (figure 5.37) (see section 5.8, Barriers).
- Provision of clear zones. Clear zones i.e., unobstructed and traversable areas beyond the edge of the through travelled way are useful for providing sight distance along curves and recovery areas for errant vehicles. Fixed objects such as poles or trees should not be located in the clear zone, especially within the vicinity of horizontal curves (also see section 5.7).

- Slope flattening. Flattening the slopes on the outside of curves may provide significant benefits by allowing recovery of a vehicle that leaves the travelled way and traverses over the shoulder. As a cost-saving measure, excavated material from other locations can be used to flatten slopes. For critical slopes and depending on the height of the slope, barriers should be installed.
- Delineation on barriers. Delineating barriers is particularly useful during nighttime, as it not only gives the indication that the barrier is present but also provides information about the alignment conditions of the roadway.

Further Reading

- AASHTO. 2010. Highway Safety Manual. Must read part B, Roadway Safety Management Process.
- AASHTO. 2015. Roadside Design Guide. https://downloads.transportation.org/RSDG-4-Errata.pdf.
- Australian Road Safety Engineering Toolkit. https://engtoolkit.com.au/default.asp?p=issue&i=15.
- European Commission. Getting Initial Safety Design Principles Right. https://ec.europa.eu/transport/road_safety/specialist/knowledge/road/getting_initial_safety_design_principles_right_en. Must read.
- FHWA. 2016. Low Cost Treatments for Horizontal Curves. Must read chapter 3, Marking, chapter 5, Pavement countermeasures, and chapter 6, Roadside improvement.
- FHWA. 2009. Manual on Uniform Traffic Control Devices (MUTCD). http://mutcd.fhwa.dot.gov/pdfs/2009/part3.pdf. Must read part 3, Marking.
- iRAP Toolkit. http://toolkit.irap.org/default.asp?page=treatment&id=23.
- PIARC. 2008. Human Factors Guidelines for Safer Road Infrastructure. https://www.piarc.org/en/order-library/6159-en-Human%20factors%20guidelines%20for%20safer%20road%20infrastructure.
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- Transport Research Laboratory. 2001. Combination of Horizontal and Vertical Curvature. http://www.rhd.gov.bd/Documents/ExternalPublications/Trl/Combination%20of%20horizontal-vertical%20curves%20DFS.pdf.

5.4. Superelevation and Cross Slope (also referred to as "camber" or "crossfall")

General description

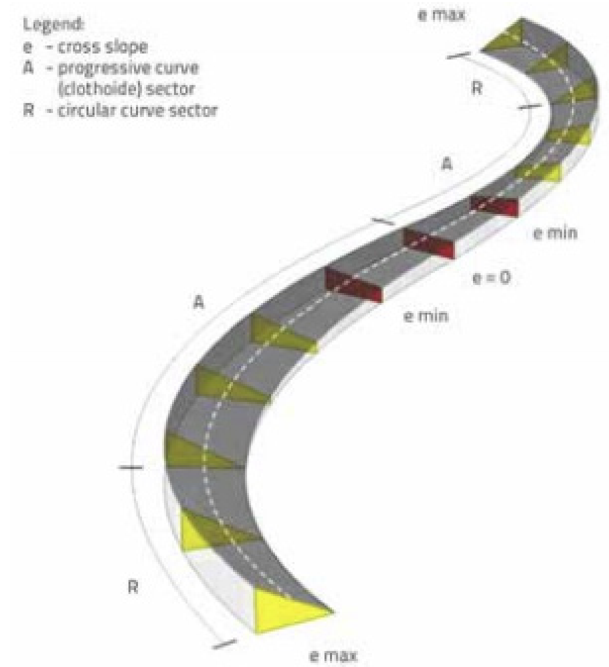
On straight sections of road, the surface is often crowned in the middle so that drivers are naturally moved away from opposing traffic. The amount of crowning is normally between 2 and 3 percent, and its value is primarily influenced by the ability of the surface to shed water.

On horizontal curves, superelevation is the transverse slope provided perpendicular to the direction of travel to counteract the centrifugal force generated by the speed in a circular motion. It is applied by raising the outer edge of the pavement with respect to the inner edge throughout the length of the horizontal curve (figure 5.38). It is usually applied over the length

Figure 5.38: Example of introduced superelevation on curve

Source: TRL Limited. 2003. CaSE Highway Design Note 2, Horizontal Curves.

Figure 5.39: Representation of two consecutive opposite transition curves



Source: Alina Burlacu, Carmen Răcănel, and Adrian Burlacu. 2018. Preventing aquaplaning phenomenon through technical solutions. Građevinar 12/2018.

of a circular curve to reduce the sideways frictional demand between the tires and road surface and to increase comfort. The superelevation value is usually selected by road designers to be consistent with the combination of design speed, curve radius, and the road authority's policy for maximum superelevation. A transition curve, inserted between the tangent and circular curve, may be used to remove the adverse cross-slope (adverse camber) created by the road crown and introduce superelevation (figure 5.39).

On urban roads, values of maximum superelevation are usually 4 or 6 percent. This is because it is desirable that the cross section of urban streets be as close as possible to the natural ground level to support ready access to adjacent properties to the road. It also facilitates drainage of surrounding properties. In addition, high values of superelevation in urban areas would require distances of 100 m or more in the development of superelevation, which closely spaced intersections would make difficult to achieve.

On rural roads, superelevation rates are normally in the range of 6 to 10 percent, with a maximum of 12 percent, owing partly to problems in construction and also the stability of heavy vehicles, in particular those with a high center of gravity. This is particularly relevant on steep uphill grades where trucks cannot generate sufficient centrifugal force to counteract the superelevation, thereby creating an imbalance. When icy conditions are present, the maximum superelevation is typically limited to 8 percent.

For gravel roads, a commonly accepted maximum superelevation is approximately 6 percent. When higher than that, it can be dangerous, especially where snow and ice can make roadways slippery. A higher superelevation also tends to cause aggregate to migrate to the bottom of the slope, or the inside of the curve. For more details, design references listed below or design codes of reference from countries should be referred.

Safety implication

- If a road is not superelevated, the centrifugal force tends to push the vehicle toward the outside of the curve. At high speeds, the driving task will be uncomfortable and more demanding. As a result, vehicles may become less stable, lose traction, and skid due to insufficient frictional force between the tire and the road to counterbalance the centrifugal force, or topple sideways if the center of gravity is high. Vehicles on the outside of curves are more likely to experience run-off-the-road crashes resulting in collisions with road users or objects on the outside shoulders, or rolling over.
- The lack of superelevation also encourages drivers to use the center of the road or the inside lane irrespective of the direction of travel, which increases the probability of head-on collisions, especially on two-way, two-lane roadways.
- Since superelevation also assists with the drainage of water, too low superelevation is more susceptible to surface defects that may result in standing water on the carriageway, which increases the risk of loss of pavement friction. The film of water developed during and after rainfall increases the risk of hydroplaning/aquaplaning. Standing water may also result in pavement damage and loss of shape in the long term, which presents an additional safety hazard. A curve with a worn or polished pavement surface that provides little skidding resistance presents increased crash likelihood, particularly in wet conditions.
- Change in superelevation, also known as roll over, from one side of the road to the other or between straights and curves, inevitably creates areas of road surface without any camber or crossfall. It is important that these areas do not coincide with very shallow longitudinal gradients, or the water will simply collect and ponds will form.
- Inadequate superelevation poses greater safety risks to motorcyclists given their lower vehicle stability, i.e., only two points of contact with the road. In the absence of superelevation, motorcyclists rely completely on the tire grip to remain on the road.
- Too high superelevation will result in the possibility of slow-moving vehicles sliding sideways or, in extreme cases, overturning. It has been observed that a 12 percent superelevation can cause trucks with high loads to lose their loads or tip over completely when trying to negotiate a curve at a low speed.[66]

Good design practice/ treatments/solutions

- Where the radius of a curve is less than the specified minimum for each design speed, the introduction of superelevation and curve widening will minimize the intrusion of vehicles onto the adjacent lanes and encourage uniformity of speed, thus increasing vehicle safety at the curves. This consistency is achieved by using minimum acceptable side friction factors between the tires of a vehicle at the design speed and the road surface. Acceptable friction factors vary from 0.15 for 100 km/h to 0.33 for 50 km/h.
- The relationship between side friction demand and speed is not linear, and the relevant guidelines should be consulted for the appropriate values and locally adjusted equations.[67], [68], [69]
- By designing to a side friction demand of 50–60 percent of the maximum, a safety factor is built into the process that allows for a margin of error in a driver's choice of negotiation speed. This means

66 Wolhuter, K. M. 2015. Geometric design of roads handbook. CRC Press.

67 Austroads. 2009. Guide to Road Design Part 3: Geometric Design.

68 AASHTO. 2018. Policy on geometric design of highways and streets (chapter 3). American Association of State Highway and Transportation Officials, Washington, DC.

69 New Zealand Transport Agency. 2000. State Highway Geometric Design Manual (chapters 2 and 4).

that a driver travelling faster than intended around a curve will feel increasingly uncomfortable well before the side friction demand exceeds that available and they lose traction. This discomfort triggers the driver's natural response to ease off the accelerator.

- On major roads with a superelevation deficiency, it is desirable to reconstruct the outer lane around the curves to provide superelevation that suits the operating speeds. It has been reported that improving superelevation may reduce the number of crashes by 5 to 10 percent.[70] It is also important to ensure that there is smooth transition between the crowned and superelevated cross sections on each end of the curve.
- Drainage conditions should be checked to ensure that combinations of slopes along and across the road are adequate to remove water from potential flat areas that can lead to standing water and potential risk of aquaplaning. Technical solutions, including transverse road gutters, diagonal slopes, and surface grooving may be applied to prevent aquaplaning for consecutive opposed curves where the vertical alignment is not helping with the drainage of pluvial waters from the carriageway.[71] The design of curves should be checked for consistency, with the selected value of maximum superelevation applied consistently on a regional basis. This will ensure that there are no variations in the rates of superelevation for curves of equal radius. It is widely accepted that drivers select their approach speeds to curves on the basis of the radius that they see and not on the degree of superelevation provided. For this reason, a lack of consistency with regard to superelevation would almost certainly lead to differences in side friction demand with possible critical consequences.
- By applying superelevation relative to the maximum value, the driver will experience a consistent level of comfort when travelling round a superelevated curve.
- If a superelevation deficiency cannot be reasonably or readily addressed, other safety measures may be considered, including:
  - Advance warning signs to warn drivers of a tight curve ahead and an indication of the reduced speed required to safely negotiate the curve,
  - Road markings, signs, and posts to draw the driver's attention to the curve,
  - Provision of shoulder and hazard free areas to provide a safe recovery area.
  - Improving the surface friction of the outside lane, and
  - Erecting safety barriers or designing clear zones around the outside of the curve (see section 5.8).
- Curves on residential streets and built-up areas are often constructed without superelevation due to the assumption of lower operation speeds. In such areas, speed management and traffic calming rather than road surface shape, is usually a more appropriate solution to reduce the additional risks created by vehicles travelling at high speeds.
- Rainfall after a long dry spell reduces side friction, especially in areas where the surface is polluted by oil spills, rubber, and other debris. Where any of these circumstances are likely to occur, a lower value of maximum superelevation is recommended in design.

Further Reading

- AASHTO. 2018. Policy on geometric design of highways and streets (chapter 3). American Association of State Highway and Transportation Officials, Washington, DC.
- Austroads. 2009. Guide to Road Design Part 3: Geometric Design.

70 Zegeer, C. V., and Council, F. M. 1995. Safety relationships associated with cross-sectional roadway elements, Transportation Research Record Issue: 1512.

71 Alina Burlacu, Carmen Răcănel, and Adrian Burlacu. 2018. Preventing aquaplaning phenomenon through technical solutions. Građevinar 12/2018. Accessed at http://casopis-gradjevinar.hr/assets/Uploads/JCE-70-2018-12-4-1578-EN.pdf.

- Aram, A. 2010. Effective safety factors on horizontal curves of two-lane highways. Journal of Applied Sciences (Faisalabad), 10(22), 2814–2822.
- Alina Burlacu, Carmen Răcănel, and Adrian Burlacu. 2018. Preventing aquaplaning phenomenon through technical solutions. Građevinar 12/2018. Accessed at http://casopis-gradjevinar.hr/assets/Uploads/JCE-70-2018-12-4-1578-EN.pdf.
- New Zealand Transport Agency. 2000. State Highway Geometric Design Manual (chapters 2 and 4).
- TRL Limited. 2003. CaSE Highway Design Note 2, Horizontal Curves. Accessed at https://www.gov.uk/research-for-development-outputs/case-note-2-horizontal-curves.

5.5. Vertical Curvature and Gradient

General description

Vertical alignment involves the road grade (the rate of change of vertical elevation) and vertical curves (i.e., crests and sags). Its design is a derivative of the interaction between sight distance criteria, the topography of the roadway, and the designer's need to meet ancillary goals (e.g., balancing excavation and fill quantities) as important safety factors of roads.

Figure 5.40: Reduction in sight distance at a crest vertical curve.

Source: Federal Highway Administration. 2007. Mitigation Strategies for Design Exceptions, US. https://safety.fhwa.dot.gov/geometric/pubs/mitigationstrategies/.

Most passenger cars can readily negotiate grades as steep as 4 to 5 percent without an appreciable loss in speed below that normally maintained on level roads.

On steeper upgrades, speeds decrease progressively with increases in the grade. Specifically, speed differentials between passenger cars and heavy vehicles should be considered when conducting a safety analysis. On downgrades, passenger car speeds generally are slightly higher than on level sections, and there are increases in braking distances, but local conditions govern.[72]

The severity or sharpness of vertical curves is usually referred to in terms of a radius (circular arc) or "K-value" (parabola). The Austroads Guide to Road Design Part 3 (2016)[73] provides comprehensive information on the design and calculation of vertical profiles (alignments) using parabolic curves.

For the combination of horizontal and vertical alignment, see section 5.3 on Horizontal curvature.

Safety implications

- Vertical alignment influences a driver's sight distance (figures 5.40 through 5.42). Crest vertical curves may limit sight distance by restricting a driver's line of sight. The crash frequency on crest

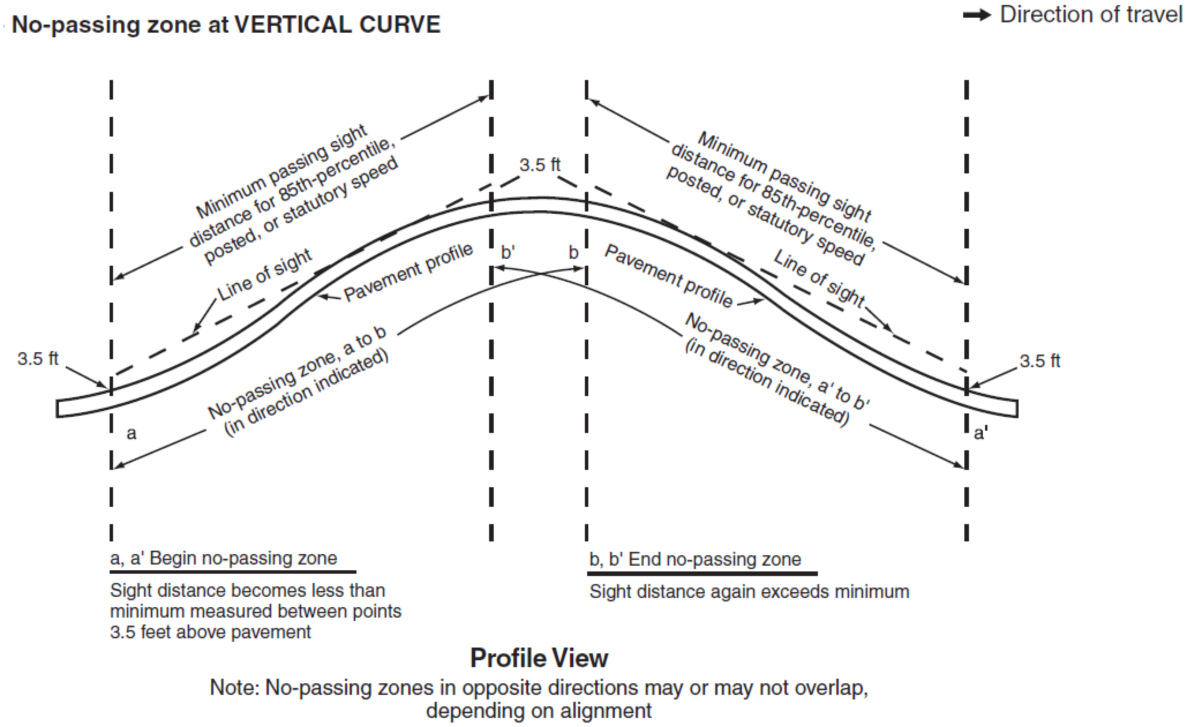
Figure 5.41: Reduction in sight distance at a sag vertical curve.

Source: FHWA, 2007.

72 AASHTO. 2018. A Policy on Geometric Design of Highways and Streets, 7th edition.

73 Austroads. 2016. Guide to Road Design Part 3: Geometric Design, section 8, and Appendix K.

Figure 5.42: Effect of crest vertical curves on sight distance.



Source: Federal Highway Administration. 2012. Manual on Uniform Traffic Control Device 2009 edition with Revision Numbers 1 and 2 incorporated, dated May 2012, US.

curves with reduced sight distance is 52 percent higher than on curves with no reduction in sight distance[74] (see section 3.3 on Sight distance).

- Overtaking will be of higher risk at this location without auxiliary lanes (i.e., climbing or overtaking lane), especially on rural roads.
- Steep gradients may increase the vehicle's speed by up to 5 percent; therefore large vehicle drivers may choose to descend grades at slower speeds to maintain better control of their vehicles.
- Long, steep downgrades may result in loss of control of vehicles, especially if present before horizontal curvature to perform sudden corrective actions. The higher the grade rate is, the higher the crash risk is. The crash risk rises more rapidly for grades over 6 percent as vehicle speeds become more difficult to manage.[75]
- Increases in braking distances and the possibility of heavy vehicle brake overheating should be concerning because this can lead to brake failure.
- Crash frequency and severity are higher on downhill grades than on uphill grades, with a high involvement of heavy vehicles.
- Other types of vehicles such as compact cars and recreational vehicles may have different speed loss and movements on vertical alignments.

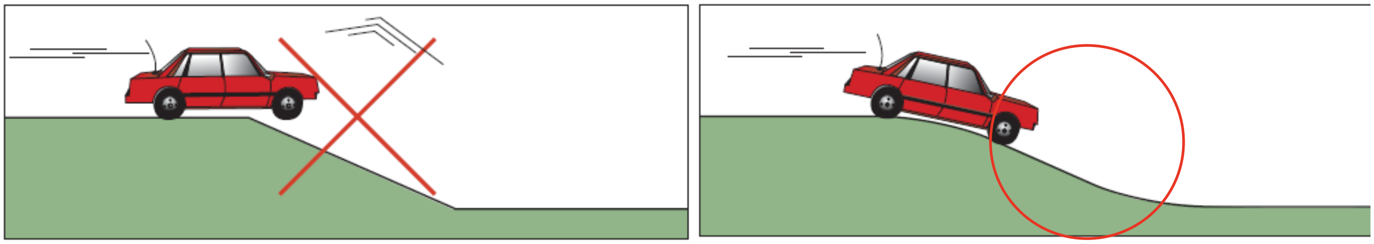
Good design practice/ treatments/solutions

- On grades, the designer must avoid a combination of features that increase the probability of having to carry out difficult maneuvers, including intersections or other crossings (railway, crosswalk, bike

74 Olson, P. L., Cleveland, D. E., Fancher, P. S., Kostyniuk, L. P., and Schneider, L.W. 1984. Parameters affecting stopping sight distance, NCHRP Report 270, Transportation Research Board.

75 Federal Highway Administration. 2000. Prediction of the expected safety performance of rural two-lane highways, US. FHWA-RD-99-207.

Figure 5.43: Smoothing of slopes.

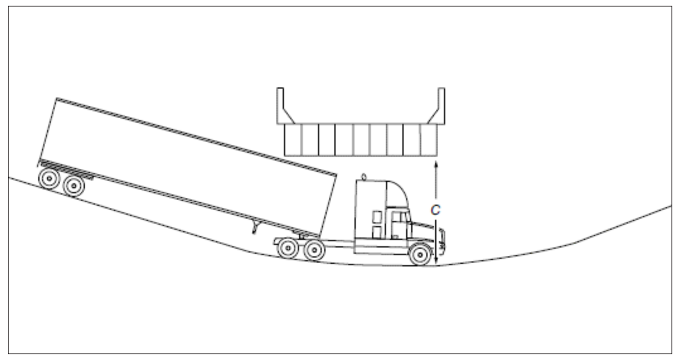


Source: PIARC, 2003.

Figure 5.44: Escape ramp (under construction) in China.

Source: © John Barrell.

Figure 5.45: Vertical clearance at undercrossings.



Source: AASHTO, 2018. A Policy on Geometric Design of Highways and Streets, 7th edition.

path, etc.), sharp horizontal curves, narrow structures, and no provision of protection.

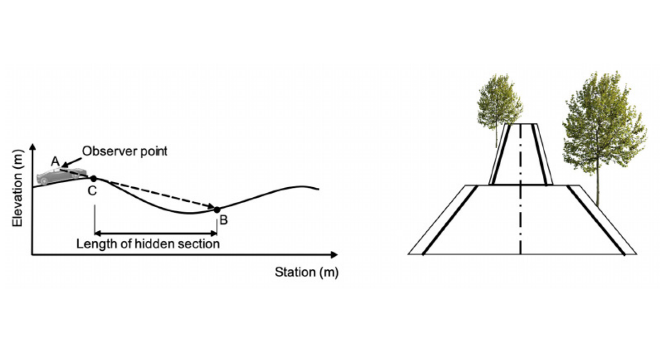
- Overtaking must be prohibited to avoid head-on collisions, preferably by physical separation between the opposite direction of travel.
- Steep side slopes should be avoided. The maximum gradient that can be travelled by errant vehicles is in the order of 1:3 to 1:4. Ideally, in order to accommodate larger and high center of gravity vehicles, such slopes should be in the region of 1:6 to 1:106. The angle between shoulder/slope and slope/adjacent land should also be smoothed in surface level[76] (figure 5.43).
- At descending steep slopes, a short passing lane, auxiliary, or "slow vehicle turn-out" can be provided. If not provided, operations may be degraded for faster-moving vehicles from behind, creating an increased risk of rear-end crashes and risky passing maneuvers.
- Increasing the superelevation on horizontal curves that coincide with steep down gradients improves heavy vehicle stability when braking.[77]
- Increasing radii at the bottom of steep downgrades is advisable, as these curves are often misread by drivers, and the visual distortion leads to "overdriving."[78]
- At descending steep slopes, the provision of escape or runaway ramps for brake failure should be provided (figure 5.44).
- Sag vertical curves at underpasses should be designed to provide vertical clearance for the largest legal vehicle that could use the undercrossing without a permit. A tractor trailer will need a longer sag vertical curve than a single-unit truck to avoid the trailer striking the overhead structure (see figure 5.45).

76 PIARC. 2003. Road Safety Manual, First edition.

77 Austroads Guide to Road Design. 2016. Part 3 section 7.6.1.

78 Austroads Guide to Road Design. 2016. Part 3 section 7.6.1.

Figure 5.46: Hidden sight dip: Left—road vertical profile; Right—road frontal 3D view.

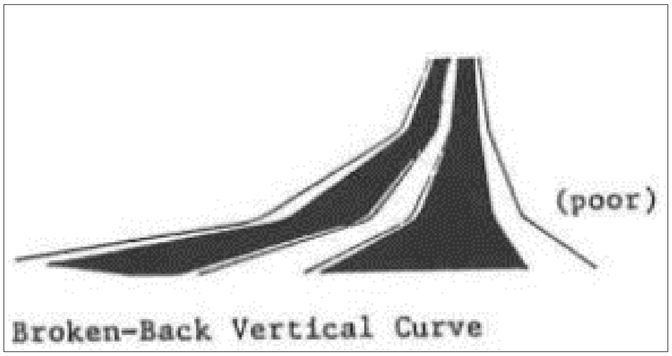


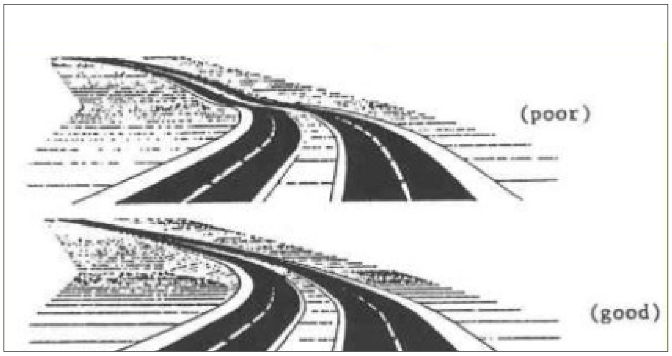
Source: González-G. and Castro, 2019.

- Grade rate of change is critical for sag curves where gravitational and vertical forces act in opposite directions. The hidden dip (roller coaster) type of profile should be avoided. Such profiles may occur on relatively straight, horizontal alignment where the roadway profile closely follows a rolling natural ground level. Hidden dips may create difficulties for drivers, because the passing driver may be deceived if the view of the road or street beyond the dip is free of opposing vehicles, even with shallow dips.[79] (see figure 5.46).
- A "broken-back" gradeline (two vertical curves in the same direction separated by a short section of tangent grade) generally should be avoided. This effect is particularly noticeable on divided roadways with open median sections (see figure 5.47).
- A minimum grade of 0.5 percent (0.3 percent for outer roadway edges) is needed for proper drainage on sag vertical curves to avoid mishandling related to ponding. However, it may be necessary to use flatter grades in some instances[80] (see section 5.11 on Drainage).

Markings and signs, roadside improvements, and terrain modifications could be treatments for vertical alignments.

Figure 5.47: Effect of broken-back vertical curves





Source: Bob L. Smith, and Ruediger Lamm. 1994. Coordination of Horizontal and Vertical Alignment with Regard to Highway Esthetics.

Marking and signs

Safety is unlikely to be affected by limited stopping sight distance, but improving limited sight distance at locations where other vehicles may be slowing or stopping can be extremely important for safety.[81]

- Other improvements that can be made are to remove objects that are within the sight limited area as well as increase crash avoidance areas through lane widening or shoulder widening.
- An entering vehicle's speed must be controlled. On vertical curves, the maximum designed speed differs from flat roads because of differences in sight distance affected by combinations of other features, including horizontal curvature, lane width, and so forth. Speed control for vehicles transitioning between a flat road and a vertical curve must be implemented.

79 González-G., Iglesias, and Rodríguez S. Castro. 2019. Framework for 3D Point Cloud Modelling Aimed at Road Sight Distance Estimations, Remote Sensing, 11. 2730. 10.3390/rs11232730.

80 Federal Highway Administration. 2007. Mitigation Strategies for Design Exceptions (archived), US.

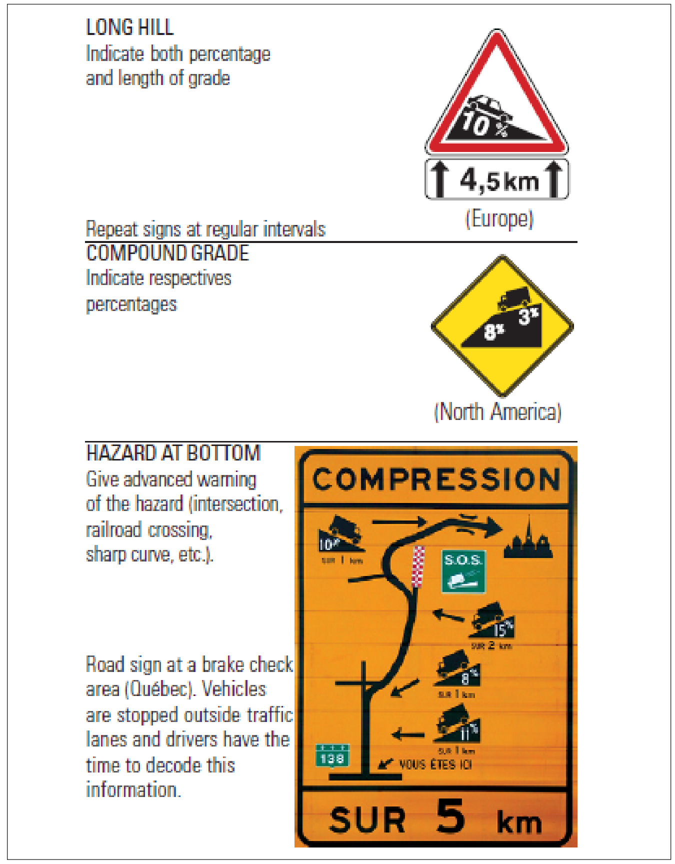
81 PIARC. 2019. Road Safety Manual. Accessed at https://roadsafety.piarc.org/en.

Figure 5.48: A steep grade warning sign along a road that appears to drop off in the distance.

Source: FHWA, 2007

- Signs can be used to provide drivers approaching a steep grade with advance warning (figures 5.48 and 5.49). Signs help drivers to adjust their behavior to deal with approaching hazards or decision points. Use of advance warning signs as a stand-alone measure is unlikely to sufficiently mitigate a design exception for grade, but it can be an effective component of a more comprehensive approach.
- Poorly designed/maintained/located signs must be re-installed. The retroreflectivity of signs is an important consideration for road use at night and when wet. Maintenance of signs can be problematic; signs may be stolen and broken in some areas (figure 5.50).
- Only placing warning signs may not attract drivers' attention. In that case, physical features (e.g., flexible, bollards) can be used to prevent crashes by prohibiting overtaking and downing the vehicle's speed.
- For increasing braking distance at downgrade, signs can indicate a lower speed and that a lower gear is required.

Figure 5.49: Examples of advance warning of a steep grade



Source: FHWA, 2007.

Figure 5.50: Broken signs without maintenance in India.

Source: Lokesh, T., Thejarathnam, T., Reddysaddam, P. et al. 2014. Road Safety Audit—Section Bhakarapet KM 77/4—Rangampet KM 93/6, India. https://www.slideshare.net/lokeshthondamanati/batch-3.

Roadside improvements—barriers

- When locations have poor visibility, steep slopes, level difference, and a slower vehicle speed is likely, overtaking should be prohibited.
- Flexible posts can be applied at locations where lane discipline needs to be ensured, such as curves and intersections (figures 5.51 and 5.52).
- Flexible posts also contribute to improve visibility of the median of the road because of level differences. Treatment for visibility must be made, even though other vertical treatments will be costly.
- Furthermore, flexible posts can also be applied where there is a requirement for lane discipline along with traffic calming.
- Flexible posts are a quick and easy solution but can result in a high maintenance cost if repeatedly struck and require replacement. In these circumstances more robust and substantial treatment may be more appropriate (barrier or concrete median).
- On a downgrade where there is a significant drop in speed limit, speed control treatments can be used. Speed control treatments include a combination of prominent signs, road markings, and traffic calming measures, e.g., raised platforms or colored pavements to make the change in road type clear (see section 3.2 on Speed compliance and traffic calming).

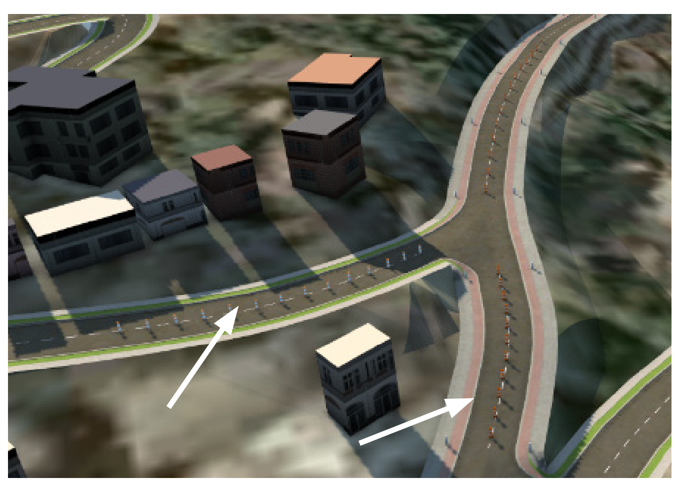
Terrain modifications

- Modifying a vertical alignment is often too costly and can have significant impacts to adjacent land uses. It is much better to design the road well before it is built than to rebuild it. The reconstruction of a crest vertical curve should be implemented when the hill crest hides major hazards from view, such as intersections, sharp horizontal curves, or narrow bridges (see figure 5.53).
- "Roller coaster" or "hidden dip" type of profiles should be avoided by use of horizontal curves or by more gradual grades.
- Road widening (either as wider shoulders or an overtaking lane) over a crest with less than adequate sight distance can be an effective countermeasure rather than flattening the crest. Long and steep downgrades can result in heavy vehicles travelling at crawl speeds to avoid loss of control on the grade. Slow-moving vehicles of this type may impede other vehicles. Auxiliary lanes can be provided to address this risk. They can be constructed on uphill and downhill grades to enable safe

Figure 5.51: Illustration on provision of flexible posts at curves with limited sight distance.

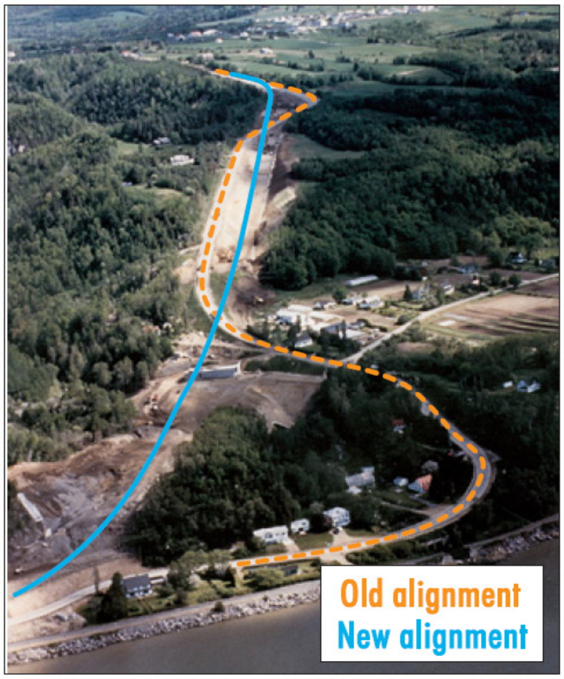
Source: © Kazuyuki Neki/GRSF/World Bank

Figure 5.52: Flexible posts improving visibility of median at intersection.



Source: © Kazuyuki Neki/GRSF/World Bank

Figure 5.53: Alignment modification to eliminate a sharp curve at the bottom of a steep grade.



Source: PIARC, 2003.

passing maneuvers by slower vehicles and reduce crashes by 5 percent to 15 percent. (see section 5.6 on Passing lanes). Since auxiliary lanes encourage passing maneuvers at relatively high speeds that are incompatible with the slower speeds of vehicles accessing and exiting the road, they should not be located in conjunction with intersections or other access points.

- Since safety problems in grades primarily involve heavy vehicles, solutions aimed at limiting their presence at high-risk locations may also be considered, when permitted by the configuration of the road network (dedicated heavy vehicle roads).

Further Reading

- FHWA. 2009. The Manual on Uniform Traffic Control Devices. Must read chapter 2, Signs and chapter 3, Markings.
- FHWA. 2007. Mitigation Strategies for Design Exceptions (archived). Must read chapter 3, Controlling criteria.
- PIARC. 2019. *Road Safety Manual*. Accessed at https://roadsafety.piarc.org/en.
- FHWA. 2003. Geometric Design Consistency on High-Speed Rural Two-Lane Roadways (NCHRP 502). Must read Interpretation, appraisal, and applications.
- AASHTO. 2018. A Policy on Geometric Design of Highways and Streets, 7th edition. Must read chapter 3, Elements of design.
- FHWA. 2016. Highway Capacity Manual: A Guide for Multimodal Mobility Analysis, Sixth edition. Must read chapter 16, Urban street facilities.
- PIARC. 2003. *Road Safety Manual*, First edition. Must read chapter 8, Design for road users, characteristics, and compliance.

5.6. Passing Lanes

General description

A passing/overtaking lane is an additional lane provided on a conventional single-lane, two-way road to provide safe passing/overtaking opportunities and improve the overall traffic operations by breaking up traffic platoons and delays (figure 5.54).

Figure 5.54: Example of a passing lane.

Source: iRAP.

Passing lanes reduce the risk of head-on crashes, lane change/sideswipe crashes, and run-off-the-road crashes that result from unsafe passing due to insufficient passing opportunities. Inadequate passing opportunities on two-lane, two-way highways may be due to the combined effect of high traffic volumes with a high percentage of trucks or slow-moving vehicles, including agricultural machinery, animal-drawn carts, and animals in both directions, and sight distance restrictions. Queues and frustration may encourage drivers to undertake dangerous passing maneuvers such as in short gaps between opposing traffic or on a road section with inadequate sight distance that may result in a crash. On steep sections, drivers may not judge the time and distance required to overtake correctly due to the changed acceleration of vehicles. Constructing a passing lane thus serves to provide a safe overtaking space while also improving the general traffic flow along the roadway.

Various types of passing lanes exist, including passing/overtaking lanes in level or rolling terrain, climbing lanes, descending lanes, and slow-vehicle lanes (turn-outs). Overtaking lanes are generally installed only on high-speed rural arterial roads. Climbing lanes are provided on steep upgrades to reduce driver delay and frustration and improve safety. Descending lanes are provided for similar reasons as climbing lanes but on steep downgrades (since heavy vehicles are limited to slower speeds even on descent). Slow-vehicle turn-outs are short overtaking lanes (can be a short section of paved shoulder or an added lane) that allow slow vehicles to pull over and be overtaken. Slow-vehicle turn-outs are more appropriate in areas with low traffic volumes or where construction costs would be high, such as hilly or mountainous terrain.

Passing lanes are best arranged in pairs with a passing lane section for each direction of travel. As such, designers can choose from a variety of configurations, including separated passing lanes, adjoining passing lanes, overlapping passing lanes, and side-by-side/short four-lane sections. The choice of the configuration and the location of the added lanes will depend on the particular local needs and constraints. The functional effectiveness of passing lanes will depend on the length of the passing section and the distance along a corridor between the passing sections.

Safety implications

Constructing passing lanes results in safer operational conditions, perceived safety by motorists, and historical crash reductions.[82] Studies indicate that injury crashes after a passing lane has been constructed are likely to be in the range of 20–40 percent less than if it had not been constructed. The extent to which the reduction in crashes applies, however, varies from being specific to the passing lane itself, the passing lane and its immediately adjacent road, or for an entire route.

However, if not well designed, constructed, and maintained, passing lanes may pose some safety risks. Some of these safety deficiencies and risks are outlined below:

- Limited sight distance at the start and end points of passing lanes. This is particularly hazardous on merging sections implemented along or near horizontal or vertical curves with limited sight distance to drivers along the passing lane. This sight distance should be provided to the road markings so that drivers can see precisely where the lane and shoulder tapers, associated with the end of the passing lane, start and finish.
- Passing lanes located near towns, major intersections, or high-volume access roads may result in collisions from the high interaction of passing vehicles with turning movements and vulnerable road users. It should be noted that vehicle speeds are influenced for a significant distance after a passing lane, as overtaking drivers desire to distance themselves from the overtaken vehicle. As a result, the need for minor improvements to the downstream road corridor should be assessed.
- Passing lanes that have intersections within their length should be avoided if at all practicable.

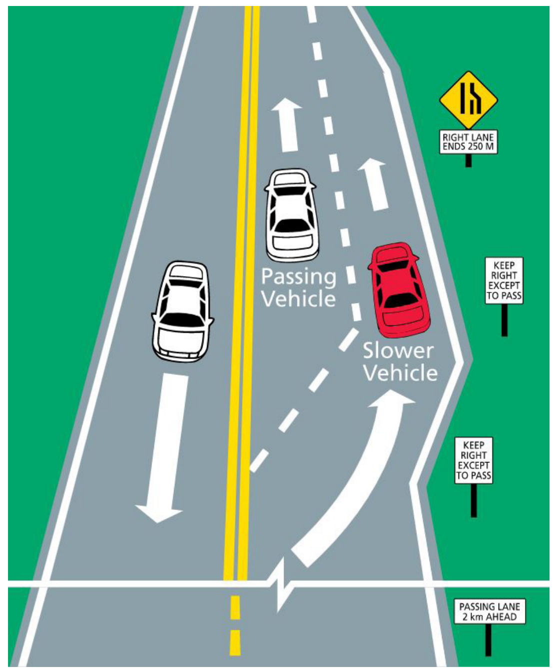
82 Espada, I., Stokes, C., Cairney, P., Truong, L., Bennett, P., Tziotis, M., and Tate, F. 2019. Passing Lanes: Safety and Performance (No. AP-R596-19).

- Narrow shoulder widths on passing sections. In many cases, the sealed shoulder width is reduced as part of the passing lane construction design, which can lower the safety benefit of three-lane passing sections. Narrower sealed shoulders are a safety risk as they may not provide an adequate space for vehicles to perform evasive maneuvers should it be necessary to avoid another vehicle.
- Inadequate signage and pavement markings. This adversely affects both the effectiveness and safety of the passing lane, as drivers are not sufficiently guided on the most appropriate action to take on the passing section, including the approaches and merges.

Good design practice/ treatments/solutions

- The design of passing lanes should be considered carefully with regard to the road designs and conditions at both ends. The passing lane location should provide adequate sight distance to the road markings at the lane addition and lane drop tapers. The length of the tapers should also be adequate in relation to the operating speeds.
- The location of passing lanes will depend on the particular local needs and constraints. However, there are sites where passing lanes should not be constructed, including sites close to towns and/or high-volume access roads and sites with major intersections. This is because collisions may result from the interaction of passing vehicles with high turning movements and vulnerable users in these areas. Locations with other physical constraints, such as bridges and culverts, should also be avoided if they restrict the provision of a continuous shoulder. Highway sections with low-speed curves are not appropriate for passing lanes since passing, which requires drivers to speed up, may be unsafe.
- Proper signing and pavement marking (see figures 5.55 and 5.56) are required to enhance the driver's understanding of the intended use of the passing section and inform them of upcoming opportunities to overtake, which results in increased efficiency and safety of the passing lane. For optimum signage, signs should be provided in the following six areas:
    - In advance of the passing lane;
    - The transition area of the lane addition of the passing lane;

Figure 5.55: Illustration of signing and markings in advance and along a passing section.



Source: Alberta. 2021. Passing on a multilane highway. https://www.alberta.ca/passing.aspx.

Figure 5.56: Example of markings on a climbing lane.

Source: Billy McCrorie/Geograph, PIARC, 2003.

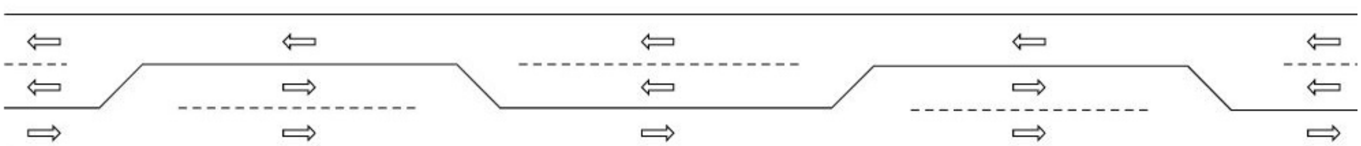
Figure 5.57: Example of advance signing of a climbing lane.

Source: Billy McCrorie/Geograph, PIARC, 2003.

- In advance of the termination of the passing lane;
- The transition of the lane reduction of the passing lane;
- The downstream area adjacent to the passing lane; and
- In the opposing direction of the passing lane.

- A strategy for advance signing of passing lanes is desirable to alert road users of upcoming passing opportunities (figure 5.57). This reduces unsafe overtaking prior to the passing lane, as motorists know that safer passing opportunities will be available shortly.
- On three-lane sections, vehicles travelling in the opposite direction to a passing lane should be discouraged from overtaking due to the high risk of a head-on collision. This information can be provided through longitudinal pavement markings or a combination of both signs and pavement markings. A site-by-site review is desirable to determine which passing lane sites are critical in the prohibition of passing by opposing traffic on the basis of limited sight distance, unusual geometrics, roadside development, and high-traffic volumes. The use of flexible posts along the centerline on these critical locations, in addition to the signs and pavement markings, may enhance the prohibition of passing by opposing traffic.
- 2 + 1 highways are a safety countermeasure for two-lane highways where a continuous three-lane cross section on which the central lane serves as a passing lane in alternate directions is provided throughout the length of the facility (see figure 5.58). Travel directions are separated by a median which could be physical (figure 5.59) or painted (figure 5.60). They are a cost-effective solution where a

Figure 5.58: Schematic view of 2+1 highway.



Source: Romana, M., Martin-Gasulla, M., and Moreno, A. T. 2018.

Figure 5.59: 2+1 highway with flexible barrier.

Source: Joel Torsson (Leojth). Own work, public domain. https://commons.wikimedia.org/w/index.php?curid=2096153.

Figure 5.60: 2+1 highway with painted median.

Source: © TrainSimFan.

two-lane road is not providing enough safety and/or traffic efficiency and the expansion to a four-lane roadway seems unjustified due to cost, demand, or environmental issues. Before implementing a 2+1 highway, unique design aspects linked to this configuration should be considered, including traffic volume; passing lane length; transition areas; cross section, intersection, and access design; and signing and markings.

Case Study

Based on recommendations provided from Road Safety Inspection reports and from the 2017 World Bank capacity review report,[83] a national company of motorways and roads launched several road safety pilot infrastructure upgrade programs on high-risk sectors of their national roads.

For example, on national highways built in Eastern Europe under the communism era, where shoulders were 2.5 meters wide. Those highways are currently used as four-lane roads, although the road width is 12.00 meters: 3.50-meter lane width in each direction and 2.50-meter shoulders/emergency lane, which is a very dangerous design solution. On one of the national highways in Romania, a pilot section was upgraded into 2+1 alternative lanes, following the positive fatality reduction experience from other neighboring countries who implemented such upgrades (see figure 5.61).

Further Reading

- Austroads. 2016. Guide to road design part 3, geometric design (No. AGRD03-16).
- Lindsay Schumaker, Mohamed M. Ahmed, and Khaled Ksaibati. 2016. Policy considerations for evaluating the safety effectiveness of passing lanes on rural two-lane highways with lower traffic volumes: Wyoming 59 case study, *Journal of Transportation Safety & Security*, 10.1080/19439962.2015.1055415. http://www.uwyo.edu/ahmed/papers/2016%20safety%20&%20security%20policy%20and%20safety%20considerations%20of%20adding%20passing%20lanes%20on%20rural%20two-way%20roadways.pdf.
- Potts, I. B., and Harwood, D. W. 2004. *Benefits and design/location criteria for passing lanes* (No. RDT 04-008).
- Wooldridge, M. D., Messer, C. J., Heard, B. D., Raghupathy, S., Parham, A. H., Brewer, M. A., and Lee, S. 2001. Design guidelines for passing lanes on two-lane roadways (super 2). Austin, Texas. https://journals.sagepub.com/doi/10.3141/2301-06.

Figure 5.61: Romanian National Road 2 (DN2) pilot road upgrade program in 2019.

Source: © World Bank.

83 Global Road Safety Facility (GRSF) and World Bank Group Transport. 2017. Romania, Road Safety Management Capacity Review—Improving Safety of Road Infrastructure. Washington, DC: World Bank.

5.7. Roadsides—Forgiving Roadsides and Clear Zones

General description

Forgiving roadsides[84]

The fundamental principle for designing safe roadsides is based on the knowledge that drivers (or riders) will make mistakes; occasionally they will lose control of their vehicles and leave the road. When this happens, a collision with unyielding objects such as trees or poles, or non-traversable features such as drains, steep side slopes, or rough surfaces, may result in the vehicle vaulting, rolling over, or coming to a sudden stop. This can lead to severe injuries or death for the occupants. Providing a forgiving roadside is intended to minimize the consequences of a vehicle leaving the roadway by providing a safe and forgiving area that is free of rigid objects, has flattened, smooth-sloped embankments and no other hazards, in which an errant vehicle can safely recover and stop. All aspects of the roadside should be designed to minimize the possibility of an occupant of an errant vehicle being seriously injured or killed.

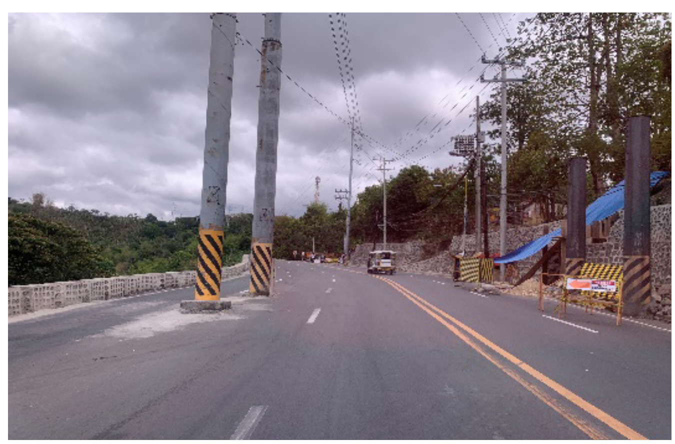
A roadside hazard is any feature or object beside the road that may adversely affect the safety of the roadside area should a vehicle leave the road at that point. Roadside hazards are generally categorized into point hazards and continuous hazards. Point hazards are individual hazards or roadside hazards of limited length. Examples of point hazards include trees (especially those over 100 mm diameter), bridge end posts, large planter tubs, monuments, landscape features, non-breakaway signposts (over 100 mm diameter), interchange supporting piers, driveway headwalls, culvert headwalls, rigid utility poles (more than 100 mm diameter), solid walls, and pedestrian overpass piers and/or stairs. Continuous hazards, on the other hand, are hazards that extend over a considerable length of the road. These include rows and forests of large trees, uncovered longitudinal drains, retaining walls, steep embankments, rock cuttings, cliffs, areas of water (such as lakes, streams, channels over 0.6 m deep), unshielded hazards (such as cliffs) within reach of an errant vehicle, concrete guideposts, curbs with a vertical face of more than 100 mm high on roads with operating speeds above 80 km/h, and fences with horizontal rails that can spear vehicles. The length of a continuous hazard increases the likelihood of an errant vehicle striking it, and some hazards (such as cliffs) have a high crash severity regardless of the speed of the errant vehicle. See figures 5.62 through 5.71 for examples of roadside hazards.

Examples of roadside hazards

Figure 5.62: Unforgiving ditch with hazardous headwall (right) on high-speed road.

Source: Soames Job/GRSF/World Bank.

Figure 5.63: Widened road but the poles not moved—Philippines.



Source: © Alina F. Burlacu/GRSF/World Bank.

84 Austroads. 2018. Research Report AP-R560-18-Towards Safe System Infrastructure: A Compendium of Current Knowledge.

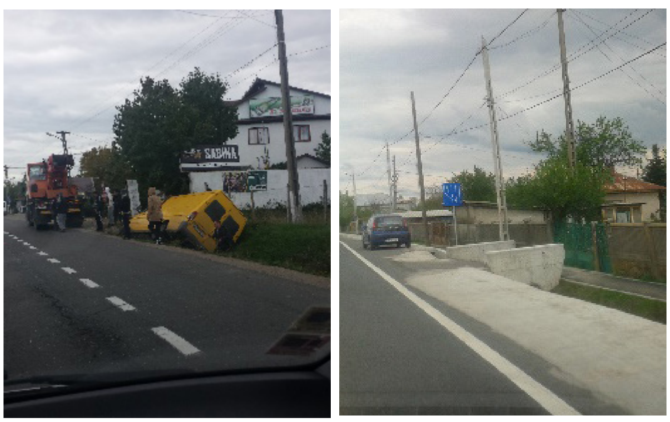
Figure 5.64: Concrete guideposts.

Source: Indian Institute of Technology. 2019. Report on Road Safety Audit of SH-11 during operation stage.

Figure 5.65: Trees (over 100 mm diameter) located too close to the carriageway.

Source: IIT, 2019.

Figure 5.66: Uncovered drain and unsafe culvert—Romania.



Source: © Alina F. Burlacu/GRSF/World Bank

Figure 5.67: Unshielded water body with steep embankment.

Source: Indian Institute of Technology. 2019. Report on Road Safety Audit of SH-11 during operation stage.

Figure 5.68: Unshielded overpass piers.

Source: CAREC, 2018.

Figure 5.69: Individual concrete blocks.

Source: CAREC, 2018.

Figure 5.70: Rigid mast on shoulder.

Source: IIT, 2019.

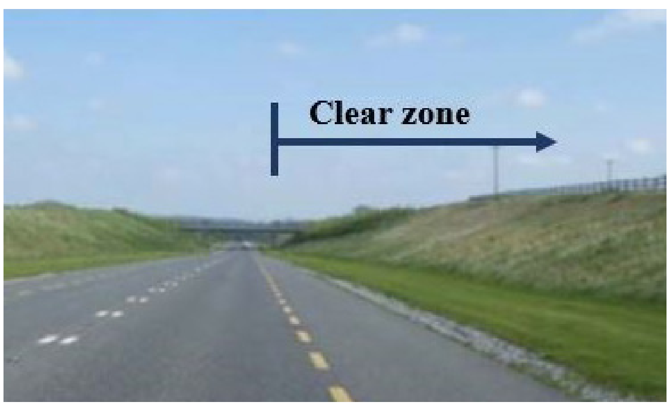
Figure 5.71: Stacked materials by the roadside. These are a particular hazard to two or three wheelers especially at night.

Source: IIT, 2019.

Clear zone

A clear zone is defined as the area beside a road (measured at right angles from the edge line or the edge of the nearest traffic lane) that needs to be kept free of fixed roadside hazards to give an opportunity for drivers of errant vehicles to recover (figure 5.72). The concept of a clear zone was developed to define an area which reflects the probability of a severe crash occurring at a site to allow engineers to design and provide a drivable roadside area clear of hazards. Calculation of the required clear zone widths takes into account the traffic volume, 85th percentile speed, curve radius, and roadside slope. The clear zone concept does not prevent run-off-the-road crashes, but it reduces their consequences. It also enables a risk management approach in the prioritization of treatments of roadside hazards at different locations. It is important to note that the clear zone figures are based on the recovery of 80–85 percent of errant vehicles, as the width required for the recovery of 100 percent of the vehicles is substantially wider and generally impracticable to achieve. Keeping this in mind, in certain situations it is more prudent to act in a way that includes the last 15–20 percent of the road vehicles that would theoretically travel beyond the normal clear zone. An example of such a situation would be in providing a barrier system when a major hazard (such as a high cliff) with certain severe consequences lies just outside the clear zone, to protect the last 15–20 percent of errant vehicles that would theoretically drive off beyond the clear zone. Given the cost of implementing and maintaining clear zones, guidance on the optimal width of clear zones differs between countries, and local guidance should be consulted. However, it is typical to find clear zones of around 9–10 m recommended on high-speed, high-volume roads, and 3–4 m for lower-speed, lower traffic environments.

Figure 5.72: Example of a clear zone.



Source: UNESCAP. 2017. Recommended Design Guidelines on Road Infrastructure Safety Facilities for the Asian Highway Network. https://www.unescap.org/resources/recommended-design-guidelines-road-infrastructure-safety-facilities-asian-highway-network.

Safety implications

- Several studies have revealed that run-off-the-road crashes are not only frequent, but are especially serious, resulting in more severe injuries and deaths than most other crash types. The main factors that influence run-off-the-road crash outcomes are the existence of vehicle recovery areas, roadside barriers, and the presence of infrangible objects. If a vehicle leaves the roadway but recovers on the shoulders or grassed verge, the outcome is likely to be no damage or minor damage. However, if an errant vehicle hits a rigid lighting column or a substantial tree at speed and comes to a sudden stop, the outcome is likely to be a severe injury or a fatality.

- The closer a roadside hazard is to the traffic lane and the higher the traffic speed, the higher the likelihood that the hazard will be struck by an errant vehicle. The presence of road curves adds to the overall likelihood of a run-off-the-road crash, as the driver needs to take more action to maintain the vehicle on the road. Ongoing traffic exposure to roadside hazards will increase the likelihood of crashes, i.e., higher traffic volumes increase the risk of a collision with the hazard over time. Rural roads have been shown to be more likely to produce severe consequences of run-off-the-road crashes due to generally high operating speeds and typically low levels of roadside modification, e.g., retaining original trees along the roadsides.
- Steep roadside slopes increase the risk of a rollover in case of a run-off-the-road crash, which generally has high severity. High speeds will add to the risk of high severity crashes. Slopes steeper than 1V:4H are deemed as nonrecoverable, i.e., a typical errant vehicle will travel to the base of the slope before being able to recover. The surface condition of the embankment also influences the recovery of an errant vehicle, with smooth firm slopes offering a better chance of recovery than soft, uneven slopes. High-volume roads with unshielded steep slopes tend to have a higher record of casualty crashes than roads with relatively flatter slopes or road safety barriers.
- Unprotected end posts of bridges are hazards due to their solid (rigid and infrangible) construction and proximity to the traffic. The narrower the bridge is, the higher the risk of a collision with an end post, as the hazard is closer to the traffic lane. Single lane bridges that can be approached at high speeds and have no active traffic control have a high risk of head-on crashes, crashes into the bridge end posts, and pedestrian/cyclist crashes. Bridges with narrow lane widths, especially two-lane bridges and bridges that lack pedestrian/cyclist separation, can lead to increased risk of sideswipes, head-on crashes, or large vehicles becoming wedged.
- Overgrown or poorly planned vegetation can be a serious hazard depending on its location with respect to the road. When located close to the carriageway, they can obscure signs, hazard markers, and roadside hazards like ditches. Roadside vegetation may also interfere with sight distances at intersections and on road curves, which increases the risk of intersection, run-off-the-road, and head-on crashes.
- Overhanging tree branches can also interfere with the driving task, especially for buses and trucks, causing drivers to swerve into adjacent lanes to avoid damage to the vehicle or load. In urban areas, low decorative shrubs can block the visibility of pedestrians (especially children) at road crossing points, while overhanging tree branches can block sightlines to traffic signal displays. Trees, however, provide benefits, including shade for pedestrians and reduced soil erosion on site, and those less than 100 mm diameter are less likely to contribute to the severity of a crash.
- On high-speed facilities, curbs may be a safety hazard as they could cause an errant vehicle at high speed to jump or roll over (see section 5.12).

Good Design practice/ treatments/solutions

- The safety of a roadside (or median) may be gauged by the width of the clear zone, which depends on operating speeds, traffic volumes, roadside slopes, and the road geometry. Wider clear zones are recommended near intersections or bends, where the complexity of the driving task and interaction with other vehicles adds to the likelihood of run-off-the-road crashes. It should be noted that the clear zone widths are not a guarantee of safety but a compromise, a way of managing roadside risks. Nonetheless, generous forgiving roadside widths should be provided where feasible.

- In addition, the longer an errant vehicle traverses the roadside area, even if this is an extended clear zone, the greater the likelihood that the vehicle will roll over.[85]
- Clear zones need to be of good quality and well maintained to maximize their safety benefit. Uneven surfaces or exposed tree roots can snag vehicles causing them to roll, and this often results in severe crash outcomes.
- Some countries are moving to the use of continuous safety barriers (see section 5.8 on barriers) as their preferred roadside treatment over clear zones, as there are indications that the safety performance is better than for that of clear zones. In more densely populated areas where land is at a premium, land requirements to install a safety barrier system are greatly reduced compared to a clear zone, as are maintenance costs associated with vegetation control required in providing a clear zone that is of adequate width, of good quality, and that is well maintained. It is important that countries put in place appropriate controls for the design, installation, and maintenance of continuous safety barrier systems if they are to be used in preference to clear zones.
- In contrast, where land is relatively inexpensive, readily available, and only sparsely vegetated, applying the clear zone principles may provide an acceptably safe outcome for the limited funding and roadside risk.
- Avoid locating any new hazardous objects within the clear zone when designing a new road. This can be achieved through the development of policies that restrict the placement of new potentially hazardous objects on the roadside.
- All existing fixed roadside objects that are 100 mm in diameter or larger should also be removed from the clear zone. In circumstances where it is not possible to completely remove a hazard from the clear zone, consideration should be made to relocate the hazard, preferably beyond the clear zone. Rigid poles, rigid lighting columns, and drains can be relocated to reduce the risk or replaced with frangible/passively safe columns (see below).
- The removal of trees, on the other hand, needs to be undertaken with consideration to the environment and community values. Large trees (more than 100 mm in diameter) that are close to the carriageway may be replaced with more appropriate plants to avoid soil erosion and regrowth affecting the site. Care should be taken not to leave large stumps and deep holes upon the removal of a tree, as these are also hazards. It is also important to trim and regularly maintain vegetation along the roadside.
- In locations where removing or relocating a hazard that is within the clear zone is not feasible or practicable due to economic or environmental constraints, altering or modifying the hazard can reduce the severity of a crash and the potential for serious injury. Common modifications of hazards include:

Figure 5.73: Traversable culvert end treatment for cross-drainage culverts. Allows vehicles that leave the roadway to drive over them without rolling or experiencing an abrupt change in speed.

Source: FHWA. 2009. Maintenance of drainage features for safety, a guide for local street and highway maintenance personnel.

85 Austroads. 2018. Research Report AP-R560-18-Towards Safe System Infrastructure: A Compendium of Current Knowledge.

Figure 5.74: Lightweight guidepost that is forgiving.

Source: CAREC, 2018.

Figure 5.75: Slip-base lighting column suitable for high-speed roads with little pedestrian activity and parking.

Source: CAREC, 2018.

Figure 5.76: Impact-absorbing lighting columns suitable for low-speed

Source: CAREC, 2018.

Figure 5.77: Shielded piers with rigid barriers. An appropriate end treatment (cushions/impact attenuators) should also be applied on barrier systems.

Source: CAREC, 2018.

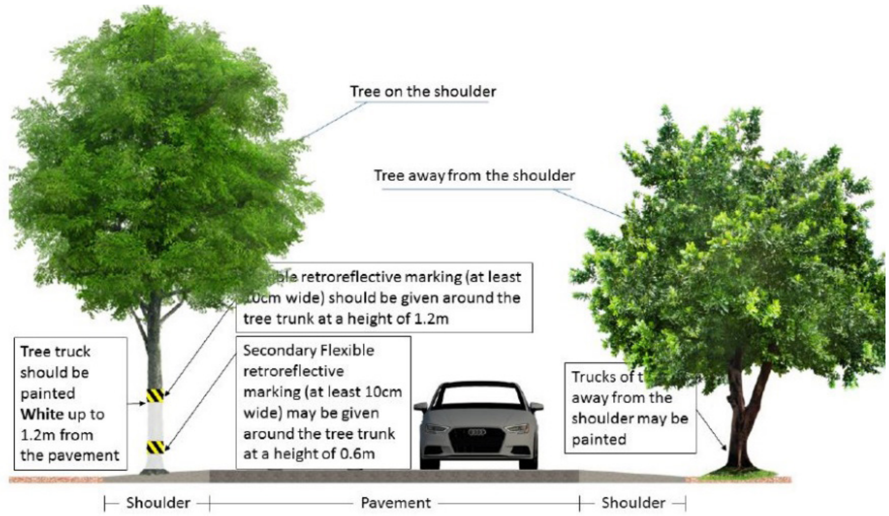
1. Modifying open longitudinal drains by piping them or covering them with a drivable cover;
2. Modifying end walls of driveway culverts to make them drivable (figure 5.73);
3. Redesigning rigid signposts and lighting columns to provide more forgiving frangible (breakaway) posts and lighting columns, i.e., impact absorbent or slip-base types (figures 5.74 through 5.76);

- Flattening a steep fill slope to make it drivable;
- Replacing bridge rails with safety barriers with appropriate end treatments; and
- Shielding bridge piers with rigid barriers (figure 5.77).
- In situations where the road reserve may be limited, it may not be practical to create a clear zone. Reducing the operating speeds instead may be a more appropriate solution. A safety barrier system may also be considered that in itself presents a (reduced) collision risk but needs the terminals appropriately treated to minimize risk.
- Good geometric design and the prudent use of road features can help to keep vehicles on the road and reduce the risk of a run-off-the-road crash. The geometric standard should be based on a realistic assessment of the likely operating speed of a road section considering the road function, the terrain through which the road exists, and the road environment. Some of the road design features that assist in keeping vehicles on the road include appropriate lane widths and shoulder widths, predictable horizontal and vertical alignment, sufficient sight distance, and a sound road surface with proper drainage.
- There are various low-cost treatments that reduce the risk of run-off-the-road crashes, including proper delineation, chevron alignment markers (CAMs), warning signs, provision of hazard markers before any roadside obstruction such as bridge parapet wall, provision of sealed shoulders and tactile edge lines, and wide centerline treatments. All these can be applied to help vehicles stay on the road.
- Delineation and signage are essential safety aspects of preventing run-off-the-road crashes, as they serve as visual guidance to drivers along a highway. Such information and guidance become

Figure 5.78: Roadside tree delineated but inconspicuous—Italy.

Source: © Alina F. Burlacu/GRSF/World Bank.

Figure 5.79: Illustration on delineation of trees as a last resort treatment. Delineating hazards may be used in combination of other treatments, including reduction in speeds and protection by safety barriers.



Source: Indian Institute of Technology. 2019. Report on Road Safety Audit of SH-11 during operation stage.

particularly important at night, requiring that the devices are fitted with retroreflective material. Good design and installation of signs and guideposts, as well as regular maintenance of the devices, are important to ensure that the devices perform as needed for the road conditions. Concrete guideposts should not be used as they are a hazard to errant vehicles. Narrow flexible guideposts made of timber, sheet metal, or plastic should be used as they present a lower risk to errant vehicles' occupants, particularly motorcyclists, if hit.

- As a last resort, it may be necessary to ensure that each hazard (particularly trees) is delineated so it can be more easily seen by drivers (see figures 5.78 and 5.79). This should be considered as a last option when treating hazards, as delineating a hazard will likely reduce incidental collisions or "innocent hits" but will not assist the occupants of an errant vehicle that is out of control. Delineating a hazard that is too close to the carriageway could be accompanied by other treatments, including a reduction in the speed of the highway (for instance to no more than 50 km/h) or protection by safety barriers. The object hazard marking provided should be retroreflective to ensure visibility at night.

Further Reading

- AASHTO. 2011. *Roadside design guide.* Must read chapter 5, Roadside barriers.
- Austroads. 2010. Guide to Road Design , Part 6: Roadside Design, Safety, and Barriers.
- Austroads. 2018. *Towards safe system infrastructure: a compendium of current knowledge* (No. AP-R560-18). https://austroads.com.au/publications/road-safety/ap-r560-18.
- Secretariat, CAREC. 2018. *CAREC Road Safety Engineering Manual 3: Roadside Hazard Management.* Asian Development Bank. Must read chapter 5, Using safety barriers correctly.
- C. A. Plaxico et al. 2005. National Cooperative Highway Research Program Report 537: Recommended Guidelines for Curb and Curb-Barrier Installations, Transportation Research Board. Washington, DC. Must read chapter 3, Summary of state surveys on curbs and curb barrier combinations.

5.8. Barriers

General description

Barriers are used to shield hazards from errant vehicles. They can be used along the median (sometimes referred to as non-traversable medians) to prohibit movement of traffic across the median or on the roadsides to shield roadside hazards. They are designed to redirect an impacting vehicle and dissipate crash forces in a controlled manner, thus reducing the severity of crashes involving out-of-control vehicles.

Barriers broadly fall under three categories: flexible barriers (e.g., wire-rope safety barriers), semi-rigid barriers (e.g., steel beam), and rigid barriers (e.g., concrete). Each type of barrier has various benefits and constraints that make them suitable for some locations, but unsuitable for others. To avoid installing unsafe barriers or wasting resources, engineers need to understand the benefits and the limitations of each barrier type. A brief description of each barrier type is provided below.

Flexible barriers (wire-rope safety barriers)

Wire-rope safety barriers (WRSBs) (figure 5.80) consist of several tensioned wire ropes (generally three or four) that are held in place by anchorages at each end and supported at the necessary height by frangible steel posts. Upon impact by an errant vehicle, the tensioned cables deflect and absorb the energy of the vehicle, causing the vehicle to slow down. The tensioned cables are designed to guide the impacting vehicle along the barrier while the posts progressively collapse when struck. Eventually, the errant vehicle is redirected back in the direction of travel or slowed down to a stop.

Semi-rigid barriers

These are usually made from steel beams or rails mounted on galvanized steel channel posts (figure 5.81). Other types of posts such as timber or concrete may be used where crash tests prove that they perform satisfactorily. These barriers deflect less than flexible barriers and, depending on the impact, they may be able to redirect secondary impacts (i.e., another impact at the same location).

Rigid barriers

These are usually reinforced concrete walls constructed to a profile and height that is suitable to contain and redirect errant vehicles (figure 5.82). They offer no or little deflection on impact; therefore, high impact forces may result in severe injuries to vehicle occupants as the vehicle entirely absorbs the impact energy. The most common types of rigid barriers include the F-profile barrier, the New Jersey barrier, the constant slope barrier and the vertical wall barrier.

Figure 5.80: Flexible (wire-rope) barrier.

Source: iRAP.

Figure 5.81: Semi-rigid barrier (W-beam).

Source: ACP. Australian Construction Products. ACP Sentry Barrier W-Beam System—Longitudinal barrier. http://www.acprod.com.au/products/acp-sentry-barrier-w-beam-system-longitudinal-barrier.

Figure 5.82: Rigid (F-profile) barrier.

Source: © Famartin.

Safety implications

- Barriers that are not well-designed fail to perform satisfactorily and can be a safety hazard (see figures 5.83 through 5.86).
- A barrier that is too low can lead to an impacting vehicle to vault over it. A barrier that is too high (for flexible and semi-rigid barriers) can cause an errant vehicle to pass beneath the cables or railing leading to severe consequences.
- A barrier that is too close to the road leads to increased incidental impacts with the barrier, while a barrier that is too far from the road (and closer to the hazard it is shielding) means less opportunity for the deflection of a flexible and semi-rigid barrier and may result in the impacting vehicle hitting the hazard. The farther away the barrier is from the road also means the greater the chance of a high angle impact which could result in severe injuries to the vehicle occupants especially when impacting a rigid barrier.
- A critical aspect of a barrier's design is the "length of need" required in order to adequately protect a hazard. A barrier that is too short in its length may cause the errant vehicle to pass behind the barrier and strike the hazardous object or collide with oncoming traffic.

Figure 5.83: Flexible barriers with too large posts.

The posts of flexible barriers should be designed to collapse when struck. However, the posts of this barrier are too large and rigid to perform in this manner.

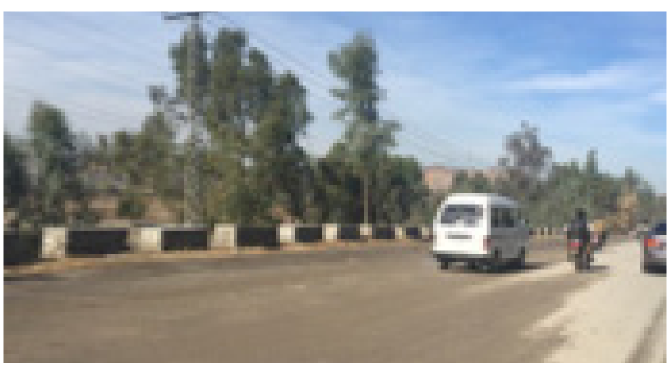
Source: CAREC. 2018. CAREC Road Safety Engineering Manual 3: Roadside Hazard Management. Asian Development Bank.

Figure 5.84: The rail units overlap in the wrong way.

The rail units overlap in the wrong way such that the closest rail would push away from the road if struck, leaving the next rail exposed to spear through the impacting vehicle. The rigid concrete posts will not absorb the impact energy and may lead to severe injuries.

Source: CAREC, 2018.

Figure 5.85: Use of nonstandard median type on high-speed road.



Source: National Highway Authority. 2019. Guidelines for Road Safety Engineering, Part 1. Government of Pakistan. Retrieved November 15, 2019, from http://www.roadsafetypakistan.pk/download/Guidelines-for-road-safety-engineering-part-1.pdf.

Figure 5.86: Light-gauge rails with concrete curbs.

Source: CAREC, 2018.

Figure 5.87: The exposed end of the guardrail can spear through an impacting vehicle.

Source: World Bank.

Figure 5.88: Unsafe ramped end of semi-rigid barrier that can launch an impacting vehicle.

Source: iRAP.

Figure 5.89: Unsafe gap between guardrail and concrete

Source: CAREC. 2018. CAREC Road Safety Engineering Manual 3: Roadside Hazard Management. Asian Development Bank.

- The end points (terminals or end treatments) of barriers can be dangerous if not properly designed, constructed, and maintained. The end of a guardrail, for example, can spear through an errant vehicle that strikes it unless a correctly installed safe terminal is used (figure 5.87). Ramped or turned down terminals on the approach end of barriers can launch an impacting vehicle, especially when struck at high speeds (figure 5.88). The blunt ends of concrete barriers are a safety hazard.
- Poorly designed transitions between different barrier types and insufficient offsets to hazards may lead to pocketing, that is, where an errant vehicle strikes a barrier but is directed by that barrier into a fixed object. This can occur, for example, where a guardrail is poorly connected to a concrete bridge parapet causing a vehicle that strikes the guardrail to be directed to hit the blunt end of the concrete parapet upon the deflection of the guardrail (figure 5.89).
- Barriers may interfere with sight distance, especially on horizontal curves or when entering or leaving the road.
- Damage to barriers can reduce the safety benefits of barriers if they are not properly repaired. This is particularly essential for flexible barriers, as even a low force impact will require timely repairs to the barrier system.
- While all types of barriers are designed to protect people from hazards, they may still pose a risk to the vulnerable human body, particularly motorcyclists, due to the limited protection their bodies have compared to someone in a vehicle.
- A curb in front of and close to a barrier can cause an errant vehicle hitting the curb at high speed to jump and either vault over the barrier or hit the barrier at a greater height than provided for in the design and testing. Injuries can be more severe in such crashes.
- Since flexible barriers rely on the tension of the cables, the horizontal and vertical alignment can limit their use. On tight curves, the required tension and height may not be maintained during or after an impact. On sag curves, depending on the degree of curvature, the wire tension may cause the posts at the bottom of the curve to lift out of their sockets. Vehicles may also pass beneath the cables or become suspended at the bottom of the curve.
- Where there is a known risk of animals accessing the road corridor, in particular large animals like

deer, roadside barriers may be installed. Such barriers require special considerations, such as exclusion of animals by perimeter closed fencing, in addition to the safety points for barriers for vehicles.

Good design practice/ treatments/solutions

- Traditionally it is has been thought preferable to remove, relocate, or modify roadside hazards, but in some situations, shielding a hazard with barriers may be the only practical option where it is not feasible or economically viable to treat the hazard in other ways.[86] It is important to first assess the need for a barrier before installing one to determine if there are other ways to treat the hazard. This is because the barrier itself can represent a hazard to errant vehicles. A collision with the barrier should be less severe than collision with the hazard that the barrier is shielding.
- In selecting the barrier type that will best suit the needs, a range of factors need to be considered, including:
    - Performance capability and level of containment requirements, which might be based on vehicle mix and significance of roadside infrastructure;
    - Available clearance to the hazard, and the dynamic deflection characteristics of the proposed barrier;
    - Site conditions, such as vertical and horizontal alignments and cross-slopes;
    - End terminals;
    - Sight distance;
    - Compatibility with adjacent barriers;
    - Installation and maintenance costs;
    - Aesthetics and environmental impact; and
    - Maintenance capacity of organization.

(See also Austroads. 2020. Guide to Road Design Part 6, Roadside Design, Safety, and Barriers; 1.5, Principles considered in roadside design to achieve the safest system; and 5.2, Factors considered in barrier selection.)

(See also section 4.4 regarding motorcycle use and barrier types.)

- Safety barriers should only be installed if the manufacturer of the product has subjected it to an internationally accepted crash test to confirm it performs satisfactorily. The barrier should then be installed fully to the supplier's instructions, following the applicable standards on which the crash test was performed.
- Sufficient clearance from the hazard should be provided so that the expected deflection of the barrier will not allow the impacting vehicle to contact the hazard (figure 5.90). Barrier deflection depends on the type and installation arrangement of the barrier used, as well as the mass, speed, and impact angle of the vehicle. As a rule of thumb, the deflection of a semi-rigid barrier may be up to 1 m, and the deflection of a flexible barrier may be up to 3 m. Though the dynamic deflection of rigid concrete barriers is minimal (0.1m or less), hazards that are

Figure 5.90: Example of a safe flexible barrier with good clearance. Since the deflections on these barriers can be high, it is important that an adequate offset between the barrier and the hazard is provided

Source: CAREC. 2018. CAREC Road Safety Engineering Manual 3: Roadside Hazard Management. Asian Development Bank.

86 Some countries are moving to the use of continuous safety barriers as their preferred roadside treatment in light of new evidence that indicates well-installed and maintained barriers may provide superior safety performance compared to clear zones.

End Terminals Examples

Figure 5.91: Fully re-directive crash cushion—Philippines.

Source: © Alina F. Burlacu/GRSF/World Bank.

Figure 5.92: Fully re-directive terminal, flared or tangential.

Source: Chan/Auckland motorways.

Figure 5.93: Flared energy absorbing terminal.

Source: Chan/Auckland motorways.

Figure 5.94: Safe crash cushion at the end of rigid barrier at a construction site.

Source: CAREC. 2018. CAREC Road Safety Engineering Manual 3: Roadside Hazard Management. Asian Development Bank.

taller than the barrier need to be offset far enough from the face of the barrier so that during impact, vehicles (especially high vehicles such as trucks) do not lean over the barrier and strike the hazard. This is referred to as the "roll allowance." For flexible and semi-rigid systems, this roll allowance should be added to the deflection. For rigid systems, the deflection may be assumed to be zero, and a roll allowance of 1.1 m is adequate to protect a vehicle driver from impact.[87]

- Roadside barriers should be sufficiently offset from the travel way to allow space for vehicles to pull off the traffic lane.
- Since rigid barriers can cause serious injuries if struck at a high impact angle, they are located close to the traffic lane (usually within 4 m of the edge of the nearest traffic lane) to minimize the risk that vehicles will impact the concrete barrier at a high angle. On the other hand, it is desirable to install roadside flexible and semi-rigid barriers further from the traffic lane to maximize the chance of a driver regaining control of the vehicle before impacting the barrier.
- When located on horizontal curves, safety barriers may need to be offset further from the edge of the traffic lane so that they do not impede horizontal sight distance. Sight distance is a factor that also needs to be considered near intersections, median breaks, pedestrian crossings, and driveways.
- It is preferable that the slope in front of a barrier is installed as designed. This essentially means vertical for semi-rigid and flexible systems or to the required, tested slope for rigid systems. This is irrespective of the barrier manufacturer used. This is because safety barriers perform best when they are impacted by vehicles with their center of gravity at or near the normal position.
- The terminals of barriers should be well designed to provide controlled deceleration of errant vehicles below recommended values that cause injury to vehicle occupants. They should also ensure that the vehicle is not speared, vaulted, snagged, or rolled on impact. Various types of terminals are commercially available, and the manufacturer's specifications for installation should be followed to ensure that the terminals meet appropriate performance standards (see figures 5.91 through 5.94 for examples). It is also important that a terminal of known impact performance is installed on

87 AASHTO-Roadside-Design-Guide-4th-ed-2011 Fig 5–31.

the departure end of a barrier if that end is within the clear zone for oncoming traffic on a two-way carriageway.

- Semi-rigid barriers are often used to shield concrete bridge parapets that could result in a serious crash. The transition from the approach barrier to the bridge parapet should provide a continuous face along which an errant vehicle can be controlled. To prevent pocketing of the vehicle upon impact, it is important to enhance the strength and stiffness of the barrier gradually as it approaches the parapet, e.g., through reductions in the post spacings and to affix/embed the barrier firmly to the parapet (see figure 5.95).
- Minor damage to flexible and semi-rigid barriers needs to be repaired in a timely manner to maintain the integrity of the barrier. If incidents are not reported, manual inspections of the barrier systems may be required. It is also important to continuously monitor the wire tension of flexible barriers.
- It is preferable to avoid the use of curbing near safety barriers. But if a curb is necessary for drainage, the location of safety barriers relative to the curb needs to be considered carefully, as it may affect the barrier performance when impacted (see section 5.12 on curbs).

Figure 5.95: Safe connection between guardrail and rigid barrier on bridge with a transition section. Adding extra posts to the guardrail near the rigid barrier helps to create a transition section. The marker also helps in alerting drivers of sudden narrowing of the road ahead

Source: CAREC, 2018.

- It should be noted that while both the F-type and New Jersey have similar cross sections, studies show that the lower slope of the F-profile barrier reduces the likelihood that small cars will overturn and are thus preferred. The vertical face barrier and constant slope barrier help to further reduce the potential for small vehicles to overturn, but they also generate higher impact severities and are thus not so widely used.

Further Reading

- AASHTO. 2011. *Roadside design guide*. Must read chapter 5, Roadside barriers.
- Austroads. 2010. Guide to Road Design, Part 6: Roadside Design, Safety, and Barriers.
- Austroads. 2018. *Towards safe system infrastructure: a compendium of current knowledge* (No. AP-R560-18). https://austroads.com.au/publications/road-safety/ap-r560-18.
- Secretariat, CAREC. 2018. C*AREC Road Safety Engineering Manual 3: Roadside Hazard Management.* Asian Development Bank. Must read chapter 5, Using safety barriers correctly.
- C. A. Plaxico et al. 2005. National Cooperative Highway Research Program Report 537: Recommended Guidelines for Curb and Curb-Barrier Installations, Transportation Research Board. Washington, DC. Must read chapter 3, Summary of state surveys on curbs and curb barrier combinations.

5.9. Medians

General description

A road median is an area of separation between opposing flows of traffic. In effect, the median converts a “two-way” movement into two “one-way” movements. It can be constructed (often referred to as “raised”) using curbing or median barriers (for example—see section 5.8); provided via paint (sometimes called a "flush" median or wide centerline); or provided using an unpaved or grassed area (see figures 5.96 through 5.103). Vehicles are physically prevented from crossing the median with constructed medians, while they are only discouraged when using other types of medians.

Medians provide a degree of separation between opposing directions of traffic, meaning that when vehicles stray from their lane, they have time to recover and return safely to their lane, or are physically directed back into their lane (in the case of median barriers, and to some extent with curbed medians). They can be used in urban areas as well as on high-speed roads. They may be supplemented with rumble strips, particularly on higher-speed roads, to alert inattentive or distracted road users that they are leaving their lane. In some settings, a median can provide a holding point for pedestrians trying to cross multiple lanes of traffic, especially when the median is accompanied by a pedestrian refuge island.

Median openings are typically provided for cross traffic movement at intersections and sometimes at access points allowing left, right (or both), and U-turns

Types of road medians

Figure 5.96: Flush median.

Source: FHWA.

Figure 5.97: Flush median with rumble strips.

Source: FHWA.

Figure 5.98: Median with pavement bars.

Source: Speed uHUmp Australia.

Figure 5.99: Grassed median with curb.

Source: Florida Department of Transportation.

Figure 5.100: Curbed median.

Source: Austroads road safety engineering toolkit.

Figure 5.101: Painted median on high-speed road.

Source: © Blair Matthew Turner/GRSF.

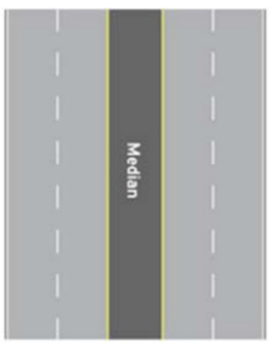
Figure 5.102: Semi-rigid median barrier on expressway.

Source: Tony Mathew. (n.d.). Road Safety Infrastructure Facility Standards—Indian Context.

Figure 5.103: Raised median on dual carriageway.

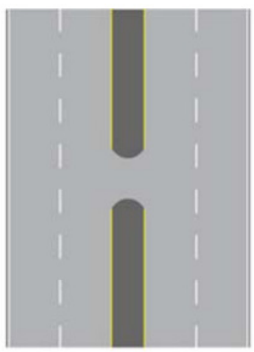
Source: Tony Mathew (n.d.).

Figure 5.104: Full median with no opening.



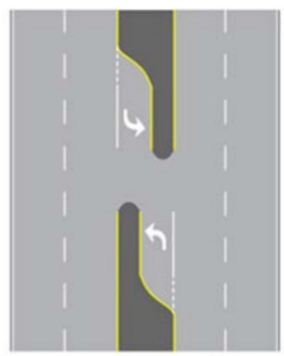
Source: FHWA.

Figure 5.105: Median crossover opening, with no left/right turn bay.



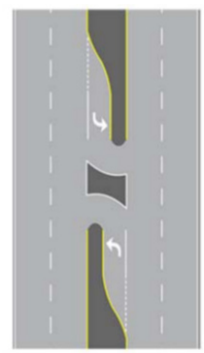
Source: FHWA.

Figure 5.106: Median crossover, opening, with left/right turn bay.



Source: FHWA.

Figure 5.107: Median crossover, with directional left/right turn bays (prevents crossing).



Source: FHWA.

on the roadways where a physical median is present. Different types of median openings are shown in figures 5.104 to 5.107.

Although median openings facilitate traffic movements, they can also introduce risks, especially when no turning bay is provided, or if the median is not of adequate width. It is essential that adequate turning provision be provided, especially in higher-speed locations.

Safety implications

- Medians are used to improve overall safety and efficiency for vehicles, and if designed correctly may also provide benefits for vulnerable road users. By providing a central refuge, pedestrians are required to cross traffic from only one direction at a time.
- Road crashes can result from the presence of unnecessary or less predictable (readable) median openings (both for pedestrian crossings and vehicular U-turn movement) and smaller medians. Narrow medians and lack of adequate turning provisions, especially in higher-speed environments, can significantly increase crash risk.
- Proper planning and designing of median openings are critical for safety, access control, and maintaining traffic flow. This includes allowance for large vehicles, particularly buses or articulated ones to turn without their envelope encroaching into a through lane. Median openings should also not encroach on the functional area of another median opening or intersection.
- Specific benefits of adequately sized medians, especially non-traversable medians, include:

- Reduced chance of vehicles travelling in opposing directions colliding (reduced head-on crashes by approximately 40 percent.[88]
- Reduce all crash types by approximately 15 percent for painted medians, and between 45–55 percent for built-up median in urban areas and rural areas, respectively.[89], [90], [91]
- Reduced lane width can lead to reduced vehicle speeds on the roadway.[92]
- Better access control.
- Providing refuge area for pedestrians crossing the street.
- Managing the location of intersection traffic conflict points.
- Provide space to install improved lighting at pedestrian crossing locations (shown to reduce nighttime pedestrian fatalities at crossings by 78 percent).[93]
- There are significant benefits from providing medians at certain high-risk intersections to eliminate cross traffic turning movements (see section 6.6), but care needs to be taken to ensure alternative, compensatory safe U-turning arrangements are provided in close proximity.

- Drainage issues may occur when using a raised median resulting in an increase in crash risks (for instance due to reduced road surface friction).
- For painted medians or where rumble strips are used, the risk for two-wheeled vehicles can be increased due to reduced or variable skid resistance.
- Where curbing or raised pavement devices are used, there may be an increase in risk for two-wheeled vehicles and pedestrians (trip hazard).
- There are also some efficiency benefits in addition to those for road safety, including decreased delays for motorists and increased capacity of roadways.

Good design practice/ treatments/solutions

- Reduction in head-on crashes can be achieved through selection of a suitable width of the median or the use of median barriers. Few out-of-control vehicles travel further than 9 meters from the edge of lane, so that this width of median would be sufficient to avoid many head-on crashes.[94] The use of a wide open-space median may also be useful in withholding the land reserve for future expansion of the road to avoid encroachments.
- Adequate widening to provide an optimum turning radius should be provided to ensure vehicles do not block the roadway while turning, as shown in Figure and figure 5.109. Dedicated turning lanes should also be provided to ease congestion or conflicts between turning and non-turning vehicles. This includes allowance for large vehicles, particularly buses or articulated ones, to turn without their envelope encroaching into a through lane. Consideration should also be given to the distance of the U-turn to access points in order to reduce congestion, depending on the amount of traffic flow on the road.

88 Beck, D. 2016. Guidance on median and centreline treatments to reduce head-on casualties (No. AP-R519-16).

89 Bahar, G. B., Masliah, M., Wolff, R., and Park, P. 2007. Desktop reference for crash reduction factors (No. FHWA-SA-07-015; 7067). United States. Federal Highway Administration. Office of Safety.

90 Turner, B., Steinmetz, L., Lim, A., and Walsh, K. 2012. Effectiveness of road safety engineering treatments (No. AP-R422/12).

91 Austroads road safety toolkit.

92 King, M. R., Carnegie, J. A., and Ewing, R. 2003. Pedestrian safety through a raised median and redesigned intersections. Transportation research record, 1828(1), 56–66.

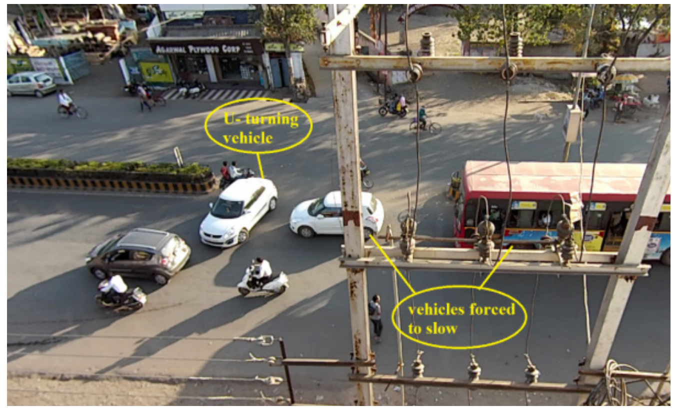
93 The Federal Highway Administration, FHWA. 2019. State Best Practice Policy for Medians—FHWA-SA-11-019. FHWA Safety Program. Accessed at https://safety.fhwa.dot.gov/ped_bike/tools_solve/fhwasa11019/fhwasa11019.pdf.

94 SANRAL. Geometric Design Guidelines.

Figure 5.108: U-Turn on narrow median (with waiting lane).

Source: Al-Jameel, H. A. 2015. Contribution to the U-turn Design at Median Openings in Iraq: Al-Najaf City as a Case Study. Kufa Journal of Engineering, 6(1).

Figure 5.109: U-turning vehicle encroaching on road space for approaching traffic.



Source: Sharma, V. K., Mondal, S., & Gupta, A, 2017.

Figure 5.110: Vehicles using raised median as lane during congestion.

Source: Great about Perth. Accessed at https://whatssogreataboutperth.wordpress.com/2010/03/16/traffic-in-perth-ha/.

Solution: Median should be adequately raised to stop vehicles from using it as an additional lane.

Figure 5.111: Illegal U-turn over the median.

Source: Ghana web. Accessed at https://www.ghanaweb.com/GhanaHomePage/features/Tema-Motorway-A-necessary-death-trap-872413?gallery=1.

Solution: Medians should be designed to prohibit illegal U-turns, and adequate median openings should be provided.

- Both flush and raised road medians may be used illegally by drivers during traffic congestions (see figures 5.110 and 5.111). Pavement bars or flexible posts should be used on flush medians in sections where congestion may cause drivers to illegally use the flush median as a lane. Frangible signs can be used at intervals on raised medians to deter drivers from using it as an additional lane during congestion.
- Unnecessary median openings (both for pedestrian crossings and vehicular U-turn movement) should be removed, and smaller narrow medians should be avoided where possible. Figures 5.112 through 5.115 illustrate some unsafe and safe median strips.
- Restriction of turning movements may be an issue for raised medians, and community input and acceptance should be sought. Regular provision of

Examples of unsafe median strips

Figure 5.112: Unsafe median opening leading to contraflow.

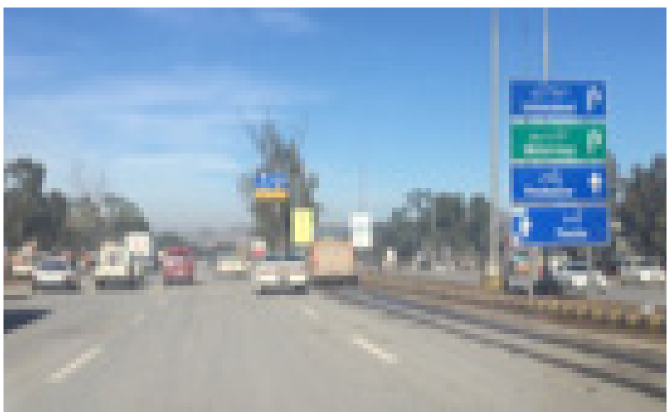
Source: World Highways. India's road to safety. Accessed at https://www.worldhighways.com/sections/world-reports/features/indias-road-to-safety/. November 15, 2019.

Figure 5.113: Use of nonstandard median type and unsafe median opening on a high-speed road.

Source: Tony Mathew (n.d.). Mathew T. 2019. Road Safety Infrastructure Facility Standards—Indian. International Road Federation. Accessed at https://www.unescap.org/sites/default/files/3.3%20India_Mr.%20Tony%20Mathew.pdf. November 15, 2019.

Examples of safe medians strips

Figure 5.114: Raised median with turn lane dedicated for the U-Turn



Source: National Highway Authority. 2019. Guidelines for Road Safety Engineering, Part 1. Government of Pakistan. Accessed at http://www.roadsafetypakistan.pk/download/Guidelines-for-road-safety-engineering-part-1.pdf. November 15, 2019.

Figure 5.115: Raised median on carriageway.

Source: © D. Allen Covey/VDOT

gaps may be needed to address this issue (ensuring that such gaps are well designed with appropriate turning facilities).

- Appropriate median widths should be determined according to the road classification and function of the median. This will include whether turning movements are required (into and out of side streets), U-turn requirements, and pedestrian use.
- Check there is adequate sight visibility for drivers turning in/out of accesses and at intersections.
- Median should be highly visible both night and day and should contrast with the travelled way.
- Clear advance warning and visibility should be provided for raised medians.

- Appropriate drainage facilities should be included when installing raised medians.
- Placement of rumble strips, curbs, and raised pavements should be carefully considered so as to avoid being a hazard for two-wheeled vehicles. Similarly, painted medians with poor skid resistance should not be used where they might become a hazard for these road users.
- Raised medians can also be used to provide additional plastic shields to prevent glare from opposing traffic lanes (figure 5.116).
- Traffic volume should be carefully considered when deploying a flush median. Four-ft flush medians have positive safety benefits (CMF < 1) under lower average daily traffic volumes (e.g., ≤ 6,000) while negative benefits (CMF > 1) under greater average daily traffic volumes (e.g., ≥ 15,000).[95]
- Flush medians with rumble strips or chatter bars were found to be the safest medians in reducing crashes, followed by raised medians and undivided segments.[96]

Figure 5.116: Anti-glare barrier on top of median.

Source: © Alina F. Burlacu/GRSF/World Bank.

Further Reading

- The American Association of State Highway and Transportation Officials, AASHTO. 2018. A Policy on Geometric Design of Highways and Streets—Green Book. 7th edition. Must read chapter 4, Cross-sectional elements.
- Austroads. Guide to Road Design. Must read Part 3, Geometric Design.
- Florida Department of Transportation. 2017. 2014 Median Handbook FDOT. https://www.fdot.gov/docs/default-source/PLANNING/systems/programs/sm/accman/pdfs/FDOT-Median-Handbook-Sept-2014.pdf.
- Kennaugh D. Median Design. Accessed at https://www.cedengineering.com/userfiles/Median%20Design.pdf.

95 Li, X., Liu, J., Yang, C., and Barnett, T. 2021. Bayesian Approach to Developing Context-Based Crash Modification Factors for Medians on Rural Four-Lane Roadways. Transportation Research Record, 03611981211007141.

96 Jiang, X., Yan, X., Huang, B., and Richards, S. H. 2011. Influence of Curbs on Traffic Crash Frequency on High-Speed Roadways. Traffic Injury Prevention, Vol. 12, No. 4, pp. 412–421.

Case Studies/ Examples

Central medians and median openings in Addis Ababa [a,b]

Figure 5.117: Narrow unsafe median

Source: James Jeffrey/The World. The World, US-Ethiopia relationship changing amid Horn of Africa power struggle. November 8, 2018. https://www.pri.org/stories/2018-11-08/us-ethiopia-relationship-changing-amid-horn-africa-power-struggle.

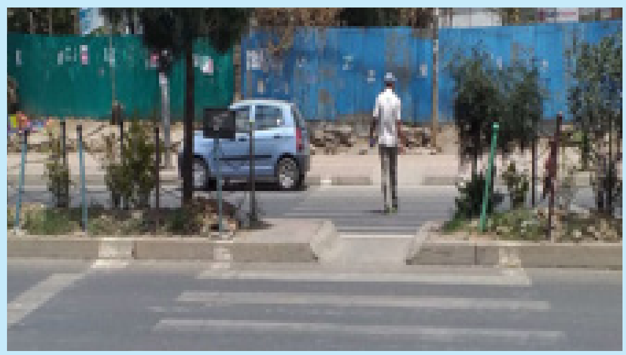
Unsafe narrow median, with insufficient width to provide refuge for crossing pedestrians (figure 5.117). Pedestrians are forced to stand within the traffic lanes. The median's contrast and height may not be visible for road users, especially in dark conditions.

Note: Sufficient width needs to be provided for pedestrians while crossing multilane highways to protect them from vehicles on the roadway. In some situations where there is inadequate width, a full height median barrier may be considered instead.

Figure 5.118: Wide median opening with concrete stumps

Source: © John Barrell.

Figure 5.119: Median opening for pedestrian use



Source: Eskindir, Z. 2019. Investigation of the Effect of Roadway Elements on Traffic safety in Addis Ababa: A Case of Nifas Silk Lafto Sub City (Doctoral dissertation, Addis Ababa University).

A central median with trees and shrubs in Addis Ababa helps green the street, prevents conflict between vehicles, and provides a refuge (at grade) for pedestrians crossing. The median openings for pedestrians are also adequately sized, and wider openings have concrete stumps to prevent vehicles from using them as areas for U-turn movements (figures 5.118 and 5.119). However, the vegetation may obscure pedestrians and needs to be maintained to ensure adequate visibility to other road users.

a Welle, B., Liu, Q., Li, W., Adriazola-Steil, C., King, R., Sarmiento, C., and Obelheiro, M. 2015. Cities safer by design: guidance and examples to promote traffic safety through urban and street design.

b Eskindir, Z. 2019. Investigation of the Effect of Roadway Elements on Traffic Safety in Addis Ababa: A Case of Nifas Silk Lafto Sub City (Doctoral dissertation, Addis Ababa University).

5.10. Road Surfacing

General description

Road surface characteristics affect road safety in several ways. One way is the surface friction which affects the resistance to sliding or skidding of tires across the road surface. This friction force, known as skid resistance, provides the grip that a tire needs to maintain vehicle control and for emergency stopping. Skid resistance is particularly important during wet weather conditions, as water on the pavement acts as a lubricant, reducing the direct contact between the tire and the pavement. In addition to climate and water on the pavement, the potential for a skidding crash depends mainly on the speed of the vehicle, the cornering path, the magnitude of acceleration or braking, the condition of the vehicle tires, and the characteristics of the road surface.[97] The road surface characteristics that influence surface friction include microtexture, macrotexture, megatexture/unevenness, chemistry of materials, temperature, thermal conductivity, and specific heat.

Microtexture refers to irregularities in the surfaces of the stone particles, that is, the fine-scale texture. The magnitude of microtexture depends on the initial roughness on the aggregate surface and the ability of the aggregate to retain this roughness against the polishing action of traffic. As such, microtexture is an aggregate-related property that can be controlled by the careful selection of aggregates with desirable polish-resistant characteristics.

Macrotexture refers to the larger irregularities of the road surface, that is, the coarse-scale texture. The initial macrotexture on a pavement surface will be determined by the size, shape, and gradation of the coarse aggregates used in the pavement construction, as well as the particular construction techniques used for the pavement surface layer. Macrotexture is also essential in providing escape channels to water from beneath the tires, which reduces the potential for aquaplaning/hydroplaning. It also reduces the splash and spray potential of the road in wet conditions, which can adversely affect the visibility of the road in wet weather.

Megatexture is the unevenness in the scale of the contact surface between the vehicle tire and the pavement surface. It describes irregularities that can result from rutting, potholes, patching, surface stone loss, and major joint cracks, and it mainly affects noise levels and rolling resistance.

Roughness, on the other hand, refers to surface irregularities larger than megatexture that also affect rolling resistance, in addition to ride quality and vehicle operating costs. It provides an overall measure of the pavement condition and is computed through the International Roughness Index (IRI).

Road surface conditions can also have a significant influence on vehicle speeds, which affect both the crash risk and severity. Extensive rutting or the presence of potholes can reduce vehicle speeds, but also provide increased risk for two-wheeled users. Regrading or resurfacing provides a smoother, more comfortable ride with associated increases in speed. As such, increases in speeds from road improvement and rehabilitation schemes can result in higher safety risks unless mitigating safety strategies are used.

Figures 5.120 through 5.122 illustrate various types of road surfacing.

Safety implications

- The relationship between skid resistance and crash risk is well understood, with low skid resistance being directly related to increased crash risks,[98] especially on wet roads. Low skid resistance is likely to result in longer stopping

97 Harwood, D. W., Blackburn, R. R., and Heenan, P. J. 1980. Pavement macrotexture review (No. FHWA-RD-80-505 Final Rpt.).

98 Wang, C., Quddus, M. A., and Ison, S. G. 2013. The effect of traffic and road characteristics on road safety: A review and future research direction. Safety Science, 57, 264–275.

Figure 5.120: An asphalt road surface in good condition.

Source: Highways Today. 2017. AfDB funded Thika Highway continues to impact Kenyan lives five years on. https://highways.today/2017/11/09/afdb-thika-highway-kenya/.

Figure 5.121: Concrete blocks (adoquines) surfacing in good condition and appropriate drainage facilities.

Source: World Bank.

Figure 5.122: Otta seal surfacing on low volume road in good condition with satisfactory results. (left image: close-up of the otta seal surfacing).

Source: World Bank.

distances and may cause longitudinal or sideways skidding and loss of vehicle control. Loss of control of the vehicle may lead to run-off-the-road crashes, head-on crashes, sideswipes, and rear-end crashes. Research performed in some EU countries demonstrated that the use of road pavements with sufficiently high skid resistance could improve road safety by not only reducing the vehicle's sliding risk but also the crash risk and severity[99]. This is because drivers who lose their ability to brake effectively are more likely to encounter higher impact speeds compared to vehicles that decelerate prior to impact. The risk of crashes is also much higher at high traffic volume intersections than at low traffic volume locations owing to increased exposure to the pavement deficiency. Pavement defects that indicate poor skid resistance include:

- A polished surface (rounded or worn out aggregates) in the wheel path,
- "Bleeding" of the pavement (upward movement of bitumen/asphalt as evidenced by a shiny black surface film),

99 Gothie, M. 1996. Relationship between Surface Characteristics and Accidents, in Proceedings of 3rd International Symposium on Pavement Surface Characteristics, 271–281.

    - Accumulation of oil or localized spill of slippery substance (especially on curves and intersection approaches),
    - Loss of top layer of aggregate (bitumen pavement), and
    - A significant difference in friction between wheel paths.
- Several studies have investigated the relationship between road surface characteristics such as macrotexture, rutting, potholes, and roughness to road safety outcomes. Such studies are almost exclusively from high-income countries (HICs), and may not be easily transferable to low- and middle-income countries (LMICs), where there may be more extreme levels of surface defects as well as a different traffic mix. However, the evidence indicates that the crash risk increases considerably when the macrotexture is less than 1 mm in sand-patch texture depth (SPTD) units,[100] and crash rates may increase by 25 percent when the rut depth exceeds 20 mm.[101] Studies relating roughness to crash rates are mixed, with one study summarizing the research by indicating that increased unevenness is related to increased, decreased, and unchanged safety outcomes.[102] Some studies have found that the conflicting results may be due to good pavements inducing higher speeds and therefore higher severity crashes.[103]. One recent study[104] summarized much of the previous research and conducted further analysis on this issue. The study found a relationship between rutting and roughness and safety, and concluded that these can be contributing factors to crashes. However, the study also identified that the relationships can be unclear, with the need to combine information on these surface factors with other contributory elements such as human factors and road geometry.
- There is evidence that relates road surface condition, particularly roughness, to vehicle speeds, which are known to affect the crash risk and severity. Recent US research[105] indicates that when the IRI exceeds 80 inches per mile (127 cm/km), speeds reduce substantially; by around 10 mph (16 km/h) when the IRI increases from 80 inches per mile to 130 inches per mile (206 cm/km). One review of research[106] based on experience in HICs identified increases of up to 10 km/h from resurfacing where unevenness is improved, although speed increases of 2–5 km/h were more typical. One limited study from India[107] found a similar relationship, with a substantial decrease in speeds for different types of vehicles, with speeds dropping by 30–40 km/h when roughness increased from around 470 IRI (cm per km) to 800 IRI. Speeds were around 60 km/h at the lower levels of roughness (already a low free speed given the existing level of roughness) but dropped to between 20 and 30 km/h at the higher roughness level.
- Evidence indicates a strong relationship between changes in vehicle speeds and safety outcomes. One comprehensive analysis[108] of over 100 prior

100 Cairney, P., and Bennett, P. 2008, May. Managing road surfaces for safety at the network level: is macrotexture enough. In *2008 Saferroads International Conference–Managing Roads and Runway Surfaces to Improve Safety*. Cheltenham England (pp. 11–14).

101 Cairney, P. 2010. Road safety engineering risk assessment part 11: road safety and maintenance.

102 Cairney, P. 2010. Road safety engineering risk assessment part 11: road safety and maintenance.

103 Li, Y., L. Chunxiao, and D. Liang. 2013. Impact of Pavement Conditions on Crash Severity. *Accident Analysis & Prevention*, 59, pp. 399–406.

104 Mamlouk, M., Vinayakamurthy, M., Underwood, S., and Kaloush, K. 2018, Effects of the International Roughness Index and Rut Depth on Crash Rates *Transportation Research Record*, Vol. 2672(40) 418–429.

105 Liccardo, N. 2017. Methodology for Roughness-Speed Relationship with SHRP2 Naturalistic Driving Study Data. Unpublished Masters thesis, University of Nevada, Reno.

106 Liccardo, N. 2017. Methodology for Roughness-Speed Relationship with SHRP2 Naturalistic Driving Study Data. Unpublished Masters thesis, University of Nevada, Reno.

107 Ch. Ravi Sekhar, J. Nataraju, S. Velmurugan, Pradeep Kumar, and K. Sitaramanjaneyulu. 2016. Free Flow Speed Analysis of Two Lane Inter Urban Highways. Transportation Research Procedia 17, 664–673.

108 Elvik, R. 2009. The power model of the relationship between speed and road safety: update and new analyses, TOI Report 1034: 2009, Institute of Transport Economics, Oslo, Norway.

studies identified this relationship for different types of roads. For rural roads, the results indicate that for every 1 km/h increase in speed, there is around a 4.5 percent increase in risk of a fatal crash outcome. Increasing speeds through road reconstruction and improvements could thus result in substantial increases in crash risk, even taking into account the benefits from better quality road surfacing. The Global Road Safety Partnership[109] highlighted that it is frequently the case that road improvement and rehabilitation schemes in LMICs result in increased traffic, higher speeds, and increased crashes. Gichaga (2017)[110] reports that the improvements to a 50-km high class, high traffic volume road in Kenya has brought with it the unfortunate consequence of speeding vehicles colliding with pedestrians crossing at undesignated locations on the high-speed road (design speed of 100 km/h). The issue of speeding has also been documented in HICs in the US, noting that paved roads tempt drivers to travel faster.[111] They suggest that to facilitate such an increase in speed safely, roads must be straighter, wider, and as free as possible from obstructions for them to be safe.

Good design practice/ treatments/solutions

- Skid resistance is most important at locations where enhanced braking performance may be required including curves, approaches to intersections, areas near pedestrian crossings, etc.
- Crash rates can significantly be reduced by implementing proper measures to increase skid resistance at potentially dangerous locations such as curves, intersections, and bridges. There are two main options for the treatment of pavements with low skid resistance:
  - Retexturing: This treatment type involves mechanical reworking of the existing road surface to improve its frictional characteristics. The methods include diamond grooving, shot blasting, bush-hammering, and high velocity water blasting.
  - Resurfacing: These include relatively low-cost thin surfacing treatments that not only improve the surface texture and resistance to wet road skidding but can also seal the surface against water penetration and arrest disintegration of the existing road surface. They include surface dressing applications and high friction surfacing (HFS) (figures 5.123 through 5.125)

Figure 5.123: High friction surface treatment on high-risk curve.

Source: FDOT.

Figure 5.124: A high friction surface applied at both approaches of the intersection.

Source: iRAP.

Figure 5.125: High friction surface (colored) applied on the approach to a mini roundabout.

Source: iRAP.

109 Global Road Safety Partnership. 2008. Speed Management: a road safety manual for decision-makers and practitioners. Geneva.

110 Gichaga, F. J. 2017. The impact of road improvements on road safety and related characteristics. *IATSS research, 40*(2), 72–75.

111 FHWA. 2015. *Gravel Roads Construction & Maintenance Guide*. Federal Highways, Washington, DC.

- Since skid resistance lessens over time, especially on roads with high heavy vehicle volumes and in tropical climates, regular monitoring of the pavement's skid resistance is essential. Several road authorities carry out proactive periodic programs of pavement surface testing which are prioritized on the basis of traffic volume, operating speeds, the requirement for stopping, wearing course age and type, concerns over crashes in wet conditions, and known drainage deficiencies. The pavement testing and inspection reports are then assessed against the recommended investigatory levels for different situations, e.g., curves, approaches to signalized intersections, or pedestrian crossings. For sites that fall below the recommended level, further investigation is undertaken to determine the remedial action that may be required.
- While much of the research relates to improvement and rehabilitation of sealed roads, there is evidence that applying the same principles of ensuring regular road surface maintenance to provide low roughness (an IRI of 1.9m/km) and providing incentives for a smooth pavement over the design life will ensure better pavement and construction quality, and can reduce safety risk for all users.[112]
- Special attention on the pavement's skid resistance should be given on road sections where the effect of aggregate polishing caused by traffic is known to be most frequent. These include curves, roundabouts with small radii, sections where vehicles accelerate or decelerate, and in areas close to crossings.
- The choice of aggregates and bituminous mixes that retain skid resistance (rather than polish with wear) may be considered. Studies show that the polishing behavior of aggregates is influenced by their mineralogy composition, with rocks containing metamorphic parts being less susceptible to wearing than sedimentary materials with better frictional properties of pavement surface,[113] and that just by choosing the right type of aggregates for a road surface, the stopping sight distance can be reduced by about 10 m at speeds of 100 km/h and more than 20 m at higher speeds.[114] As such, a petrography examination is a valuable tool for understanding the behavior of aggregates at polishing and their use in an asphalt mixture. In some situations, the use of synthetic aggregates may also be appropriate. Laboratory testing and screening of aggregates provide the necessary control on the quality of aggregates used in the asphalt mix.
- The selection of the appropriate pavement marking material is important when considering pavement friction, especially in wet conditions. This is because large pavement markings such as stop bars, large arrows, school zone marking, and box junctions can decrease skid resistance, particularly in the approach to a roundabout or intersection.
- There are a number of safety strategies that can be implemented to mitigate increases in crash risks resulting from increased speeds due to resurfacing. When included at initial design, many of these interventions can be included at low cost or even no additional cost. These include:
  - Traffic calming at key locations
  - Gateway treatments on entering a village or other built-up area
  - Speed limits
  - Provision of wide sealed shoulders
  - Visual narrowing of roads
  - Segregated footpaths
  - Widening of curves
  - Centerline and edge-line marking
  - Advanced warning signs
  - Advanced warning signs with advisory speeds

112 B King University of South Queensland. 2014. The Effect of Road Roughness on Traffic Speed and Road Safety.

113 West, T. R., Choi, J. C., Bruner, D. W., Park, H. J., and Cho, K. H. 2001. Evaluation of dolomite and related aggregates used in bituminous overlays for Indiana pavements. *Transportation Research Record*, 1757(1), 137–147.

114 Burlacu, F. A., Racanel, C., and Burlacu, A. 2016. The influence of road materials characteristics on road safety. *Revista Romana de Materiale—Romanian Journal of Materials*, 46(4), 552–559.

- Chevrons
- Barriers (median and roadside) (see section 5.8)
- Route-based curve assessment and intervention
- Improved sight distance
- Increasing visibility of intersections

Further Reading

- High Friction Surface Treatments. https://austroads.com.au/publications/pavement/agpt04k/types-of-sprayed-seal-treatments/other-treatments/high-friction-surface-treatment.
- Institute for Transportation and Development Policy. 2019. Street Design Manual for Kenyan Cities. Must read chapter 4, Street elements.

5.11. Drainage

General description

The primary purpose of highway drainage facilities is to prevent surface runoff from reaching the roadway and to remove rainfall or surface water efficiently from the roadway. Drainage facilities, including channels, shoulders, and surfaces, capture sheet flow from the highway pavement and backslope and convey that runoff to larger channels or culverts within the drainage system. The gradient of drainage typically parallels the grade of the roadway. A stable conveyance design is a critical component in roadside channels.

Highway drainage facilities can be broadly classified into two major categories based on construction: (1) open-channel (figure 5.126) or (2) closed-conduit facilities (figure 5.127). Open-channel facilities include roadway channels, median swales, curb and gutter flow, and others. Closed-conduit facilities include culverts and storm drain systems.

Drainage structure includes:

- A gutter, the triangular-shaped area defined by the curb on roadsides, is an open-channel flow section for conveying runoff. A gutter section can be an effective countermeasure for reducing spread on the pavement.
- Shoulder curbs are placed at the outer edge of the shoulder, as combined with a gutter section, to control drainage, improve delineation, control access, and reduce erosion. Swale sections, typically circular or V-shaped (figure 5.128), are used where curbs are used to prevent water from eroding fill slopes.

Figure 5.126: Open channels.

Source: Department of Transport and Main Roads, Brisbane, Qld. 2010. Road drainage manual.

Figure 5.127: Closed drainage filled in with porous materials for anti-erosion and falling.,

Source: Department for International Development, UK. 2003. CaSE Highway Design Note 1, Surface Water Drainage Channels.

Figure 5.128: Conventional v-shaped drainage.

Source: DFID, 2003.

Safety implications

- The lack of good drainage can lead to the ingress of water into the road structure leading to structural damage and costly repairs, while surface water can form a road safety hazard. Water on the pavement will contribute to crashes from hydroplaning and loss of visibility from splash and spray. The aim of drainage facilities is to prevent surface runoff from reaching the roadway and to remove rainfall or surface water efficiently from the roadway.
- Water may accumulate in shoulder areas like ponds, also creating a risk.
- Poor drainage causes early pavement distresses and damage of shoulders, leading to driving problems and structural failures of the road (figure 5.129).
- One study showed that 22 percent of all run-off-the-road (ROR) rollover crashes involved hitting a ditch or embankment and another study determined that 55 percent of ROR rollover crashes result in injury. A very high proportion of these are on rural roads.
- Culvert end treatments may become hazardous obstructions to errant vehicles (figure 5.130). Culverts that have unprotected headwalls close to the carriageway are a hazard to vehicles using the sealed shoulder.
- Drainage is usually more difficult and costly for urban than for rural highways. This is because of more rapid rates and larger volumes of runoff, costlier potential flood damage to adjacent property, higher overall costs from more inlets and underground systems, greater restrictions from urban development, lack of natural water body areas to receive flood water, and higher volumes of vehicular and pedestrian traffic.
- Swale sections present less hazards to traffic than a near vertical curb and hydraulic capacity that is not dependent on spread on the pavement.
- Pavements (surface drainage) typically require a minimum gutter slope of 0.3 percent to promote drainage, and this differs depending on a design discharge and an allowable spread of water across the pavement. In high-speed and high-volume roads, minimizing the spread of water on the traffic lanes should be achieved. Roadway geometric features greatly influence pavement drainage design.[115]
- Partial overlays and pavement repairs can result in water being trapped and retained on the travel way surface (figure 5.131). Partial overlays, either to correct shoulder deterioration or widen the roadway surface, result in a pavement edge where

Figure 5.129: Wide paved shoulder and drainage facility on a downhill slope.

Source: PIARC. 2003. Road Safety Manual, First edition.

Figure 5.130: Typical culvert headwall to be extended/replaced.

Source: © John Barrel.

Figure 5.131: Edge of partial pavement overlay causing water to be retained on surface

Source: Federal Highway Administration. 2009. Maintenance of Drainage Features for Safety, US.

115 AASHTO. 2018. Green Book (GDHS-7), US.

the overlay stops. Depending on the size of aggregate in the overlay mix and the effort taken to feather the lip into the existing pavement, water can be retained on the travel way. When the lip is along the wheel path, the thin layer of retained water can initiate hydroplaning, reduce braking ability, or freeze and contribute to skidding.[116]

Good design practice/ treatments/solutions

- An important part of highway design is consistency, which prevents discontinuities in the highway environment and considers the interrelationship of all highway elements. The interrelationship between the drainage channel and sideslopes is important because good roadside design can reduce the potential severity of crashes that may occur when a vehicle leaves the roadway.
- Discontinuous sections of curbing, as at the gore of ramps, and variable curb offsets should not be used as expedients to handle pavement drainage where these features could contribute to loss of control by vehicles that run off the road.
- Deep and open drainage structures near the roadway must be avoided, as they constitute rigid obstacles that may aggravate crash severity.
- Adequate sight distance for drivers must be provided to ensure vehicles can stop before entering any floodwaters. The floodway longitudinal profile should be horizontal so that the same depth of water exists over the entire floodway length. The floodway length should be limited and on a straight stretch of road where possible. Adequate permanent and temporary signage and delineation must be installed.
- When combined with the design of an elevated roadway on earth embankment to ensure drainage of the subgrade, the streamlined cross section results in a roadway that needs minimal maintenance and operating costs and operates with fewer severe crashes. Inadequate height and slope of the embankment and any infrastructure to prevent run-off-the-road can be a risk.
- Hydraulic capacities and locations should be designed to take into consideration damage to upstream and downstream property and to reduce the likelihood of traffic interruption by flooding.
- Inadequate drainage can lead to high maintenance costs and adverse operational conditions.
- In areas of significant snowfall, roadways should be designed so that there is sufficient storage space outside the travelled way for plowed snow and proper drainage for melting conditions.
- Median areas should preferably not drain across travelled lanes, and often the inside lanes and shoulder of multilane highways will drain to the median area where a center swale collects the runoff. Medians may be drained by drop (grate)-type inlets.
- Drainage channel design in rural areas should incorporate traversable roadsides, good visibility, control of pollutants, and economical maintenance. This may be accomplished with flat sideslopes, broad drainage channels, rain gardens, and liberal warping and rounding. In urban areas, runoff is often captured in enclosed storm drains, and rain gardens may be used to reduce the amount of runoff.

For roadside users

- Drainage facilities should be designed to minimize their impacts on motor vehicles. Culvert end treatments should not be an obstruction, either through relocation of the feature outside of the 5 m clear zone from the edge of the running lane, or where this is not possible, an assessment

116 FHWA Federal Highway Administration. 2009. A Guide for Local Street and Highway Maintenance Personnel, US. https://safety.fhwa.dot.gov/local_rural/training/fhwasa09024/.

should be undertaken to establish whether the end treatments can be made traversable (figure 5.132). If neither remedial treatment is possible then safety barriers should be considered. All shoulder slopes into ditches should be at a maximum of 1:3 and desirably 1:6.

- In areas where roadway surfaces are warped, such as at cross streets or ramps, surface water should be intercepted just before the change in cross slope. Flumes are used to carry the water collected by intercepting channels down cut slopes and to discharge the water collected by shoulder curbs. Flumes can either be open channels or pipes (figure 5.133), but closed flumes or pipes are preferred to avoid failure due to settlement and erosion.
- Visual, audible, and other physical deterrents, such as safety barriers, should be used to warn drivers of hazardous locations (e.g., steep slopes or drains close to a carriageway) and to prevent vehicles straying from the carriageway (figure 5.134).
- When the capacity of the curb/gutter/pavement section has been exceeded (e.g., near low points of sag vertical curves, pedestrian crossings, etc.), drainage inlets that are connected to a storm drain pipe can be installed to divert runoff from the roadway surface. However, grate inlets alone are not recommended in sag locations because of potential clogging.
- Pit lids of inlets and channels should be designed to ensure the safety of motor traffic, maintenance vehicles and plants, and pedestrians and cyclists. Pit lids should be designed to carry the appropriate motorist's, cyclist's and pedestrian's passing and loading if necessary.
- For high-speed roads, pit lids should not be located within the traffic lanes. If necessary, they should be located outside the clear zone. On low-speed roads, pit lids should also be located outside of traffic lanes, as the lids can cause impacts, cause noise, come loose, and cause safety problems.

For maintenance

- To prevent reduction in the hydraulic capacity or clogging, drainage facilities should be designed and located to prevent silt and debris carried in suspension from being deposited on the travelled way where the longitudinal gradient is decreased.
- Lining materials (e.g., glass, concrete, chutes, etc.) should be considered depending on flexibility, durability, cost, and so forth.
- Drainage channels should be kept clean and free of material that would lower the channel's capacity by timely and periodic maintenance (e.g., removing garbage, backfilling for erosion, weeding, etc.). As floodwaters recede, silt and debris can be left on the road surface of a floodway, and this can be

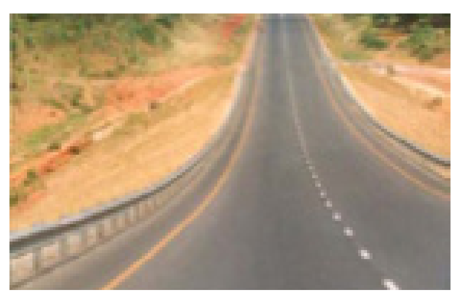
Figure 5.132: Typical extended culvert and revised headwall design.

Source: © John Barrel.

Figure 5.133: Piped flume.

Source: FOA, 2020. NZ Forest Owners Association. 2020. NZ Forest road engineering manual, operators guide 2020, New Zealand.

Figure 5.134: Physical barrier in front of the drain.



Source: DFID, 2003.

Figure 5.135: Poorly drained road with rough driving surface (sediment source).

Source: -> USAID. 2003. Low- Volume Roads Engineering: Best Management Practices Field Guide, US.

Figure 5.136: Poor road location with creek and hydrological connection to streams.

Source: USAID.

Figure 5.137: Slide material blocking drainage ditches.

Source: USAID.

a hazard to road users. The road agency should inspect each affected floodway as soon as possible after a flood event and clear the surface if required.

- Figures 5.135 through 5.137 show some examples of poorly drained roads.
- Below is a summary of minimum grades; however, no general recommendation can be made for adopting any particular axis of rotation or conditions.

Cross slopes

- Drainage of curbed roadways on sag vertical curves needs careful profile design. At a level point on a crest vertical curve, there is no difficulty with drainage if the curve is sharp enough or the road surface has sufficient crossfall or superelevation.
- Flat grades can typically provide proper surface drainage on uncurbed highways where the cross slope is adequate to drain the pavement surface laterally. With curbed highways or streets, longitudinal grades should be provided to facilitate surface drainage.
- Warping of the gutter for curb-opening inlets should be limited to minimize adverse driving effects. The width of a vertical or sloping curb is considered a cross-section element entirely outside the travelled way. Also, a gutter of contrasting color and texture should not be considered part of the travelled way. When a gutter has the same surface color and texture as the travelled way and is not much steeper in cross slope than the adjoining travelled way, it may be considered as part of the travelled way. This arrangement is used frequently in urban areas where restricted right of way width does not allow for the provision of a gutter.
- In the superelevation transition section, the combination of an inadequate crossfall and a longitudinal design gradient may result in the edge of the pavement having negligible longitudinal fall. This can lead to poor pavement surface drainage, especially on curbed cross sections. This length of the transition section should be closely contoured to understand the wider pavement shape, including the tangent runout section and an equal length of the runoff section on the curve (see section 5.4 Superelevation).
- For these problems, providing a minimum profile grade or a minimum edge-of-pavement grade in the transition section can be considered to maintain a certain profile grade and edge-of-pavement grade.

- The depth of a roadside open drain or channel should be minimized, but less than 150 mm in depth to prevent the vehicle from overturning. Deeper drains should be accompanied with flatter slopes.[117]

Channel side slopes

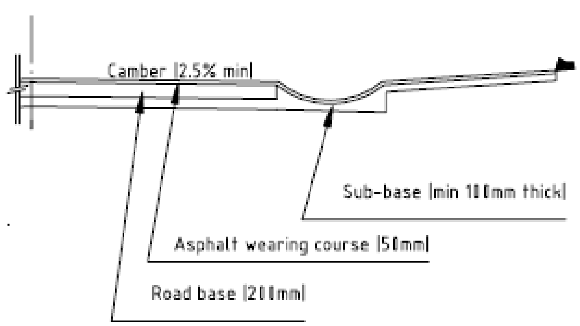
- A broad, flat, rounded drainage channel provides a sense of openness with a sideslope of 1V:4H or flatter. Weather conditions should be considered.

Good practices/examples

Figure 5.138: Hazardous drainage facility on a narrow and hilly road.

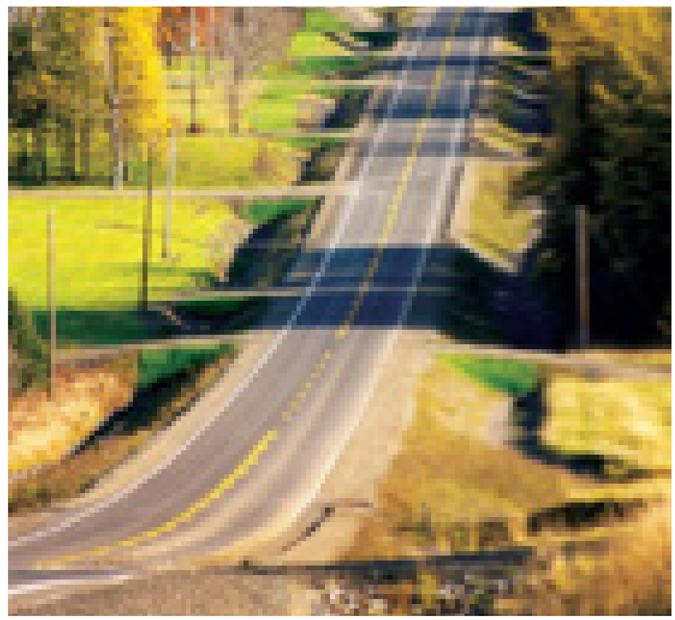
Source: PIARC, 2003.

Figure 5.140: Parabolic dish drainage (good hydro-dynamics but low capacity).



Source: DFID, 2003.

Figure 5.139: The combination of roadside accesses and deep opened drainage ditches increase the risk and potential severity of crashes.



Source: PIARC, 2003

Figure 5.141: Earth excavated drainage in Malawi.

Source: DFID.

117 DFID. 2003. CaSE Highway Design Note 1 Surface Water Drainage Channels. DFID (2003). CaSE Highway Design Note 1, Surface Water Drainage Channels.

Figure 5.142: Unprotected drainage.

Source: DFID, 2003.

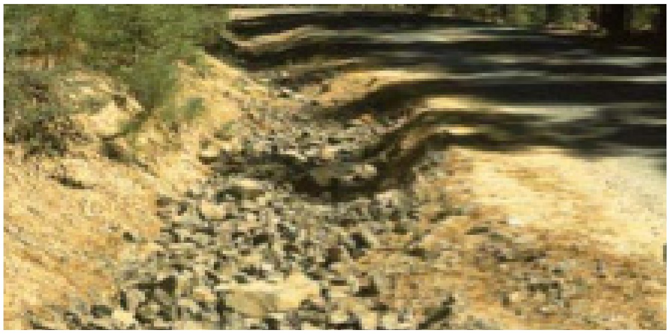
Figure 5.143: Armor ditches with vegetation, rock, masonry, or concrete to resist ditch erosion.

Source: USAID, 2003.

Figure 5.144: Safely widened shoulder and drainage.

Source: DFID, 2003.

Figure 5.145: Armored roadside ditch with graded rock (riprap) for erosion control.



Source: USAID, 2003.

Case Study

Transverse Gutters on Highway, Germany[118]

In the German region of Brandenburg, in a sector of the A10 Highway south of Berlin, there is a highly dangerous road segment made of concrete, which was built in the years immediately following the unification of Germany. Even though its design took into consideration weather conditions with heavy rainfall, due to climate change the proposed transverse slope was not sufficient, which subsequently resulted in a high number of road crashes due to the phenomenon of aquaplaning. The only adequate method for this section involved construction of transverse gutters made of concrete and covered with metal bars (figure 5.146). These gutters were built across the entire width of the carriageway, including the emergency lane in the case of highways. The gutters are no less than 30

Figure 5.146: Transverse gutter.

Source: Burlacu, F. A., Răcănel, C., and Adrian Burlacu, A., 2018.

118 Alina Burlacu, Carmen Răcănel, and Adrian Burlacu. 2018. Preventing aquaplaning phenomenon through technical solutions. Građevinar 12/2018. Accessed at http://casopis-gradjevinar.hr/assets/Uploads/JCE-70-2018-12-4-1578-EN.pdf.

cm in width, and several can be assembled along a sector, at a minimum distance of 5 meters between individual gutters. An analysis of this solution using a dedicated computer software called "Pavement Surface Runoff Model" showed that the transverse gutters result in the decrease of water film depth from 6 mm to 4 mm, and even to 2 mm, which considerably diminishes the risk of aquaplaning.

Further Reading

- AASHTO. 2018. Green Book (GDHS-7). Must read chapter 3, Elements of design.
- Austroads 2018. Guide to Road Design Part 5, Drainage—General and Hydrology Considerations.
- USAID. 2003. Low-Volume Roads Engineering: Best Management Practices Field Guide. Must read chapter 5, Hydrology for drainage crossing design.
- DFID. 2003. CaSE Highway Design Note 1, Surface Water Drainage Channels. https://www.gov.uk/research-for-development-outputs/case-note-1-drainage.
- FHWA. 2009. A Guide for Local Street and Highway Maintenance Personnel. https://safety.fhwa.dot.gov/local_rural/training/fhwasa09024/.

5.12. Curbs

General description

Curbs (also kerbs) are raised or vertical elements located very near the edge of the travelled way that usually extend 75 to 200 mm above the road surface. They serve the following purposes: drainage control, delineation of the pavement edge, delineation of pedestrian walkways, right-of-way reduction, reduction of maintenance operations, aesthetic purposes, and assistance in orderly roadside development.[119]

Curbs are commonly used in urban areas, with a major benefit in containing drainage within the pavement area, separating pedestrians from traffic flow, and in channelizing or controlling traffic into and out of adjacent properties. They can be placed on medians or edges of the travelled way. Curbs may be constructed using various materials, including cement concrete, granite, and asphalt/bituminous concrete and are often combined with gutter sections.

There are two basic curb design types: vertical (figure 5.147) and sloping curbs (figure 5.148). Vertical curbs, also referred to as barrier curbs, have a vertical or

Figure 5.147: Concrete vertical curb.

Source: Government of UK, Department of Transport. 2020. Transport Secretary acts to make pavements safer for pedestrians. Accessed at https://www.gov.uk/government/news/transport-secretary-acts-to-make-pavements-safer-for-pedestrians.

Figure 5.148: Sloping curb providing access to driveway.

Source: Wayne Eddy. http://lgam.wikidot.com/fully-mountable-kerb-and-channel-photo-no-1.

119 AASHTO. 2001. Policy on geometric design of highways and streets. American Association of State Highway and Transportation Officials, Washington, DC, 1(990), 158.

nearly vertical face and deter vehicles from leaving the roadway. Sloping curbs, also referred to as mountable curbs, have a sloped face to permit vehicles to encroach on them readily when needed. They are usually used in situations where it is desirable to provide access to the roadside in emergency situations and to adjacent properties. From these basic curb design types, there are further types, including semi-barrier and semi-mountable curbs with a variety of designs.

Safety implications

- Curbs are primarily used on low-speed facilities, and caution should be applied when installing curbs on high-speed facilities. According to AASHTO (2010),[120] installing curbs instead of narrow flush shoulders on urban four-lane undivided roads appears to increase off-the-road and on-the-road crashes of all severities. Installing curbs on suburban multilane highways instead of narrow flush shoulders appears to increase crashes of all types and severities.
- Vertical curbs have an ability to redirect an errant vehicle in a direction parallel to the travelled way provided the impact velocity and angle are modest; a situation applicable to low-speed facilities. The redirectional capabilities occur at speeds of approximately 40 km/h or lower.
- Vertical curbs or steeply sloped curbs can be a hazard to cyclists and motorcyclists.
- On high-speed facilities, vertical curbs are a safety hazard (figure 5.149). A high-speed impact with the curb will introduce a roll moment since the vehicle's center of gravity is much higher than that of the top of the curb. This in turn introduces instability into the vehicle's trajectory that may limit a driver's ability to control the vehicle. Since curbs are primarily used for drainage purposes, they are often found in conjunction with steep side-slopes where a rollover would be even more likely.[121]

Figure 5.149: Hazardous vertical curbs on high-speed road.

Source: National Highway Authority. 2019. Guidelines for Road Safety Engineering, Part 1. Government of Pakistan. Retrieved November 15, 2019, from http://www.roadsafetypakistan.pk/download/Guidelines-for-road-safety-engineering-part-1.pdf.

- Figure 5.149: Hazardous vertical curbs on high-speed road.
- There are often circumstances that warrant the use of curbs in combination with safety barriers, for example on the approach to bridge structures where a curb is needed for drainage purposes and an approach guardrail is needed to shield motorists from the steep side slopes of the approaching structure. Concrete barriers can be used as drainage devices so there is no significant reason why a curb would be necessary. It is also unusual to have curb-flexible barrier combinations since these barrier types accommodate very large deflections, up to 3 m, and the vehicle would likely mount the curb while interacting with the barrier. Semi-rigid barriers, on the other hand, are widely used in conjunction with curbs, and an inadequate design of this curb-barrier combination can result in unpredict-

120 AASHTO. 2010. Highway Safety Manual. American Association of State Highway and Transportation Officials, Washington, DC.

121 National Academies of Sciences, Engineering, and Medicine. 2005. Recommended Guidelines for Curb and Curb-Barrier Installations. Washington, DC: The National Academies Press. https://doi.org/10.17226/13849.

Figure 5.150: Example of dangerous curb-barrier combination with the steel barrier just behind the curb.

Source: UNESCAP. 2017. Recommended Design Guidelines on Road Infrastructure Safety Facilities for the Asian Highway Network. Accessed at https://www.unescap.org/resources/recommended-design-guidelines-road-infrastructure-safety-facilities-asian-highway-network.

Figure 5.152: Triple curb in Bucharest, limiting access by pedestrians.

Source: Cozmei, V. 2019, April 23. The sidewalk in Bucharest with three rows of different curbs. HotNews.ro. https://www.hotnews.ro/stiri-administratie_locala-23104851-foto-trotuarul-din-bucuresti-trei-randuri-borduri.htm.

able impact trajectories causing vehicles to vault or underride the barrier (see figure 5.150).

- Very high curbs (greater than 150 mm) on the edges of sidewalks limit access by pedestrians (see figures 5.151 and 5.152).

Figure 5.151: Very high curb (approx. 250 mm) limiting access by pedestrians to the walkway.

Source: UTTIPEC, Delhi Development Authority. 2011. Kerb Heights for Footpaths and Medians PPT. New Delhi.

Good design practice/ treatments/solutions

- Vertical curbs are recommended for built-up areas adjacent to footpaths with considerable pedestrian traffic, shared use paths, and at bus bays (figures 5.153 and 5.154). This is because they reduce the risk to pedestrians, not only as a physical barrier, but also as a psychological barrier as drivers generally tend to shy away from the curb line.
- While curbs are to be designed to discourage motorists from encroaching onto the pedestrian realm, it is desirable that pedestrians can still step up and down from the pedestrian realm to the travelled way. The typical preferred curb height is 150 mm.
- At pedestrian crossing locations, dropped curbs are ideal, as they allow pedestrians, particularly the physically disabled, elderly, and those with prams/strollers, to cross the road with ease[122].
- As an alternative, particularly for unsignalized pedestrian priority crossings, the carriageway can

122 World Bank. 2013. Improving Accessibility to Transport for People with Limited Mobility : A Practical Guidance Note. Washington, DC. https://openknowledge.worldbank.org/handle/10986/17592 License: CC BY 3.0 IGO.

Figure 5.153: Vertical curb adjacent to footpath.

Source: Designing Buildings. 2021. Kerbs. https://www.designingbuildings.co.uk/wiki/Kerbs. World Bank. 2013. Improving Accessibility to Transport for People with Limited Mobility : A Practical Guidance Note.

Figure 5.154: Bus-stop curb to ease passenger access.

Source: Designing Buildings, 2021.

Figure 5.155: Dropped curb at both ends of pedestrian crossing with tactile paving surface.

Source: Zigmars Rozentals. 2017. The "Curb cut effect"—why making things accessible helps everyone, Medium. https://medium.com/@rozentals/the-curb-cut-effect-why-making-things-accessible-helps-everyone-2f712b2c86e.

Figure 5.156: Dropped curb providing access to property.

Source: © Merton Council/Government of the UK.

be raised to footway level and act as a speed control measure (see also section 3.2).

- Where drop curbs are used, they need to be matched at both ends of the crossing location, with a tactile paving surface to facilitate the movement of visually impaired persons (figure 5.155). Drop curbs are also used to allow access by vehicles to properties (figure 5.156).
- Where encroachment by motorists onto the pedestrian realm is an issue, protective techniques such as bollards and planters may be employed, rather than higher curbs.
- Sloping curbs are generally used in the following situations:
    - At the outer mountable island area of intersections, small corner islands, and roundabouts to outline standard vehicle travelled paths.
    - To define the edge of a through carriageway where the crossfall of the adjacent shoulder or parking strip is opposite to that of the through carriageway.
    - Where crossing or encroachment by vehicles larger than the design vehicles is permitted

(e.g., at roundabouts) or expected under emergency conditions (fire truck turnings, etc.).

- ◦ On pedestrian and cycle paths along the grassed edge of asphalt paths to reduce damage to the path from the grass growing into the asphalt path. Curbing along paths also provides visual contrast to the path edge and prevents the verge material erosion onto the path. Figure 5.157 shows an example of the use of sloping and vertical curbs.

- The use of curbs is generally discouraged in higher-speed roadways (greater than 60 km/h) because of their effect on a vehicle's trajectory upon impact. However, they may be required because of restricted right-of-way, drainage considerations, access control, delineation, and other curb functions. It is recommended that sloping curbs be used where such a need exists and should be located at the outer edge of shoulders rather than the edge of the travelled way. Sloping curbs would also enable access to the roadside in case of emergency situations, and motorists can park clear from the travelled way in case the width of the sealed shoulders is not wide enough.
- Since the appearance of cement concrete and bituminous concrete curbs offers little visibility in contrast to normal pavements, particularly during foggy conditions or at night when surfaces are wet, marking of curbs with reflectorized materials such as paints (figure 5.158) and thermoplastics or attaching reflectorized markers to the top of the curb enhances their visibility. Periodic cleaning or repainting is required to maintain this visibility.
- For curb-barrier combinations, it is important to note that a curb can have an effect on a vehicle's trajectory, which often involves the transformation of longitudinal kinetic energy to vertical and rotational kinetic energy that is hard to control. For this reason, one approach to the design is to place the curb behind the face of the barrier or flush with the barrier and limiting the deflection of the barrier by stiffening. It is recommended that the curb to be used should be of the sloping type and not more than 100 mm in height. Common methods of stiffening the guardrail include nesting two sections of W-beam, adding a W-beam on the back of the barrier, adding a rub rail, and reducing the post spacing. A second approach is to laterally offset the barrier behind the curb by a distance sufficient to allow a traversing vehicle to return to

Figure 5.157: Sloping curb provided on the median to allow occasional mounting by vehicles on the traffic island as needed, while the vertical curb is provided on the edge of the carriageway to delineate the footpath and discourage mounting by vehicles.

Source: UNESCAP. 2017. Recommended Design Guidelines on Road Infrastructure Safety Facilities for the Asian Highway Network. https://www.unescap.org/resources/recommended-design-guidelines-road-infrastructure-safety-facilities-asian-highway-network.

Figure 5.158: Painted curb on median. The curb, however, does not provide access for persons with disabilities at the crossing.

Source: UTTIPEC, Delhi Development Authority. 2011. Kerb Heights for Footpaths and Medians PPT. New Delhi.

its predeparture vehicle suspension rate.[123] This distance will depend on the impact speed but it is recommended that a minimum distance of 2.5 m is adopted for operating speeds greater than 60 km/h. It should be borne in mind that the alternative situation in which the barrier is omitted may not be an acceptable safety outcome. Careful consideration and safety risk assessment are needed for locations where the above solution cannot be achieved to determine whether a modified outcome is safer than providing no barrier at all.

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- AASHTO. 2001. Policy on geometric design of highways and streets. American Association of State Highway and Transportation Officials, Washington, DC, 1(990), 158. Must read chapter 4, Cross-sectional elements.
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- Transportation Officials. Task Force for Roadside Safety. 2011. Roadside design guide. AASHTO. Must read chapter 3, Roadside topography and drainage features.
- UNESCAP. 2017. Recommended Design Guidelines on Road Infrastructure Safety Facilities for the Asian Highway Network. https://www.unescap.org/resources/recommended-design-guidelines-road-infrastructure-safety-facilities-asian-highway-network.
- UTTIPEC, Delhi Development Authority. 2011. Kerb Heights for Footpaths and Medians PPT. New Delhi. https://www.slideshare.net/UTTIPECworks/uttipec-street-design-guidelines.

5.13. Road Signs

General description

Traffic signs are placed by the traffic authority, through the powers provided by specific national legislation, to provide warnings, information, and details of restrictions or regulations to road users at an appropriate time for them to modify their behavior accordingly. Apart from signs warning of approaching features, there are others for use at the site itself, such as direction chevrons at bends or intersections and regulatory signs at the point of enforcement. The three main functions of traffic signs are to regulate, warn, and inform. In addition, there are increasing amounts of commercial or advertising signage on the highway. These are not strictly traffic signs but do impact on road user safety.

As vehicle technology advances good quality and consistent signing will become increasingly important.

Commercial signs (both regulated and unregulated) are increasingly common in urban areas, and whilst not strictly road signs, can have a significant impact on road safety. The police and certain other public bodies and statutory authorities also have the right to place traffic signs, but only in the limited circumstances provided for by the relevant legislation.

While the national/federal government sets the legislation governing traffic signs' appearance and meaning, decisions about which signs to place and in which scenario is a matter for traffic authorities.

The legal aspects of signage are sometimes misunderstood by practitioners, particularly the prohibition on an authority unilaterally inventing its own nonstandard signs.

123 Transportation Officials. Task Force for Roadside Safety. 2011. Roadside design guide. AASHTO.

- The use of nonprescribed signs on public highways without authorization by the national/federal authority might be deemed unlawful.
- The erection of an unauthorized sign in the highway is an obstruction, and the possible consequences can be severe.

The UN Convention on Road Signs and Signals, commonly known as the Vienna Convention, is a multilateral treaty designed to increase road safety and aid international road traffic by standardizing the signing system for road traffic in use internationally. It was first introduced in 1931 and the latest European Agreement was in 1971. Adoption of the Vienna Convention is however not universal.

Road signs used by countries in the Americas are significantly influenced by the Manual on Uniform Traffic Control Devices (MUTCD), first released in 1935. This reflects the influence of the United States. There are also several American signatories to the Vienna Convention. Both systems are widely used internationally.

With increasing traffic flow and speed, the signing convention is to use more pictograms or symbols than words to convey the message. UN compliant signs must make use of more pictograms in contrast to more text-based US variants. Indeed, most Pan American nations make use of more symbols than allowed in the US MUTCD.

There is a different group of signs for each function, and the signs in each group have a uniform shape to help drivers recognize them quickly. The three groups are:

Regulatory signs. These signs give orders. They tell drivers what they must not do (prohibitory), or what they must do (mandatory). Most of them take the form of a circular disc, although two signs, the Stop sign and the Give Way (Yield) sign, have distinctive individual shapes.

Warning signs. These warn drivers of some danger or difficulty on the road ahead. Most of them take the form of a diamond or an equilateral triangle that points upward.

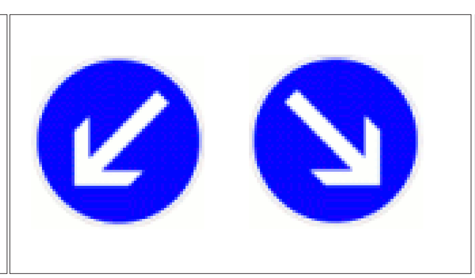
Nearly all countries in the Americas use yellow diamond warning signs, while Vienna Convention-based countries use triangular signs. Recognizing the differences in standards across Europe and the Americas, the Vienna Convention considers these types of signs an acceptable alternative to the triangular warning sign.

Information signs. Most of these signs give drivers information to enable them to find their way to their destination or information about facilities. It is a varied group of signs, but they are all either square or rectangular in shape in advance of a junction. At junctions they will include a triangular end. The background coloring depends on the status of the route (i.e., motorway, or principal or local road).

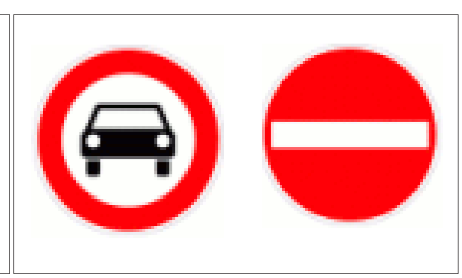
Commercial signs are large outdoor advertising structure (a billboard), typically found in high-traffic areas such as alongside busy roads. They present

Regulatory signs

Yield (Give Way) and STOP signs



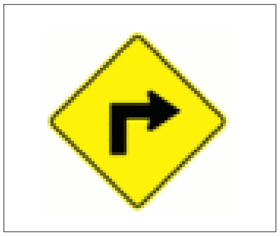
Traffic MUST pass to the right or left



Prohibition of vehicles/entry

Source: Bangladesh Road Transport Authority, 2000.

Warning signs.



Approaching turn may be hazardous without first reducing speed

Bend ahead

Roadworks ahead

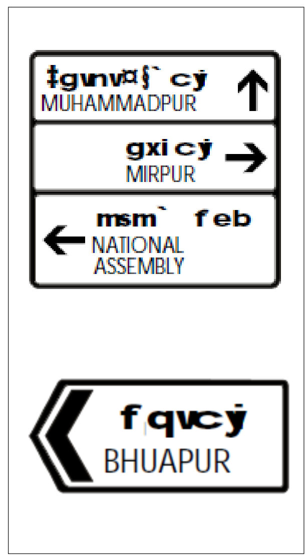
Animal warning sign

Source: Bangladesh Road Transport Authority, 2000.

Information signs

Bus stop/taxi parking

Major route direction signs



Local direction signs

Source: Bangladesh Road Transport Authority, 2000.

large advertisements to passing pedestrians and drivers. While they are present on the highway, they are not classed as traffic signs.

The largest ordinary-sized billboards are located primarily on major highways, expressways, or principal arterials and command high-density consumer exposure (mostly to vehicular traffic) (figure 5.159). These afford the greatest visibility due not only to their size, but because they allow creative "customizing" through extensions and embellishments.

Other commercial signs include extensive shopfront signs and footway mounted "A" boards (figure 5.160). They are all designed to be noticeable and can consequently distract from other relevant signage. Regulations of commercial signs usually exist through the planning process. Their location can present a distraction to drivers and obstruct nonmotorized users' movement, hence, they are a safety concern.

Figure 5.159: Highway advertising—Ukraine.

Source: © John Barrell.

Figure 5.160: Footway signage—Ghana.

Source: © John Barrell.

Safety implications

- There is often a lack of signs in LMICs, or those that are provided are nonstandard and poorly located/maintained.
- In some developing countries there is a multiplicity of languages and written signs require numerous words, which can then become small and difficult to read.
- Literacy may also be limited.
- Consistency of sign appearance and use are essential for road safety, as is the selection of sizes appropriate for the prevailing traffic speed.
- Signs need to be visible in enough time to understand the message and take appropriate action.
- Signs may not be visible at night because of poor illumination, lack of regular maintenance, or continuous power supply.
- Reflective signs not regularly cleaned may not maintain their design properties.
- Maintenance is vital as poor quality, bent, or missing signs are not able to convey messages clearly.
- A recurring problem with signs is their obscuration, either by permanent features such as street furniture, road alignment, and vegetation or by parked vehicles and, on dual carriageways, by moving vehicles in the nearside lane.
- Signs can themselves obscure other features and may be visually intrusive from an environmental point of view
- A major issue in LMICs is the theft and vandalism of signs.
- Overuse of signs is distracting to the road user.
- Too many signs can detract from their objective by overloading the driver with information leading to confusion, or to a situation where the driver ignores some signs.
- Warning signs sited at different distances from the associated hazards in different localities, for instance, could mislead road users who venture outside their local area.
- Inconsistency in route guidance can result in drivers making unsafe and inappropriate lane and turn decisions.
- Advertising signs are designed to attract the user's attention and pose a major distraction. Their prominent use at junction and complex locations is dangerous.

- A common problem occurs at roadworks as signs are often poorly placed by contractors.
- There is an emerging trend in the literature suggesting that roadside advertising signs can increase crash risk, particularly for those signs that have the capacity to frequently change (often referred to as digital billboards).[124]
- A comprehensive review found that crash risk increases by approximately 25–29 percent in the presence of digital roadside advertising signs compared to control areas.
- However, studies based on correlations between crashes and billboards face the problem of underreporting: drivers are unwilling to admit responsibility for a crash, so will not admit to being distracted at a crucial moment. Even given this limitation, some studies have found higher crash rates in the vicinity of advertising using variable message signs or electronic billboards.[125]

Good design practice/ treatments/solutions

- In order to achieve safe and efficient operation of a highway network, it is essential that all signing provided is:
    - Necessary,
    - Clear and unambiguous,
    - Gives its message to road users at the appropriate time and is easily understood at the point it is needed—neither too soon that the information might be forgotten, nor too late for the safe performance of any necessary maneuver, and
    - Does not provide an unnecessary distraction.
- To obtain the fullest benefits of uniformity, therefore, there should not only be uniformity of signs but also uniformity in their use, siting, and illumination (figure 5.161).
- The siting of signs is critical—they need to be far enough in advance of a feature to give sufficient time for the message to be understood and obeyed, but not so far in advance for the message to be forgotten by the time the feature is reached.
- The amount of information given at a single location or sign should be limited to no more than four lines/messages, as anything more cannot be absorbed in time (figure 5.162).

Figure 5.161: Inconsistency of guidance information.

Source: © Alina F. Burlacu/GRSF/World Bank.

Figure 5.162: Overuse of signs is distracting.

Source: © Alina F. Burlacu/GRSF/World Bank

124 Oviedo-Trespalacios, Oscar; Truelove, Verity; Watson, Barry; and Hinton, Jane A. April 2019. "The impact of road advertising signs on driver behaviour and implications for road safety: A critical systematic review." Transportation Research Part A: Policy and Practice, 122: 85–98.

125 Farbry, J., Wochinger, K., Shafer, T., Owens, N., and Nedzesky, A. 2001. Research review of potential safety effects of electronic billboards on driver attention and distraction. Washington, DC: Federal Highway Administration.

Figure 5.163: Expressway with interchange signs and lighting in Hyderabad, India.

Source: © Krishnan Srinivasan/World Bank.

- To avoid problems of signs not been seen in time, attention should be paid to vegetation (bearing in mind the rapid growth that occurs seasonally) and parking restrictions. If sign blockage is thought likely due to other moving vehicles then overhead signs or repeated side-mounted signs should be considered.
- Signs must be visible in darkness. In rural areas this can be achieved with reflective signs; in urban areas it may require externally or internally illuminated signs, depending upon prevailing lighting conditions, as reflectivity can be affected by other light, and drivers may not be using full headlights in urban areas (figure 5.163).
- Regular maintenance is important to maintain visibility, function, and presence of signs.
- Making signs of material that have little value or other uses, together with mounting at a height that is difficult to reach (while still being readily seen by users) can make them less susceptible to theft. Secure fixing to supports that are equally redundant if removed also helps.
- It is particularly important that they should not constitute a hazard in themselves to vehicles leaving the road or obstruct visibility or movement.
- Signs should be sited far enough away from the running lanes as to not present a hazard should a vehicle leave the highway. Where signs may present a hazard to errant vehicles, they need to be adequately protected. To this end, recent developments include a variety of signs which absorb impact energy or knock down and can be driven over but spring back into position in the event of a collision.

Further Reading

- FHWA. 2009. Manual on Uniform Traffic Control Devices (MUTCD). Must read part 2, Signs.
- UNECE. 2006. Vienna Convention on Road Signs. Accessed at https://unece.org/DAM/trans/conventn/Conv_road_signs_2006v_EN.pdf.
- Department for Transport, UK government. 2018. Traffic signs manual. https://www.gov.uk/government/publications/traffic-signs-manual.

5.14. Line Marking

General description

A line marking (or road marking) is any kind of device or material that is used on a road surface to provide guidance and information to all road users.

The essential purpose of road markings is to guide and control traffic on a highway. They supplement the function of traffic signs, serve as a psychological barrier, and signify the delineation of a traffic path and its lateral clearance from traffic hazards for the safe movement of traffic. Hence, they are very important to ensure the safe, smooth and harmonious flow of traffic. This is likely to become more important with autonomous vehicles that rely on good quality road markings for lane guidance.

They can be used to delineate traffic lanes, inform motorists and pedestrians, serve as noise generators (when installed with an audio tactile raised profile) when run across a road, or attempt to wake a sleeping driver when installed in the shoulders of a road. Road surface markings can also indicate regulations for parking and stopping. They can be either longitudinal (along the roadway); transverse (across the roadway) or provide written words or symbols.

Uniformity of the markings is an important factor in minimizing confusion and uncertainty about their meaning, and efforts exist to standardize such markings across borders. However, countries and areas categorize and specify road surface markings in different ways.

- In general European countries follow the Vienna Convention on road signs and signals, which describes what road signs and road markings shall look like. Most European countries use white for routine lane markings of any kind. Yellow is used to mark forbidden parking, such as at bus stops. However, Norway has yellow markings separating traffic directions.
- Many countries use yellow, orange, or red to indicate when lanes are being shifted temporarily to make room for construction projects.
- Almost all countries in North and South America have solid and intermittent yellow lines separating traffic directions.
- Chile and Argentina have intermittent white lines separating traffic when overtaking is permitted from both directions, and solid yellow lines when overtaking is prohibited from both directions; when overtaking is permitted from only one direction, such countries separate traffic with a combination of white and yellow lines.

Line markings serve a very important function in conveying to road users information and requirements which might not be possible using upright signs. They have the advantage that they can often be seen when an upright sign is obscured and can also provide a continuing message.

They are comparatively cheap to install but need regular maintenance, as heavy traffic can wear them out quickly. Different types of line markings have different durability and reflectivity properties (described below). Selection of type of line marking should consider these important aspects of performance.

There is continuous effort to improve the road marking system, and technological breakthroughs include adding retro reflectivity, increasing longevity, and lowering installation cost.

Safety implications

- Line markings have their limitations.
    - They can be completely obscured by snow,
    - They provide less skid resistance than the surrounding road surface,
    - Removal and repositioning of road markings can leave a ghost marking that can confuse users,
    - Their conspicuity is impaired when wet or dirty, and
    - Their effective life is reduced if they are subjected to heavy trafficking.
- Marking on traffic calming devices is very important and sometimes due to rain, or over time due to the quality of the paint, the marking is not visible (figure 5.164).

Figure 5.164: Faded pedestrian crossing markings in Cambodia.

Source: © Blair Turner/GRSF.

- They make a vital contribution to safety, e.g., by clearly defining the path to be followed through hazards, by separating conflicting movements, and by delineating the road edge on unlit roads at night.
- They can also help to improve junction capacity and make best use of available road space. In particular, widespread use of lane markings is desirable as they encourage lane discipline and improve the safety and efficiency of traffic flow.
- The guidance function is less critical (although still important) in daylight or on lit roads because there are many visual cues available to enable the driver to judge course and position. On unlit roads at night, conditions are very different; the visual stimuli in the distance and to the sides of the road are largely absent. Road markings then become the most important aid in enabling the driver to follow the road.
- Collaborative European research has shown that drivers need to be able to detect guidance markings at a distance equivalent to a minimum of two seconds of travel time. If the visibility is less than this, drivers tend to adjust too late when the road changes direction. They run too close to the centerline on nearside bends, or too close to the road edge on offside bends. The higher the prevailing traffic speed, the greater the visibility distance required to maintain this two second "preview time." If it is not provided, drivers tend to miss the curve, or proceed in a series of staggers.
- Almost all the recent crash research has been geared toward adding edge lines to highways. Recent crash studies as well as those more than a half century old have conclusively shown that adding edge lines to rural two-lane highways can reduce crashes and fatalities. In a recent study, driver workload was reduced after edge lines were added to narrow two-lane highways.[126]
- Visibility distance is adversely affected by glare from oncoming vehicles, dirty headlamps, or windscreen, and especially by rain; the glass beads which produce the nighttime luminance are drowned by excess water, greatly reducing the brightness of the line.
- Older drivers also see a marking less well than younger drivers; someone seventy years old might suffer a reduction in visibility distance of more than 20 percent compared with drivers in their twenties.

Good design practice/ treatments/solutions

- Line marking layout should always be considered in detail at the design stage of any scheme.
- Markings have two principal functions:
    - The first is symbolic; the driver needs to have learned, for example, that a hollow triangular marking with its apex downward means "yield".
    - The second is guidance; centerlines, edge lines, and lane lines help drivers to maintain their lateral position on the road. Some markings, e.g., hazard lines and double white line systems have both symbolic and guidance functions.
- A variety of factors influence the visibility distance of a road marking. It is increased when a line is wider, has a higher mark-to-gap ratio, or has a higher coefficient of retroreflected luminance (in the day time, higher contrast with the road surface).
- Longitudinal lines should be designed to ensure a flowing alignment, avoiding sudden changes of direction or sharp tapers of inadequate length (figure 5.165). They can be machine or hand laid in paint, thermoplastic, or preformed tape.
- For line markings to be effective, they need to be clearly visible both by day and by night.
- Most line markings that have a guidance function

126 Paul J. Carlson, Eun Sug Park, and Carl K. Andersen. 2008. The Benefits of Pavement Markings: A Renewed Perspective Based on Recent and Ongoing Research. US Federal Highway Administration.

Figure 5.165: Unexpected deviation of line marking—India

Source: Blair Turner/GRSF.

are required to be illuminated by retroreflecting material (figure 5.166). Retroreflectivity is achieved through the addition of glass beads applied directly to the surface of the line marking during the application process and, in the case of thermoplastic, through the presence of glass beads incorporated within the material itself. This makes the marking much brighter at night than non-reflectorized materials.

Further Reading

- FHWA. 2009. Manual on Uniform Traffic Control Devices (MUTCD). Must read part 3, Markings.
- Department for Transport, UK government. 2019. Traffic signs manual. Must read chapter 5, Road markings, MUTCD.

5.15. Street Lighting

General description

A streetlight is a raised source of light, usually situated on top of a light pole (column), lamppost, or lamp standard on the edge of a road or path, or in the median of a divided carriageway. It may also be suspended on wires over the carriageway.

Figure 5.166: Line markings illuminated by retroreflecting material.

Source: Training presentation by John Barrell, © Fabian Marsh.

It is rarely provided in isolation, but as part of a wider network to create a consistent level of illumination across a wider, usually urban, area or road corridor.

Increasingly urban lighting is also being installed in low-level bollards and flush with the footway to provide less light pollution.

Many lamps have light-sensitive photocells that activate the lamp automatically when needed, at times when there is little to no ambient light, such as at dusk, dawn, or at the onset of dark weather conditions. This function in older lighting systems could be performed with the aid of a solar dial.

Many streetlight systems are being connected underground instead of wiring from one utility post to another.

Street lighting provides a number of important benefits. It can be used to promote security in urban areas and to increase the quality of life by artificially extending the hours in which it is light so that activity can take place.

Street lighting also improves safety for drivers, riders, and pedestrians.

Incandescent lamps were primarily used for street lighting until the advent of high-intensity gas-discharge lamps. They were often operated at high-voltage series circuits. Series circuits were popular since their higher voltage produced more light per watt consumed. Furthermore, before the invention of photoelectric controls, a single switch or clock could control all the lights in an entire district.

Today, existing street lighting commonly uses high-intensity discharge lamps. Low-pressure sodium (LPS) lamps became commonplace after World War II for their low power consumption and long life. Late in the twentieth century high-pressure sodium (HPS) lamps were preferred. Such lamps provide the greatest amount of photopic (color) illumination for the least consumption of electricity.

New street lighting technologies, such as LED or induction lights, emit a white light that provides high levels of scotopic (low-level) lumens, allowing street lights with lower wattages and lower photopic lumens to replace existing street lights. However, there have been no formal specifications written around photopic/scotopic adjustments for different types of light sources, causing many municipalities and street departments to hold back on implementation of these new technologies until the standards are updated.

Safety implications

- Major advantages of street lighting include prevention of crashes and increase in safety.[127]
- White light sources have been shown to double driver peripheral vision and improve driver brake reaction time by at least 25 percent to enable pedestrians to better detect pavement trip hazards and to facilitate visual appraisals of other people associated with interpersonal judgements.[128] Studies comparing metal halide and high-pressure sodium lamps have shown that at equal photopic light levels, a street scene illuminated at night by a metal halide lighting system was reliably seen as brighter and safer than the same scene illuminated by a high-pressure sodium system.[129]
- Street lighting represents a major infrastructure cost for LMICs, and the reliability of maintenance and power supplies can render their provision less effective. Advances in solar power are increasing the viability and acceptance of street lighting as a positive social and safety improvement in communities.
- There are also physical dangers to the posts of streetlamps. Streetlight stanchions (lampposts) pose a collision risk to motorists and pedestrians.
- Most of the information drivers utilize in traffic is visual. Visual conditions can therefore be very significant for safe travel.
- In the dark, the eye picks up contrast, detail, and movement to a far lesser extent than in daylight. This is one of the reasons why the risk of a crash is higher during darkness than during daylight for all road users.
- Studies have shown that darkness results in a large number of crashes and fatalities, especially those

127 Rea, M. S., J. D. Bullough, C. R. Fay, J. A. Brons, J. Van Derlofske, and E. T. Donnell. 2009. Review of the Safety Benefits and Other Effects of Roadway Lighting (report to the National Cooperative Highway Research Program). Washington, DC: Transportation Research Board.

128 Fotios S., and Cheal C. 2013. Using obstacle detection to identify appropriate illuminances for lighting in residential roads. *Lighting Research & Technology*, 45(3); 362–376.

129 Fotios, S. A., and Cheal, C. 2007. Lighting for subsidiary streets: investigation of lamps of different SPD. Part 2—Brightness, *Lighting Research & Technology*, 39(3); 233–252.

involving pedestrians; pedestrian fatalities are 3.00 to 6.75 times more likely in the dark than in daylight.[130]

- Many local authorities (for instance in England and Wales) have reduced street lighting at night to save money and reduce carbon emissions. However, research has not found any statistical evidence that any street lighting adaptation strategy was associated with a change in collisions at night.[131]
- The loss of night vision because of the accommodation reflex of drivers' eyes is the greatest danger for drivers in terms of optical safety risk.
- As drivers emerge from an unlit area into a pool of light from a streetlight their pupils quickly constrict to adjust to the brighter light, but as they leave the pool of light, the dilation of their pupils to adjust to the dimmer light is much slower, so they are driving with impaired vision.
- As a person gets older the eye's recovery speed gets slower, so driving time and distance under impaired vision increases.
- Oncoming headlights are more visible against a black background than a gray one. The contrast creates greater awareness of the oncoming vehicle. Lighting therefore needs to highlight the silhouette of an approaching vehicle or pedestrian effectively.
- High winds or accumulated metal fatigue also occasionally topple streetlights if not maintained.
- Similarly, streetlights are only effective when working. Poor maintenance or lack of consistent power supply can render them ineffective and a collision hazard.

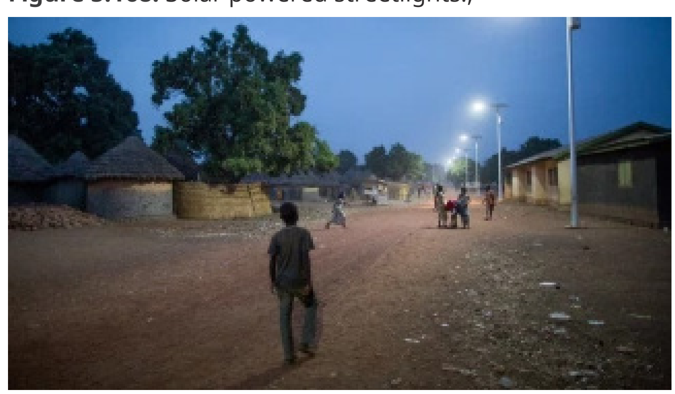
Good design practice/ treatments/solutions

- Lighting is most appropriate in urban streets, and key locations include intersections and places where pedestrians cross.
- The level of illumination needs to be consistent, and maintenance is most important.
- Lighting should provide a uniformly lit road surface against which vehicles, pedestrians, or other objects are seen in silhouette (figure 5.167).
- The design of the lighting system should relate to the road surface reflection characteristics in order to provide the optimum quality and quantity of illumination.
- Light colored surfaces give better silhouette vision than do dark ones.
- Lighting systems can be expensive to install and

Figure 5.167: Village lighting—India.

Source: World Bank.

Figure 5.168: Solar powered streetlights.,



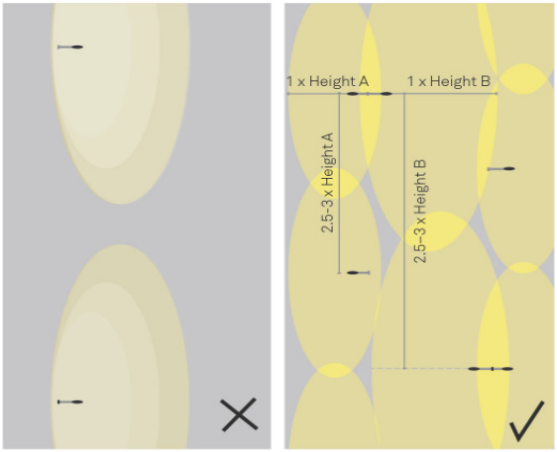
Source: World Bank.

130 John M. Sullivan, and Michael J. Flannagan. 2002. The role of ambient light level in fatal crashes: inferences from daylight saving time transitions. *Accident Analysis & Prevention* Volume 34, Issue 4, July 2002, pages 487–498.

131 Steinbach, R., Perkins, C., and Tompson, L. et al. 2015. The effect of reduced street lighting on road casualties and crime in England and Wales: controlled interrupted time series analysis. J Epidemiol Community Health 69:1118–1124.

maintain. Frequent interruptions to power supplies can also reduce effectiveness. Recent technological advances in solar power generation are making lighting more appropriate for remote communities and LMICs (figure 5.168).

- Spacing between light poles is typically 2.5 times the height of the light source. A single row of lights might be sufficient for a narrow street, but multiple sources are needed for wider streets.
- Light poles that are too far apart result in areas of darkness and can leave users feeling unsafe, as well as affecting the driver's perception of shadow and silhouette
- Rigid lighting columns may be redesigned to provide more forgiving frangible (breakaway) posts and lighting columns, i.e., impact absorbent or slip-base types (figures 5.169 and 5.170).



- Collision risk can be reduced by locating columns away from runoff areas or designing them to break away when hit (frangible or collapsible supports), protecting them by guardrails, or marking the lower portions to increase their visibility, particularly for pedestrians.

Figure 5.169: Slip-base lighting column suitable for high-speed roads with little pedestrian activity and parking.

Source: CAREC, 2018.

Figure 5.170: Impact-absorbing lighting columns suitable for low-speed environments with higher pedestrian activity and parking.

Source: CAREC, 2018.

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- Transport Infrastructure Ireland (TII). 2018. Design of Road Lighting for the National Road Network.
- DN-LHT-03038. https://www.tiipublications.ie/library/DN-LHT-03038-03.pdf.
- Texas Department of Transport. 2018. Highway Illumination Manual. http://onlinemanuals.txdot.gov/txdotmanuals/hwi/hwi.pdf.

6. INTERSECTIONS

An intersection is a location on the highway network where two or more roads or streets meet or cross. They may be classified by:

- Number of roads that meet (approach arms),
- Level (grade-separated or at-grade),
- Form of traffic control (uncontrolled, signalized, or unsignalized), or
- Layout ('T','Y', roundabout, raised).

Grade-separated intersections are sometimes referred to as interchanges.

It is often difficult to determine the best intersection type for any particular location, taking into account all relevant factors and several options that may be possible. The selection of an intersection involves considerations of safety and operational performance, including capacity, compatibility with adjacent intersection treatments, topography at the site, and other factors (see further reading: Guide to Traffic Management Part 6).

Generally, it can be expected that different driving standards and driving behavior will exist in low- and middle-income countries (LMICs) and this may result in some intersection types being unsuitable for use in such countries.

However, from a safety perspective some intersection types are far safer than others. This section provides some general principles related to intersection safety to aid in the selection of intersection types from a safety perspective. More detailed information on each intersection type and other intersection considerations are provided in the following sections.

Safety implications

- The safety needs of all road users, including pedestrians, cyclists, motorcyclists, and people with mobility difficulties, must be considered, as their needs may be a significant factor in the choice of treatment and the type of traffic control adopted.
- Vehicle speeds through an intersection must be managed safely. Low relative impact speeds provide a safer environment for conflicting maneuvers. When collisions do occur at lower speeds, the severity outcome tends to be lower. Speeds above 50 km/h for motorized vehicles, and above 30 km/h for nonmotorized road users lead to increasingly severe crash outcomes (see section 3.1 on Design speed). Lower speeds enable drivers to break and stop more quickly when there are hazards; to make easier judgements regarding speeds of other vehicles and therefore decisions about appropriate gaps in traffic; and to accept smaller gaps thus reducing delays and increasing capacity.
- A change in gradient on approaches to the intersection from more than 3 percent to less than 3 percent appears to be associated with a (marginally significant) reduction in the number of injury crashes of 17 percent, but with an increase in the number of material damage-only crashes.[132]

Good design practice/ treatments/solutions

- The basic principles of good intersection design are that they should allow transition from one route to another or through movement on the main route with minimum delay and maximum safety. To do this, the layout and operation of the intersection

132 Conference of European Directors of Roads. 2008. Best Practice for Cost-Effective Road Safety Infrastructure Investments.

should be obvious and unambiguous, with good visibility between conflicting movements. These objectives need to be achieved at reasonable cost, so the provision of unnecessarily high standards as well as inadequate ones needs to be avoided. Different intersection types will be appropriate under different circumstances depending on traffic flows, speeds, and site limitations.

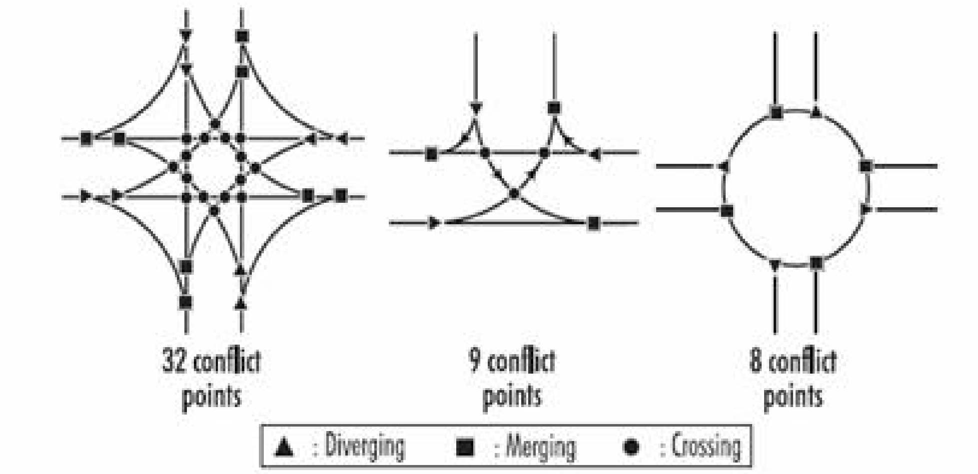
- Intersections should be as simple as practicable and designed to guide users safely through conflict points.
- Intersections introduce an elevated level of risk due to the number of conflict points. One strategy for reducing risk is to remove unnecessary intersections, although this requires the existence of alternative and safe options for road users.
- The various types of intersection layout can provide a hierarchy of alternative layouts catering for increasing levels of traffic flow:
    - Junctions without any designated priority—uncontrolled intersections,
    - Simple priority intersection—Stop or Yield control,
    - Priority intersections with channelization,
    - Roundabouts or signal-controlled intersections, and
    - Grade separated intersections.
- Road network planning must be well considered to avoid creating multi-arm and skewed intersections. Inappropriate approach angles will obscure a driver's sight triangle in the intersection area (figure 6.1). Furthermore, impact angles must be as small as possible (i.e., as close to parallel as possible).
- The potential for severe injury within an intersection can also be minimized through reductions in speed, reduction in the number of conflict points, separation of road users, and/or reductions in the angle of vehicle impact.
- Large intersections with little channelization or deflection can create large open unregulated spaces with multiple conflict points and high vehicle speeds. While solutions would be site specific, the general principle of reducing speed and managing conflict points should be applied to all intersection designs.

Figure 6.1: Uncontrolled Y-intersection in India.

Source: IIT, 2019.

- Conflict points can be reduced through geometric design, including channelization and provision of roundabouts, the addition of deceleration lanes, realignment of the intersection, turn bans, and a reduction in traffic lanes. In general, the number of conflict points at four-leg intersections is much greater than for T-intersections. However, the number of lanes also greatly affects the number of conflict points. Roundabouts result in the fewest conflict points for a four-arm intersection (Figure 6.2).
- Separation of traffic at intersections is another effective means to improve safety, and can also produce benefits in traffic capacity. Grade separation (underpasses and overpasses) are the most substantial form of separation. These substantially reduce the change of conflict between vehicles, especially when well designed.
- Other strategies to address intersection risk include the application of traffic control devices such as signs, markings, and traffic signals. These have benefits in reducing crash risk but do not always reduce the severity of crashes. It is often beneficial from a safety perspective to combine these devices with other measures (such as reductions in speed) to achieve significant safety benefits.
- Cost and necessary activities for maintenance at an intersection should be considered.

Figure 6.2: Conflict points of different intersection types at single-lane intersections.



Source: © European Union, 2021.

Table 6.1: Advantages and disadvantages of different forms of intersections

Intersection type	Traffic characteristics	Primary safety characteristics	Supporting safety measures
Priority	Low flows. Can have high delay to minor road traffic. No delay to major road. Major road needs stopping sight Distance.	Crossing conflicts retained and speed control issues.	Channelization Slip lanes Turn lanes Banned movements Skid resistance improvement Raised platform Advance signing
Roundabout	Low/medium flows. Good for turners having to both cross and merge with traffic streams. Minimal delays at lower flows (i.e., offpeak). Not good for safety of cyclists and other slow vehicles when lacking adequate provision (e.g., segregation).	Although land-hungry, single-lane versions are the closest to safe system compliance for at-grade intersection. Removes all motorized crossing conflicts and reduces them to low angle or merge/diverge. Relatively low speed environment for all, although there are challenges for nonmotorized users unless off-road facilities are provided in moderate to high-speed environments.	Flared approach Skid resistance improvement Advance signing Raised platforms Off-road facilities for cyclists Well defined crossing points for pedestrians and cyclists on each arm
Traffic signals	Low/medium flows. Can accommodate heavy offside turning flows by using filter signal and channelization. Require less space than roundabout. Relatively high delays at off-peak times. Maintenance and power supply can be issues in LMICs.	Separates all conflicts by time control. Requires enforcement or good compliance from all road users. Key risks to crossing traffic or vulnerable users with noncompliance.	Channelization Slip lanes Turn lanes Banned movements Speed/red light cameras Skid resistance improvement Vehicle activated signs Advance signing
Grade separation	High flows. Minimal delays. Requires large area. Expensive.	Removes all crossing conflicts and reduces them to merge/diverge.	Street lighting Advance signing Speed reduction/limits

Further Reading

- Austroads. 2019. Guide to Traffic Management Part 6.
- Austroads. 2016. Safe System Assessment Framework (Research Report AP-R509-16).

6.1. Uncontrolled and Unsignalized (yield) Intersections

General description

An uncontrolled intersection is an intersection controlled by only general road rules (i.e., traffic laws), with no traffic control devices such as signs, road markings additional lanes, or channelization in place. They are the simplest form of intersection provided on the road network. For example, in the US, "when two vehicles approach or enter an intersection from different highways at approximately the same time, the driver of the vehicle on the left shall yield the right-of-way to the vehicle on the right." Uncontrolled intersections are usually limited to very low-volume roads in rural or residential areas.[133]

If traffic control devices are in place, then the intersection can be called an unsignalized or priority intersection. Unsignalized intersections can also be subdivided into those where the minor approach is required to yield to traffic on the main road and those where circulatory movement controls the entry of approaching traffic. This section only considers those intersections where no circulatory control is provided.

All control of potential conflicts at yield intersections, including those achieved by regulatory signs or road markings, are supported by relevant road rules. At uncontrolled intersections, only general road rules, which differ by country/region, control traffic.

However, yield intersections still often account for a high proportion of network delays, conflicts between vehicles, and conflicts between vehicles and other road users (e.g., pedestrians).

Yield intersections are suitable for situations where there are no (or are not likely be) operational problems, such as excessive delays/queues or safety problems (i.e., low traffic volume and low-speed roads, etc.).

Safety implications

- Straight four-arm intersections often have a poor safety record because of minor road traffic failing to stop for main road traffic, either because of driver indiscipline or because the driver is not aware that there is a major road ahead.
- The major crash types at both uncontrolled and yield intersections are where vehicles fail to stop, implying inadequate visibility or awareness of the intersection.
- Crashes with emerging vehicles suggest inadequate sight lines along either the major road or minor road.
- In most of unsignalized intersections, the minor roads lack adequate sight distance, mainly due to encroachments.
- Wrong turns and chaotic traffic movements are commonly observed at these locations. Such untreated minor intersection and access roads may lead to unsafe movement of pedestrians and vehicles whenever present.
- Where intersections are uncontrolled, the lack of awareness by main road drivers for turning vehicles can result in rear-end collisions.
- If the yield line is in the dip at the edge of the major road camber, it can be invisible from a distance on the minor road.
- Speeds of approaching vehicles are also a major cause of collisions.

133 Uniform Vehicle Code at https://iamtraffic.org/wp-content/uploads/2013/01/UVC2000.pdf.

- For all types of uncontrolled or yield intersections, the problem of delay exists for minor road traffic. If the delays are excessive, emerging drivers may take undue risks in order to enter or cross the main stream.
- Multiple lane approaches place greater demands on the emerging driver and tend to be more hazardous locations.
- Slow-moving or stationary vehicles turning into a side road across a main road stream of traffic are often the cause of serious crashes, particularly at night.
- Problems can also be caused in urban areas by inadequate curbs that give an unclear layout and make little or no provision for pedestrians.

Good design practice/ treatments/solutions

- In cases where there are no control devices (i.e., traffic signals and roundabouts), designating or clarifying priority rules (e.g., stop or yield signs/ markings) must be provided to give clear indication of expectation to drivers (figure 6.3). This will also aid separation of conflicting movements in addition to the general intersection rules. These devices prevent or discourage inappropriate traffic movement at the intersection.
- Traffic islands (e.g., triangular left-turn islands) and medians would help to provide delineation and direct traffic into the appropriate path through intersections.
- Although controlling traffic by police officers (or authorized persons) is often used in exceptional circumstances (e.g., peak traffic hours, road work, incidents), this might result in extra delays at the intersection.
- In case any safety treatments cannot be implemented at an uncontrolled intersection, redirecting traffic to a higher quality intersection should be considered.
- Improving intersection conspicuity and driver's sight distance at intersections must be prioritized to increase awareness and readability.
- All obstacles within intersection areas must be removed (figure 6.4). And all unnecessary conflict points must be eliminated. For example, placing a waiting space at the center of an intersection is dangerous because passengers have to enter the intersection to reach the space. Furthermore, the waiting space will be an obstacle for other road user's sights (figure 6.5).

Figure 6.3: Yield signs being used as intersection control.

Source: National Cooperative Highway Research Program. 2015. Unsignalized Intersection Improvement Guide.

Figure 6.4: Sight triangle obstacles from minor road at T-intersection.

Source: IIT, 2019.

Figure 6.5: Obstacle (bus stop waiting space) at center of intersection in India.

Source: IIT, 2019.

Figure 6.6: Stop signs with traffic calming measures at unsignalized intersection.

Source: PIARC. 2003. *Road Safety Manua*l, First edition.

Figure 6.7: Left turn restriction by signs and median at unsignalized T-intersection.

Source: Palo Alto online. Residents frustrated by repeated traffic violations in north Palo Alto, July 5, 2017. https://www.paloaltoonline.com/news/2017/07/04/residents-frustrated-by-repeated-traffic-violations-in-north-palo-alto.

Below is a summary of treatments for uncontrolled/unsignalized intersections:

Approach and minor road treatment

- Advanced warning signs and road markings would help to indicate the existence of an intersection to drivers.
- Placing stop signs on the minor road approach to an intersection can be effective where the sight distance from the minor leg of the intersection is insufficient and it would be unsafe to proceed without stopping. But reassignment of a priority might not perform safely if placed contrary to driver expectation and it does not work as a stand-alone treatment.
- A decision as to whether a stop sign rather than a yield sign is required is based on sight distance available for drivers on the minor road approach, i.e., whether the sight distance from the minor leg of the intersection is inadequate and it would be unsafe to proceed without stopping. It has been found that the use of stop signs in locations with adequate sight distance does not provide additional safety benefits and can lead to a loss of credibility, and their effectiveness will be compromised (see section 5.13 on signs).
- Speed management, also known as “traffic calming” features (e.g., speed humps, raised intersections, etc.) are used in conjunction with stop/yield signs on approaches of intersections to help control speed (see section 3.2 on Speed compliance and traffic calming; section 6.4 on Raised intersections; figure 6.6).
- Channelization, adequate sight distance, or supplemental visibility enhancement, including lighting, should be made available at all the minor junctions.
- Provide flexible poles on both major and minor roads to separate traffic from the opposite direction. This can reduce certain types of crashes.

Movement prohibition measures

- Prohibition of selected movements (e.g., left in/left out, no left or right turn, full-time or part-time, etc.) can reduce certain types of crashes related to

Figure 6.8: No left turn sign with stop marking at unsignalized intersection in Dominica.

Source: DAVIBES. 2016. New signs erected to ease traffic congestion, March 22. https://www.dominicavibes.dm/news-196869/.

limited sight distance and pedestrians that involve left or right turning vehicles. This strategy can also reduce the frequency and severity of crashes.

- The prohibitions can be implemented by channelization, markings, and/or signs (figures 6.7 and 6.8). Signs and/or markings alone will require other physical interventions.
- The prohibitions may be appropriate where a turning movement is considered to be high risk and other strategies are impractical or not possible to implement. This strategy may be difficult to justify at a major intersection unless the left-turn volumes are very low. It is generally preferred to more safely accommodate the turning movement at the point where the driver desires to turn than to displace the turn activity to an alternative location.
- An auxiliary lane provides separation for the maneuvering of a vehicle and is typically used in rural areas where high-speed, low-volume traffic occurs and the volume and slow maneuvering of turning traffic is sufficient to create a conflict with following traffic.
- A left/right turning lane allows traffic to decelerate and turn without affecting through traffic (figure

Figure 6.9: Segregated diverge nearside unsignalized intersection.

Source: AfDB, 2014.

6.9). A right-turn auxiliary lane in left driving (left-turn auxiliary lane in right driving) without channelization might not be effective (see section 6.5 on Turning lane and Channelization).

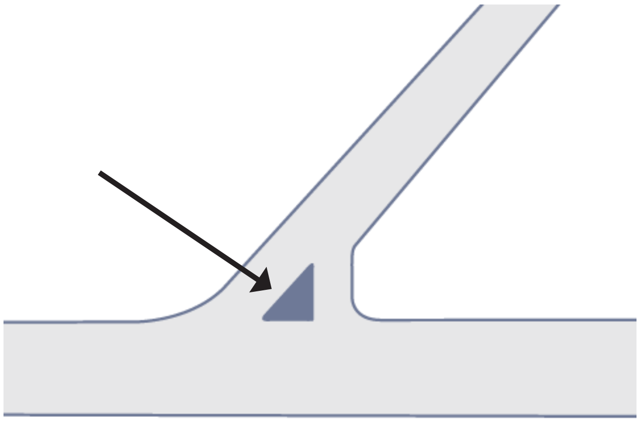
The following are the summary of treatments for Y-(skewed) intersection.

- The speed of approaching vehicles at the intersection is affected by approach angles. Approach angles also affect the crossing distance (footprint) of vehicles at the intersection. Furthermore, appropriate approach angles may improve driver's sight triangle in the intersection area. Approach angles must be determined to achieve the following principles:[134]

1. Limit turning speed around obtuse angle. Acute angled intersections reduce visibility for motorists, while obtuse intersections allow for high-speed turns. A right-angle treatment can work as speed enforcement and can improve a driver's sight triangle (figure 6.11).
2. Shorten the crossing distance (footprint) of vehicles. Compact intersections reduce pedestrian exposure, slow traffic near conflict points, and increase visibility for all users. Both acute- and obtuse-angled intersections create unnecessarily long pedestrian crossings.

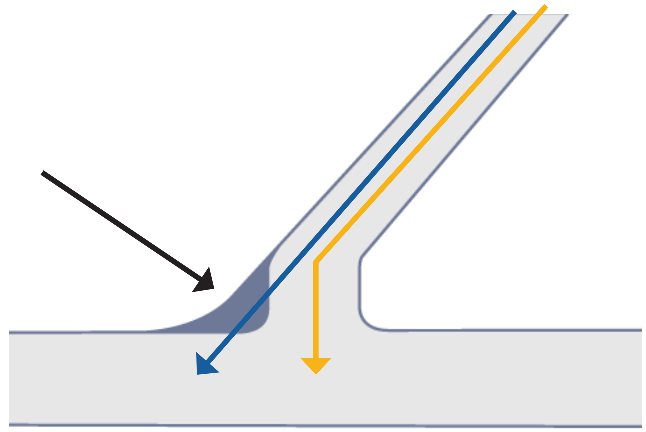
134 National Association of City Transportation Officials (NACTO). 2019. Urban Street Design Guide. Accessed at https://nacto.org/publication/urban-street-design-guide.

Figure 6.10: Island separating traffic at center of minor road.



Source: NACTO

Figure 6.11: Curb changing angle of entering intersection from minor road



Source: NACTO.

3. Separate vehicle flows to reduce conflicts (figure 6.10).

- An angle of less than 90 degrees gives the fewest injury crashes and the opposite appears to be the case for material damage-only crashes. Redesigning an intersection of an angle less than 90º to an angle of 90º may increase injury crashes by 80 percent. On the contrary, redesigning a junction of an angle of 90º to an angle of more than 90º appears to bring a reduction of injury crashes by 50 percent.[135]
- Realignment of an intersection may impact sight distance and/or the impact angle for vehicles involved in collisions at the intersection. Realignment of an intersection is often too costly. It is much better to design the intersection well before it is built than to rebuild it. The reconstruction of an intersection should be implemented when adequate sight distance and countermeasures are not available.

Further Reading

- FHWA. 2009. Manual on Uniform Traffic Control Devices (MUTCD). Must read chapter 2b, Regulatory signs, barricades, and gates.
- Austroads Guide to Traffic Management Part 10: Traffic Control and Communication Devices (Austroads 2019e).
- Institute of Transportation Engineers (ITE). 2015. Unsignalized Intersection Improvement Guide. https://toolkits.ite.org/uiig/.

135 Conference of European Directors of Roads. 2008. Best Practice for Cost-Effective Road Safety Infrastructure Investments.

Case Studies/ Examples

Figure 6.12: Minor road treatments—traffic calming and warning signs in India from minor road perspective.

Source: IIT, 2019.

Figure 6.13: Minor road treatments—traffic calming and warning signs in India from major road perspective.

Source: IIT, 2019.

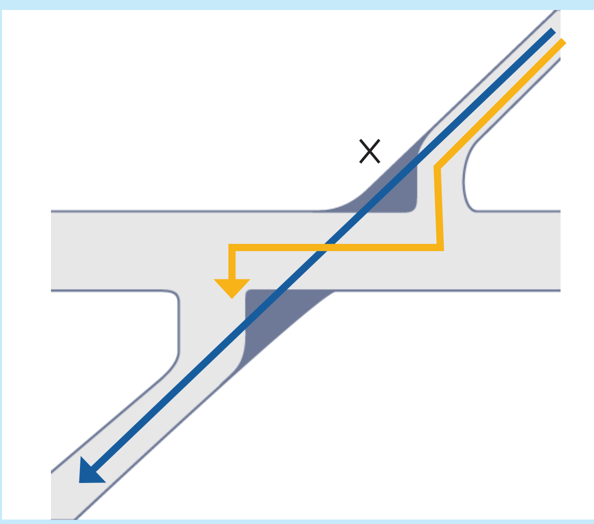
Figure 6.14: Installing movement prohibition measures and pedestrian protection measures—Colombia.

Source: iRAP.

Box 6.1: Staggered Intersections

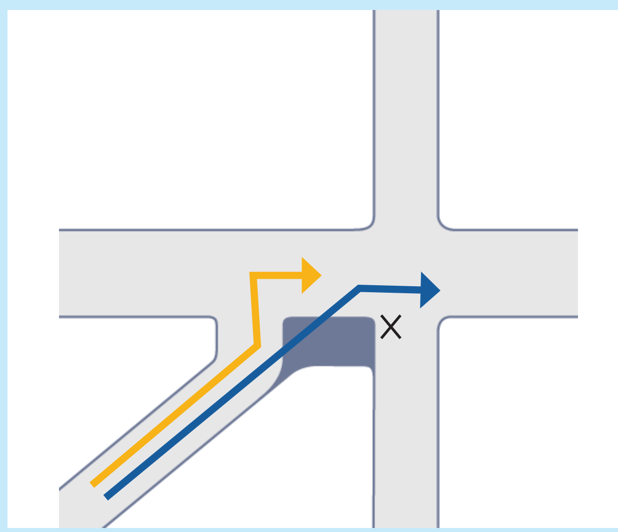
- Staggering intersections (converting to two mini-intersections) results in a reduction of the number of conflict points. This treatment can be applied at over five-arm intersections and four-arm intersections, which have obscure sight distances or have crash records (figures 6.15 and 6.16). Staggering needs to be far enough apart to operate as two, or close enough to operate as one.
- Staggered intersections may result in a 33 percent reduction of injury crashes when the traffic on the minor road is normal or heavy. The effect of staggering intersections strongly depends on the proportion of original traffic on the minor road.
- An Australian study indicates staggered T-intersections should have the following features:
  i. Low major road traffic volumes (< 2000 vpd),
  ii. No significant curvature of the minor road approaches,
  iii. Left-right stagger type (driving on the left of the road), stagger distance ≥ 15 m,
  iv. Warning signs on the major road, and
  v. Not implemented at operation at or near capacity within its design life.

Figure 6.15: Convert four-leg intersections to two T-intersections (right-left staggered intersections). Source: NACTO.



Source: © Alina F. Burlacu/GRSF/World Bank.

Figure 6.16: Convert offset T-intersections to four-leg + three-leg intersection (realign intersection approaches to reduce or eliminate intersection skew). Source: NACTO.



Source: © Alina F. Burlacu/GRSF/World Bank.

Right-left staggered intersections (when left-side driving in the vehicle) induce shorter travel times than both left-right staggered intersections and four-leg intersections, in the sense that drivers coming from the minor road have to give way to only one traffic stream, i.e., when turning to the right onto the main road and then left into the minor road. However, this treatment could be detrimental to traffic operations when the offset between the two T-intersections is insufficient to allow main road traffic to react to slower moving vehicles.

6.2. Signalized Intersections

General description

A traffic signal controlled intersection restricts conflicting traffic movements in time or space by only allowing nonconflicting movements to proceed through the intersection at the same time. It controls vehicular and pedestrian traffic and assigns the right-of-way to the various traffic movements for a given duration, thereby profoundly affecting free traffic flow.

Traffic signals (figure 6.17) operate on the basis of phases and stages. A signal phase is a single movement stream that is assigned a green signal to move or a red signal to stop. Several phases can be combined to create a single signal stage. Once all phases have been allowed to proceed, a full signal cycle of movement through the intersection is completed.

Note: In some countries (e.g., Australia and New Zealand), the terminology is different with a "phase" being a period of time during which a set of traffic movements receive a green signal. This is equivalent to the concept of a "stage" in the UK and the US. One electrical output from the traffic signal controller is called a "signal group," similar to the UK and the US concept of "phase."

The amber signal is used to warn drivers of the approaching change in status between stop and go. The amber period is required to allow for driver reaction time and clearance of conflicting movements through the intersection. The potential conflict points vary by approach and size of the intersection.

The standard sequence of signal changes is:

Red: stop

Red and amber: prepare to go (used in only a small number of countries, including the UK)

Green: go

Amber: prepare to stop

Red: stop

Figure 6.17: Traffic control signal for vehicles in India.

Source: *Times of India*. 2016. Cops want 19 more road signals in city. July 20, 2016. https://timesofindia.indiatimes.com/city/nashik/Cops-want-19-more-road-signals-in-city/articleshow/53296116.cms.

Traffic signals are primarily for the control of motorized traffic but can include specific phases for pedestrian and cycle movement. The amount of time that each movement stream is given to proceed throughout the signal cycle is determined by knowing the amount of traffic that has to negotiate the intersection during a particular period. Different times can be given for different times of day or days of the week. The signals can either operate to a fixed time for each phase/stage/cycle or on "vehicle actuation" where minimum and maximum time periods for any stage can be varied depending on how many vehicles are needing to negotiate the intersection. This usually operates at times of low flow with fixed time plans being used at peak demand periods. The signal operational parameters are reviewed and updated (if needed) on a regular basis (as engineering judgment determines that significant traffic flow and/or land use changes have occurred) to maximize the ability of the traffic control signal to satisfy current traffic demands.

Where a road corridor encompasses two or more signalized intersections, these may be coordinated to achieve greater efficiency gains. In some countries, this principle may be used to create a "green wave" to prioritize a particular movement.

Safety implications

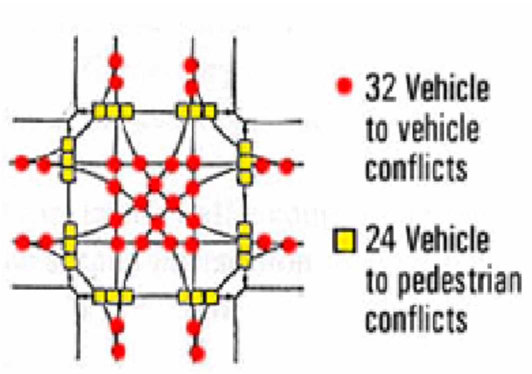
- Appropriate phase control sequences can reduce the frequency and severity of certain types of crashes, especially right-angle collisions, by separating these from other conflicting movements, including pedestrians.
- The common practice of allowing nearside turns through a signal-controlled intersection can still result in substantial collision risk for crossing pedestrians.
- Traffic control signals are sometimes installed at locations where they are not needed, adversely affecting the safety and efficiency of vehicular, bicycle, and pedestrian traffic. The judgment of implementation of traffic control signals at an intersection must be done after consideration of alternatives (e.g., installing pedestrian beacon, roundabout, and so forth). (See section 6 on Intersection selection.)
- The improper or unjustified use of traffic signal control can result in:
  i. Excessive delay,
  ii. Disobedience of the signal indications,
  iii. Increased use of inadequate routes to avoid the traffic signals, and
  iv. Increases in the frequency of collisions (e.g., rear-end collisions).
- Furthermore, the possibility of increase in delays and noise and emissions should be considered.
- It is important to understand that installation of traffic control signals is not a "cure all," and there may still be several risks (e.g., from noncompliance, lack of maintenance, remaining crashes, etc.).
- Visual obstructions of traffic signals and other traffic control devices should be removed. Traffic signals often are hidden by branches of a tree or other obstructions. This makes urban travel particularly difficult and potentially life-threatening.
- Figure 6.18: Signal hidden by the branches of a tree in Gurudwara, India; tree/branches must be removed or replace signal.
- Source: Hindustan Times.[136]
- Land use, traffic, and other changes can cause existing traffic control signals to become obsolete or ineffective. Examples are harmful invisibility and grown branches of trees covering traffic signals (figure 6.18).
- Improper condition of signals makes it harder for road users to detect them and may be misleading. Dysfunctional signals during disasters or technical difficulties may cause issues (e.g., blackouts) because signals need electricity.
- Reduced conflict points for both vehicle-to-vehicle and vehicle-to-pedestrian can reduce certain types of crashes. For example, there are 32 vehicle-to-vehicle conflict points and 24 vehicle-to-pedestrian conflict points in a typical four-leg intersection

Figure 6.18: Signal hidden by the branches of a tree in Gurudwara, India; tree/branches must be removed or replace signal.

Source: *Hindustan Times*. 2019. Blocked vision, technical glitches of traffic lights in Gurugram fixed, April 5, 2019. https://www.hindustantimes.com/gurgaon/blocked-vision-technical-glitches-of-traffic-lights-in-gurugram-fixed/story-3RV1l9hYpCjho4LCxXqO7I.html.

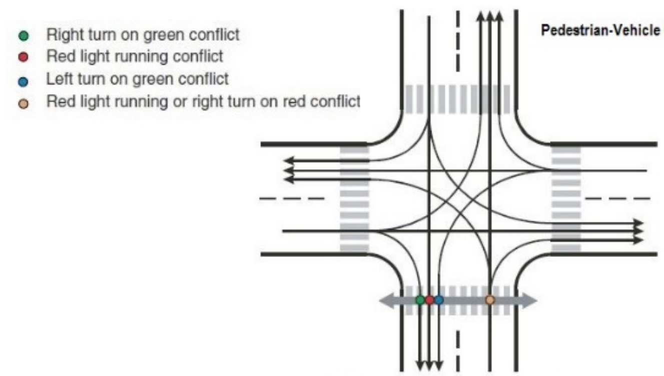
136 Hindustan Times. 2019. Blocked vision, technical glitches of traffic lights in Gurugram fixed, April 5, 2019. https://www.hindustantimes.com/gurgaon/blocked-vision-technical-glitches-of-traffic-lights-in-gurugram-fixed/story-3RV1l9hYpCjho4LCxXqO7I.html.

Figure 6.19: All conflict points at four-leg intersection.



Source: Eugene R. 2019. *Operational Performance of Kansas Roundabouts: Phase II.* https://www.researchgate.net/figure/Figure-Showing-the-Reduction-of-Conflict-Points-in-a-Roundabout-When-Compared-to-a_fig5_267548567.

Figure 6.20: Example of conflict points in specific phase at four-leg intersection.



Source: National Cooperative Highway Research Program. 2010. Report 672 Roundabouts: An Informational Guide, Second edition.

(figure 6.19). During a green light phase for pedestrians and vehicles approaching from the same direction, the number of vehicle-to-pedestrian conflict points can be reduced to only one if nearside turn on red is permitted (figure 6.20). Without that, ALL conflicts can be removed.

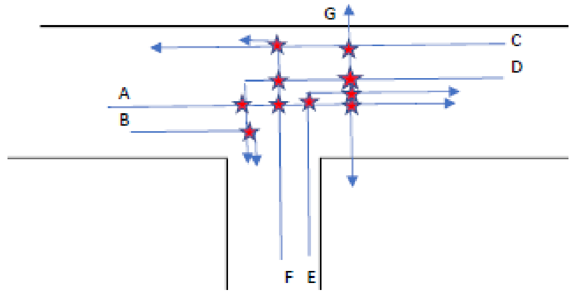
- Implementation of traffic control signals at unsignalized intersections reduced injury crashes by 30 percent according to a recent multi-country review.[137]

Good design practice/ treatments/solutions

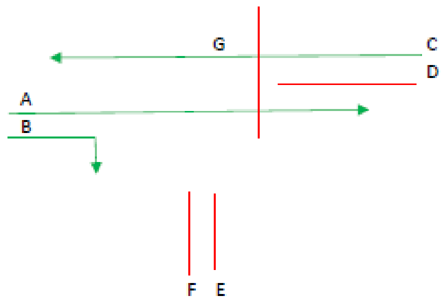
- Signal intersections simplify drivers' decision-making by preventing conflicting movements as illustrated in figure 6.21. The possibility of misjudging whether it is safe to enter or cross an intersection by both the vehicles on a minor street and pedestrians crossing the street can be reduced.
- Layout of traffic signals must be considered with the visibility of signals for road users. Driver's sight triangle and the height of signals must also be considered.
- The signal head must also be visible at a point in the crosswalk which allows the pedestrian clear sight before and while crossing.
- Pedestrians must have sufficient time to travel (at 3.5 ft/s) to the center of the farthest travelled lane before crossing vehicles receive a green.[138]
- Periodical maintenance and consistency of power supply to traffic control signals is a recurring problem in LMICs (figures 6.22 and 6.23). When traffic signals are not working, their benefits are less effective, although vehicles do tend to use such intersections with more caution due to lack of certainty. The introduction of solar power offers a realistic and affordable option to a fixed power supply.
- Special attention for road users should be given if signals become dysfunctional or hidden.
- Alternative staging of signals can reduce all potential conflicts, but care is needed to maintain cycle times that do not result in users becoming impatient for change. Cycle times between 90 seconds to 2 minutes are preferred.

137 Turner, B., Steinmetz, L., Lim, A., and Walsh, K. 2012. Effectiveness of Road Safety Engineering Treatments. APR422–12. Austroads Project No: ST1571.
138 FHWA. 2019. The Manual on Uniform Traffic Control Devices.

Figure 6.21: Typical Signal Cycle for above stages.

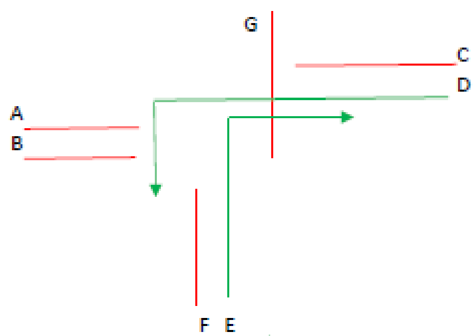


- A simple three-leg uncontrolled intersection with a pedestrian crossing on arm CD has 10 potential crossing points.
- All these can be removed under signal controls by preventing the conflicting movements operating together.
- By identifying each movement stream separately, alternative staging can be considered, depending on traffic volumes



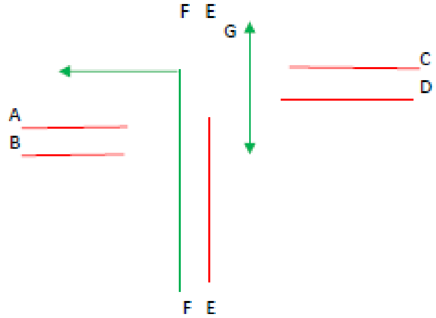
Stage 1

- Green indicates those movement streams moving, and red indicates those movement streams stationary.
- The amber period between Stage 1 and 2 is required to allow phases A–D to clear the conflict point as being the longest.



Stage 2

- Green indicates those movement streams moving, and red indicates those movement streams that are stationary.
- The amber period between Stages 2 and 3 is required to allow phases D–F to clear the conflict point.



Stage 3

- Green indicates those movement streams moving, and red indicates those movement streams that are stationary.
- The amber period between Stages 2 and 3 is required to allow phases A–G to clear the conflict point.

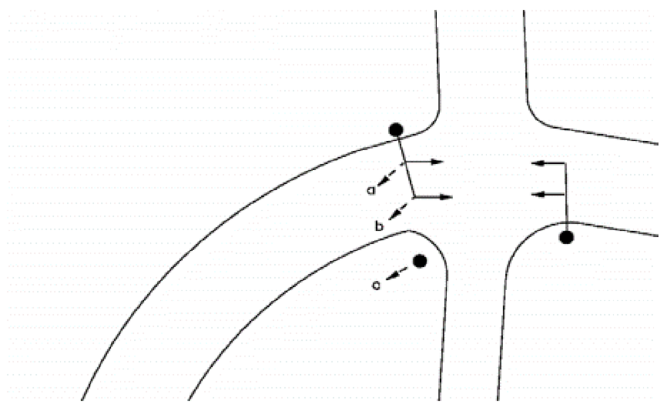
Note: Pedestrian phase G requires green period to close before F to allow pedestrians to clear the roadway before the conflicting phase A starts.

Source: © John Barrell.

Figure 6.22: Intersection where signals are not functional in India

Source: Hindustan Times. 2016. Faulty traffic signals pose threat to city commuters, December 4, 2016. https://www.hindustantimes.com/noida/faulty-traffic-signals-pose-threat-to-city-commuters/story-IdSjGgtFlx-ievzSZ0MCp9M.html.

Figure 6.24: Supplemental signal at horizontal curves.



Source: FHWA, 2019.

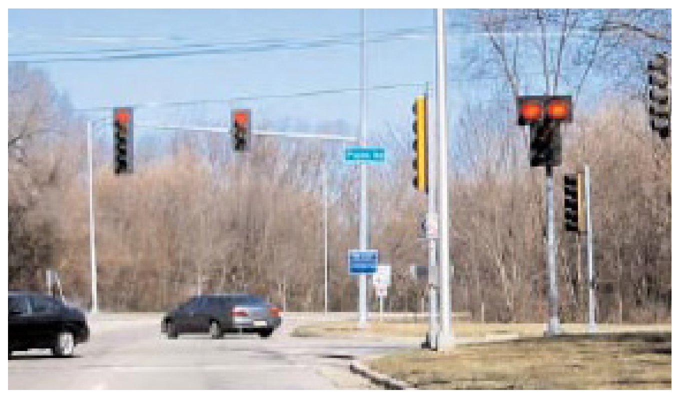
Signs and markings

- Supplemental pole mounted traffic signals may be placed on the nearside of intersections particularly where sight distance is an issue such as on approaches to intersections on curves (figures 6.24 and 6.25).
- In LMICs, motorists may crowd and stop too close to pedestrian crossings. Advanced stop lines at traffic signals are helpful in improving the visibility of pedestrians to motorists. Motorists may ignore the line if placed too far in advance of the pedestrian crossings (figure 6.26).

Figure 6.23: Dysfunctional signal in Dwarka, India.

Source: Times of India. 2019. Hidden traffic signals dangerous for drivers, April 25, 2019. https://timesofindia.indiatimes.com/citizen-reporter/stories/hiddentrafficsignalsdangerousfordrivers/articleshow/69034168.cms.

Figure 6.25: Supplemental signal for intersection in middle of reverse curve.



Source: Institute of Transportation Engineers. 2003. Making Intersections Safer: A Toolbox of Engineering Countermeasures to Reduce Red-Light Running.

- At signalized intersections, advance stop lines back from the crosswalk at traffic signals must be placed away from the crosswalk to allow pedestrians and drivers to have a clear view of each other and more time in which to assess each other's intentions.[139]
- At large signalized intersections with multiple turn lanes, continuation of the lane markings through the intersection can provide additional guidance for motorists and reduce the occurrence of side impact collisions.

139 Pedestrian Safety Guide and Countermeasure Selection System. 2019. http://www.pedbikesafe.org/pedsafe/index.cfm.

Figure 6.26: Unsafe manner at stop line (overcrossing stop line).

Source: © Bahnfrend.

Alternative devices

- There are several other types of traffic control devices which are similar to traffic signals controlling intersections. A pedestrian (hybrid) beacon is an example (figure 6.27). The difference of pedestrian beacons from pedestrian signals is that it remains dark over the traffic lanes unless a pedestrian pushes the crossing button, but it brings a higher rate of compliance on stopping traffic so pedestrians can cross much more safely. Early studies have shown up to 97 percent driver compliance, which is a better compliance rate by drivers than other devices at pedestrian crossings.242
- As a new innovation, signals on a crosswalk have been suggested (figure 6.28). This new form of traffic signal is fitted to the width of the road right before the zebra crossing. The lights are embedded into the road like reflector road signs and are waterproof. This signal works as a supplemental signal working with the traditional signals at the intersection when the visibility of the traditional traffic lights is obstructed by large vehicles, weather, and so forth. The effectiveness of this new type of traffic signal has been studied in New York, and the study team concluded signal lights on pavement implies that it is more noticeable although not impossible to miss.[140]

Figure 6.27: Pedestrian (hybrid) beacon in US.

Source: Federal Highway Administration. 2014. Pedestrian Hybrid Beacon Guide—Recommendations and Case Study. https://safety.fhwa.dot.gov/ped_bike/tools_solve/fhwasa14014/.

Figure 6.28: Pedestrian-cross-assistance devices (signals on cross walk) in Hyderabad, India.

Source: Anjani Kumar @CPHydCity/Hyderabad.

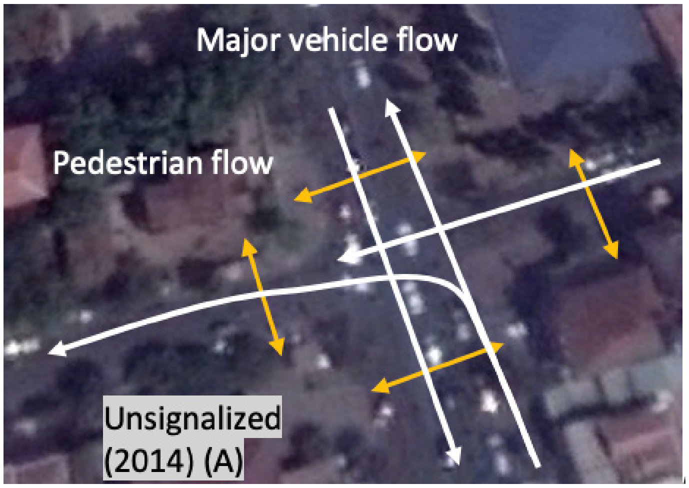
Signal phasing strategy and lane management

- The distribution of movement phases through the signal cycle is determined by analyzing the various road user demand flows through the intersection at various times of the day. The allocation of phases to different stages is then determined to minimize

140 John F. 2003. Evaluation of In-Pavement, Flashing Warning Lights on Pedestrian Crosswalk Safety.

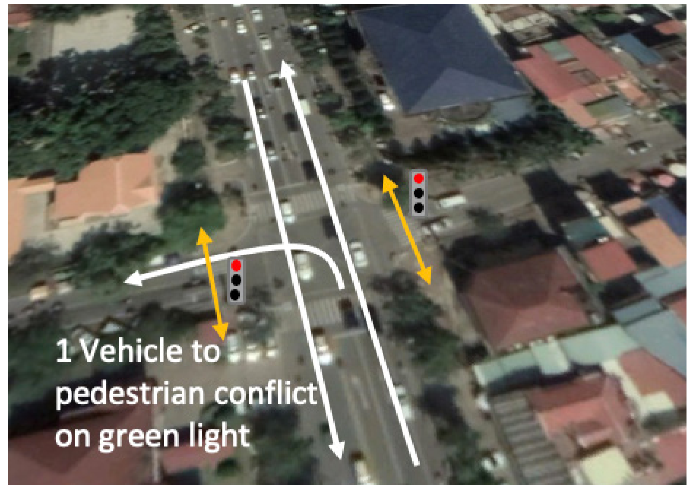
Case Studies/Examples

Figure 6.29: Traffic flows at unsignalized intersection without pedestrian crossings in Phnom Penh, Cambodia.



Source: © Google Earth.

Figure 6.30: Ordered traffic flow at signalized intersection with reduced conflict points.



Source: © Google Earth.

overall delay and maximize safe operation. Timings for these stages are then developed through various simulations to determine the optimum timings for a given traffic pattern.

- Traffic signal phasing strategies can be adopted. The number of traffic control signal phases and their type and length are a significantly important factor on road safety at signalized intersections. The phases must be set by following references to appropriate consultations and manuals (e.g., FHWA, MUTCD).
- Signals for buses, trams, and cyclists can also be considered for road users' safety.
- Separately running phases on the same approach require a separate signal head to control the movement and appropriate lane management.
- Lane management is achieved through the use of traffic control devices that may include physical devices, static signs and road markings, electronic signs and markings, or colored pavement. Guidance on traffic control devices and their use is provided in Part 10 of the Guide to Traffic Management (Austroads 2019) and MUTCD.

Figures 6.29 and 6.30 illustrate vehicle-pedestrian conflict points in unsignalized intersections vs signalized intersections.

Further Reading

- FHWA. 2019. The Manual on Uniform Traffic Control Devices.
- FHWA. 2013. Signalized Intersections Informational Guide, Second edition. https://safety.fhwa.dot.gov/intersection/signal/fhwasa13027.pdf.
- Austroads. 2019. Guide to Traffic Management Part 6: Intersections, Interchanges and Crossings.

6.3. Roundabouts

General description

- A roundabout is a form of intersection channelization in which traffic circulates in one direction around a circular central island, and all entering traffic is required to give way to traffic circulating on the roundabout.
- Benefits include reduced conflict points and therefore driver workload associated with perpendicular junctions and, depending on traffic flows, reduced queuing associated with traffic lights.
- They provide facility for U-turns within the normal flow of traffic, which often are not possible at other forms of junction.
- When entering, vehicles only need to give way at relatively low speeds, and do not always perform a full stop. As a result, by keeping a part of their momentum, the intersection performs more efficiently from a traffic flow perspective. In addition, engines will require less effort to regain the initial speed, resulting in lower emissions. Research has also shown that slow-moving traffic in roundabouts makes less noise than traffic that must stop and start, speed up and brake.
- Originally roundabouts (sometimes referred to as traffic circles or rotaries) were designed with approaches that were both flared and tangential. This encouraged high speed and sometimes complex weaving maneuvers.
- Modern roundabouts were first standardized in the mid 1960s, with smaller diameter central islands, circulating space, and slower approaches. They were found to be a significant improvement over previous traffic circles and rotaries.
- Because low speeds are required for traffic entering roundabouts, they are physically designed to manage the speeds of traffic approaching and entering the junction to improve safety. Approaches are designed so that vehicles enter the circulating carriageway with limited vehicle path radius naturally slow down.[141]
- Roundabouts can be used satisfactorily at a wide range of intersection sites, including:
  - i. Urban local and collector roads;
  - ii. Arterial roads in urban areas;
  - iii. Rural roads;
  - iv. Freeway/motorway ramp terminals; and
  - v. As a grade-separated treatment at an interchange.

Safety implications

- Roundabouts provide a highly readable and consistent physical intersection layout that predictably and consistently limits the potential for higher speed and high impact angle conflicts.
- Transforming the control method from a two-way stop or traffic control signal to a roundabout with single/two lanes is effective in reducing the percentage of fatalities and injuries at intersections.
- For well-designed single lane roundabouts in particular, the rate of crashes between pedestrians and vehicles can be significantly reduced.
- By limiting the entry path curve and thereby introducing horizontal deflection to the approaches, vehicular entry speeds can be reduced, which provides drivers more time to react to potential conflicts and reduces crash severities.
- There are fewer vehicular conflict points and less potential for high severity conflicts, such as right-angle, left-turn, and head-on crashes because of the roundabout's design and because all drivers are going in the same direction.
- Generally, there is a reduced speed differential between vehicles travelling through the intersection, which reduces crash severity.

141 Austroads Guide to Road Design Part 4B. 2015. section 4.5.

- They are effective during power outages. Unlike traditional signalized intersections, which must be treated as all-way stop or require police to direct traffic, roundabouts continue to work as normal.
- As remaining safety risks, the following factors can be considered; however, because of the reliably low-speed environment, the severity of injuries from roundabout crashes, even for vulnerable users, tend to be low:
  1. **Misunderstandings of rules and not every driver knows roundabout rules.** In some countries/areas new to roundabouts, people have never learned the rules (yield and driving directions) of roundabouts. They might drive wrong directions and not yield to other vehicles;[142]
  2. **Poor judgement of gaps** by drivers entering a high-speed flow of circulating traffic, especially when there are multiple lanes;
  3. **Rear-end collisions** between vehicles waiting to join the roundabout may increase (although these are far preferable than the high-speed impacts seen at other intersection types);
  4. **Sideswipe collision** during changing lanes or entering/exiting the center circle;
  5. **Pedestrian/cycle collision** by not yielding to pedestrians and cyclists; and
  6. **Painted (or low height) islands become less visible and negligible for drivers.** Drivers may not make sense of what looks like painted circles on intersections that are meant to act as roundabouts.

Good design practice/ treatments/solutions

- Properly designed roundabouts control the angle at which traffic enters the intersection and the speeds of vehicles entering and going through the intersection by creating geometric curvature with center and splitter islands. This feature results in safer intersections than other at-grade intersections where vehicles can enter the intersection without slowing their speeds.
- Newer designs may also include raised platforms or humps on the approach that have been successfully used to slow the approach speed of vehicles, reducing the need for geometric curvature, and sometimes significantly reducing construction costs.
- Circulating space within the roundabout is often restricted to a single lane; however, multiple lanes can be used provided there is sufficient size to allow the inner flow of traffic to maneuver to the outer lane to exit. However, it should be noted that, as circulating widths increase, the ability to control speed into and through the roundabout becomes less predictable.
- A key element of safe roundabout operation is to ensure that the central island or splitter islands provide sufficient deflection from the straight-ahead movement to ensure slow vehicle speeds through the intersection (see figure 6.31 for an example of a poorly designed roundabout). Where sufficient deflection is not possible (for instance due to restrictions in road space), raised platforms have been used successfully instead.

Figure 6.31: Dangerous roundabout design in Romania, where the main road has no deflection.

Source: Google street view.

142 Bhutanese. https://thebhutanese.bt/virtual-roundabouts-remain-ignored-by-motorists/. Accessed on 11/13/2019.

Figure 6.32: Vehicle ignoring flat roundabout in Croatia

Source: Novilist.hr

Figure 6.34: Roundabout with too small center island in India.

Source: © Google Earth.

Figure 6.33: Decorated roundabout obscuring driver's sight in Bhutan

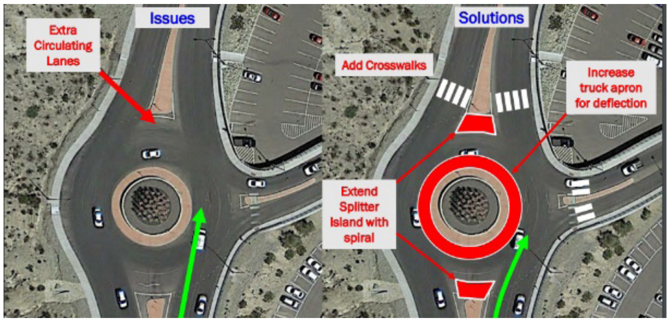
Source: The Travel Magazine.

Figure 6.35: Inappropriate location and size of roundabout in Bhutan.

Source: Kuensel.

- With splitter islands, pedestrians are required to cross only one direction of traffic at a time at a roundabout and contend with slower-moving vehicles because of the splitter islands.
- Flat/low height islands (i.e., marking) may not work (figure 6.32). Center and splitter islands should be physically raised to provide readability.
- Decoration and vegetation at center and splitter islands must not obstruct driver's sight distance of approaching or circulating traffic (figure 6.33). However, it should be sufficiently high to obstruct the straight through view of the road ahead and concentrate drivers' awareness on the roundabout.
- The center island and the splitter islands must be large enough to force approaching vehicles to reduce their speed in order to enter the intersection. Too small center islands and splitter islands may not work to reduce the speed of approaching vehicles during passing through the intersection because turning along the center island is not required (figures 6.34 and 6.35). This defeats the purpose of a roundabout.
- A key factor in determining the size of a roundabout, both the central island and the width of the circulating carriageway, is the safe negotiation of the design vehicle for all movements. For example, when designing for the safe passage of a semitrailer unit, as the central island radius decreases, so the circulating width must increase to allow the vehicle to get around the island. This effect depends on the vehicle dimensions and hinge point. Because this can result in less deflection and therefore higher negotiation speeds, it may be preferable to

Figure 6.36: Diameter and length adjustment of islands in a roundabout.



Source: Gus S. 2018. *Are Multilane Roundabouts a Safe and Effective Intersection Treatment*, 2018 ITE Joint Western & Texas District Annual Meeting. https://www.westernite.org/annualmeetings/18_Keystone/Presentations/3B/3B.Randy%20Johnson.Multi-lane%20Roundabouts_Johnson-Berger-Sanchez.pdf. Accessed on 11/14/2019.

Figure 6.37: Truck apron with correct design for use by trucks only with a narrow circular carriage in South Africa.

Source: Southern African Transport Conference 2017.

Figure 6.38: Truck apron not serving the purpose of design in South Africa (too high apron to ride on for larger trucks and too low to block riding on passenger cars).

Source: Southern African Transport Conference 2017.

provide a slightly raised apron or ever-run area on the central island. With a low vertical lip (50 mm), this feature allows the large vehicles to negotiate safely while still providing a narrower "target" for small vehicles, and maintains predictability.

- A traversable truck apron can be provided at roundabouts to accommodate large vehicles while minimizing other roundabout dimensions (see figures 6.36 through 6.38). A truck apron provides an additional paved area to allow the over-tracking of large semitrailer vehicles on the central island without compromising the deflection for smaller vehicles. At the roundabouts which do not have truck aprons, the circulatory lanes become too wide to accommodate larger vehicles. This can cause an inappropriate usage of lanes. These roundabouts have higher vehicle speed through the intersection.
- Humps and platforms can be used to reduce speeds, especially where there is not enough deflection on approach.
- Pedestrian and cyclist facilities can be included in the intersection design (references to earlier chapters on this).
- Education may be needed to ensure road users know how to navigate roundabouts, especially when first introduced; and to enforcement to ensure compliance. A small center island and a lack of length of splitter islands will also make extra circulating lanes.

Figure 6.39: Roundabout (rotary) with improper lane alignment and width creating extra lanes in Serbia.

Source: The Miner (CC BY-SA 3.0).

Figure 6.40: Mini-roundabout (Wetherby, England).

Source: © John Barrell

Figure 6.41: Mini-roundabout with noticeable pole—Zagreb, Croatia.

Source: © Admiral Norton.

- Lane lines must be provided with appropriate widths. Sometimes lane lines of roundabouts are missing (figure 6.39). Approaching vehicles will miss the courses they should drive in the intersection, and consequently crashes between vehicles will be caused. The lane boundaries must be provided as per the approaching roads. This can also guide vehicles to turn along the center island appropriately and reduce their speed.
- In low speed, constrained urban environments mini-roundabouts—those with no physical island and only a painted circular road marking—can be effective if flows are low and speed is well controlled. Deflection though the intersection is provided through traffic rules and approach alignments that require the central marking to be passed to the offside.
- Mini-roundabouts (figures 6.40 and 6.41) may be an optimal solution for a safety or operational issue at an existing stop-controlled or signalized intersection where there is insufficient right-of-way for a standard roundabout installation. Mini-roundabouts are characterized by a small diameter and mostly traversable (painted circle or low dome) islands (central islands and splitter islands) and offer most of the benefits of regular roundabouts with the added benefit of a smaller footprint. [143] Mini-roundabouts should be installed at only low-speed and low-volume roads because they do not have a physical coercive function to slow and curve vehicles going through the intersection.
- Signage for indication of a roundabout ahead in a clear and consistent way throughout the network is very important. The variation in the use of signs and markings (figure 6.42) reflects either the lack of knowledge, the lack of attention to detail, or the lack of clear guidance for the implementation of road signs and road markings. Similarly, the variation of road markings also causes driver's misbehaviors.
- The performance of some congested roundabouts

143 FHWA. 2010. Mini-Roundabouts.

Figure 6.42: Good quality roundabout sign but variation of sign in the same country confusing drivers in South Africa.

Source: Southern African Transport Conference 2017.

can be improved with traffic signal control by balancing entry flows and/or a continual flow of traffic on the circulating carriageway to prevent long queues causing long delays and blocking back into preceding junctions. Signals are able to keep the circulatory traffic flow fluid and hence balance and improve the roundabout capacity.[144]

- The number of pedestrians (and cyclists) can increase crash risks and delays because traffic is governed by yield-control entry at a roundabout, especially at intersections with a low volume of pedestrians. Providing specific crossing points and routes around the intersection separate from motorized traffic can improve pedestrian and cycle safety at roundabout intersections (see section 4 on Vulnerable users).
- Traffic rules and design of roundabouts must coordinate with other transportation modes to avoid increasing crash risks in arterial roads with cycle lanes and public transportation lanes (see section 4.5 on Public transport).

144 Department of Transport UL. 2009. Signal Controlled Roundabouts.

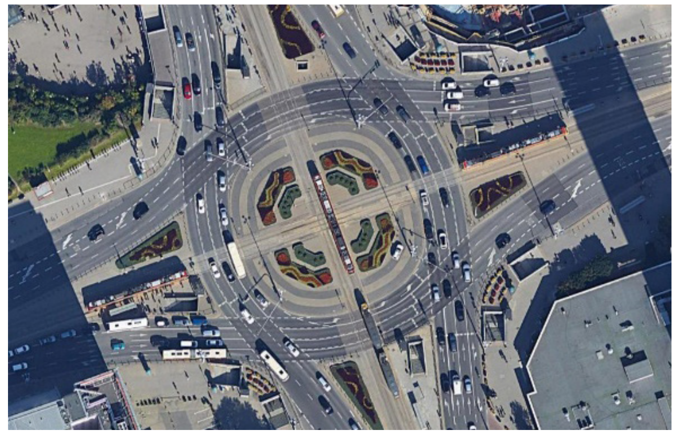
Case Studies/Examples

Figures 6.43 through 6.47 show examples of roundabouts in various contexts.

Figure 6.43: Roundabout which allows larger vehicles to mount part of central island (same conditions of mini-roundabouts applied).

Source: Imagic (CC BY-SA 2.0).

Figure 6.44: Roundabout with tram rails in Poland.



Source: © Google Earth.

Figure 6.45: Transformation from uncontrolled intersection to roundabout—The Philippines.

Source: © Google Earth, Top Gear Philippines.

Figure 6.46: Example of low-cost roundabout in Argentine

Source: Municipalidad Chivilcoy @MuniChivilcoy

Figure 6.47: Example of mini-roundabout with reflection in Italy.

Source: © Mad Vinyl.

Further Reading

- FHWA. 2009. *The Manual on Uniform Traffic Control Devices.* Must read chapter 2B, Regulatory signs, barricades, and gates; chapter 3C, Roundabout markings.
- FHWA. 2010. *Roundabouts: An Informational Guide, Second Edition* (NCHRP Report 672). https://www.virginiadot.org/business/resources/NCHRP_Report_672_Roundabout_Informational_Guide_2nd_Edition2010.pdf.
- Tomaž T. 2016. Comparative Analysis of Four New Alternative Types of Roundabouts: "Turbo," "Flower," "Target," and "Four-Flyover" Roundabout, 60(1), pp. 51–60.
- Austrods. 2018. *Towards Safe System Infrastructure A Compendium of Current Knowledge*, Research Report AP-R560-18. Must read chapter 5, Harm minimization at intersections.
- FHWA. 2007. Roundabouts in the United States (NCHRP Report 572). https://nacto.org/docs/usdg/nchrprpt572.pdf.
- Conference of European Directors of Roads. 2008. *Best Practice for Cost-Effective Road Safety Infrastructure Investments*. Must read chapter 3, Review of road safety investment and chapter 5, In-depth analysis of most promising road safety investments.
- FHWA. 2010. Mini-Roundabouts. https://www.fhwa.dot.gov/publications/research/safety/00067/00067.pdf.
- Department of Transport UL. 2009. Signal Controlled Roundabouts. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/876622/ltn-1-09_Signal_controlled_roundabouts.pdf.
- FHWA. 2010. *Highway Capacity Manual 2010 (HCM2010)*. Must read chapter 4, Unsignalized intersection.
- FHWA. 2014. *Kansas Roundabout Guide, Second Edition (A Companion to NCHRP Report 672)*. https://www.ksdot.org/Assets/wwwksdotorg/bureaus/burtrafficeng/Roundabouts/Roundabout_Guide/KansasRoundaboutGuideSecondEdition.pdf.
- Abishai P. 2005. *Evaluation of Roundabouts versus Signalized and Unsignalized Intersections in Delaware.* https://cpb-us-w2.wpmucdn.com/sites.udel.edu/dist/1/1139/files/2013/10/Rpt.-179-Roundabouts-Final-1l329b7.pdf.
- NCHRP. 2020. Report 672 Roundabouts—An Informal Guide, 2nd edition. http://onlinepubs.trb.org/onlinepubs/webinars/RoundaboutsPresentations.pdf.

6.4. Raised Intersections

General description

A raised intersection is a speed management treatment and is designed to achieve speed reductions or reinforcement for vehicles approaching an intersection by raising the entire intersection to sidewalk level or a similar level. The flat raised areas cover the entire intersections, with ramps on all approaches and often with brick or other textured materials on the flat section and ramps. Vehicles passing through a raised intersection must ascend on the approach to, and descend on the departure from, the intersection.

They are sometimes referred to as raised junctions, intersection humps, or plateaus and are similar to speed humps and other vertical speed control elements. They reinforce slow speeds and encourage motorists to yield to pedestrians at the crosswalk. As the roadway is raised to sidewalk level there is usually no need to identify specific crosswalk locations, and such arrangements are suitable for low-speed, low-flow roads.

Safety implication

- Research has found the most effective traffic-calming measures to involve vertical shifts in the roadway, such as speed humps, speed cushions, and speed tables (gateway treatments).[145]
- Similar to speed humps, raised intersections result in creating a safe, slow-speed crossing and encourage vehicles to yield to pedestrians at the crosswalk (see section 3.2 on Speed compliance and traffic calming).
- Raised intersections can typically reduce the speed of approaching vehicles by less than 10 percent.[146] Therefore, they are more reliable to emphasize or reinforce a limit rather than in achieving a speed reduction.

Good design practice/ treatments/solutions

- Raised intersections (see figures 6.48 through 6.51) are most appropriate for undivided carriageways, sites with small footprints, where high pedestrian movements are expected, or pedestrians have increased priority. However, installing approach platforms or humps on an undivided carriageway is not recommended, as it may result in drivers switching into the opposing lane to avoid them unless they extend across the full width of the carriageway.
- Raised intersections have been implemented at mostly minor intersections but have not been widely implemented on arterial roads or at intersections with higher speeds.
- Constructing raised intersections should be avoided at sites with notable horizontal or vertical curves that may impede sight lines to raised intersections and associated signing, as well as with vertical clearance restrictions.
- Raised ramps must be orientated perpendicular to the direction of traffic flow to ensure both front wheels of a vehicle begin to rise or fall on the ramps concurrently. Should this not occur, vehicles may traverse the ramps with wheels at different levels, potentially causing instability and affecting the driver's ability to safely operate the vehicle. This is a particular concern for two-wheeled vehicles turning at corners.
- Raised intersections must adopt a flat top profile, and their approach and departure ramps should be also flat with the same consistent grade.
- The flat section (i.e., the plateau) of a raised intersection must have a minimum of 6 m in the road

145 FHWA. 1998. Synthesis of Safety Research Related to Speed and Speed Management.

146 Institute of Transport Engineering. 2019. Traffic calming measures. https://www.ite.org/technical-resources/traffic-calming/traffic-calming-measures/.

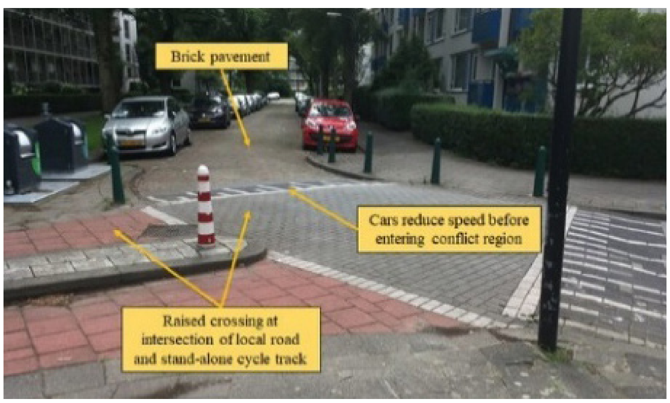
Figure 6.48: Raised intersection in Bogotá to give priority to pedestrians on an arterial street.

Source: © Ben Welle/WRI.

Figure 6.49: Raised intersection with colored pavement.

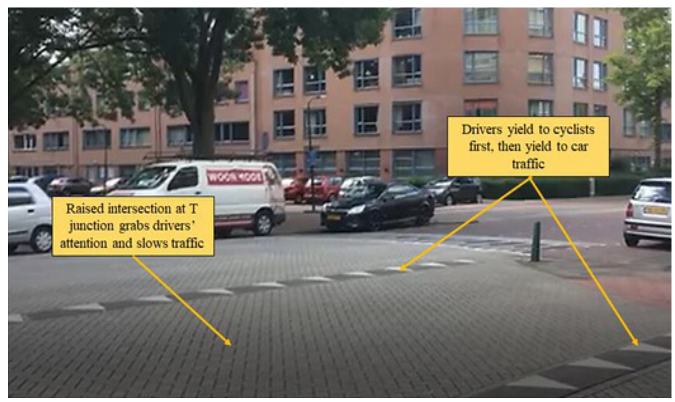
Source: NACTO.

Figure 6.50: Raised intersection with different pavement pattern.



Source: Northeastern University

Figure 6.51: Segregating conflict points in stages.



Source: Northeastern University

width to store a standard passenger vehicle, including when used as a pedestrian crossing. When raising an entire intersection, this width will extend to encompass the intersection footprint.

- The desirable height of a raised intersection's platform is 100 mm, but 75 mm may be considered where site constraints and traffic composition suggest a lower height profile is suitable (e.g., high truck or bus volume routes). Ramp heights < 75 mm are much less effective at reducing speeds and should not be considered. For low speed (< 50 km/h) and low traffic volume environments, 150 mm may be used; however, platforms > 100 mm in height may damage low-floor vehicles and are not recommended on arterial roads[147] (see section 5.5 on Vertical alignment).
- Departure ramps should be designed as a smooth exit from a raised intersection. Based on the trials in Victoria, a 1:35 grade is considered appropriate for the departure ramp. Flatter slopes may also be considered.
- The grade of the ramp must be adjusted to achieve an equivalent change in grade when constructing raised intersections ramps on an upgrade or downgrade.
- Beside their construction costs, potential impacts on services and drainage must be considered (see section 5.11 on Drainage).

147 Vicroads. 2019. Road design notes: Raised Safety Platforms (RSPs).

- Constructing raised ramps should not be placed where lane changing is necessary or frequent (e.g., at or beyond directional signs). When installed on turning lanes, raised ramps must be placed in a location that allows a turn to be commenced, or completed, prior to crossing the ramp.
- To avoid drivers misinterpreting where to stop prior to entry into a raised intersection, stop lines must be located either:

  1. Prior to the beginning of the raised intersection ramp (preferred), or
  2. On the platform, prior to the beginning of the departing ramp (for platforms) or pedestrian crossing (for raised intersections).

- A minimum clearance of 7 m is required between the start of the platform plateau or base of the platform slope and stop line to ensure a standard passenger vehicle can comfortably be stored in advance of the stop line. Similarly, where the percentage of heavy vehicles using the road is high, locating approach ramps the equivalent length of the critical stability vehicle prior to the turning point must be considered.

Larger vehicles

The following are key considerations for larger vehicles, including buses, emergency vehicles, and so forth:

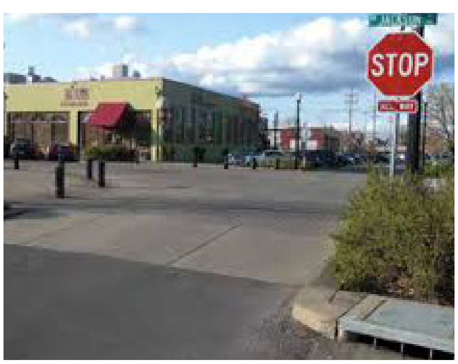
- Location and orientation of the approach and departure ramps to avoid the critical vehicle instability;
- Maximum raised intersection height to avoid critical vehicle instability;
- Potential operational deficiency and delays due to the lower acceleration and deceleration of heavy vehicles; and

Potential implications of larger vehicle drivers using alternate routes (e.g. local streets) to avoid the raised intersection.

Markings and signs

- All raised intersections should have warning signs (figures 6.52 and 6.53) with a recommended advisory speed based on a safe speed (figure 6.54).
- Where vehicle stability concerns exist, installing warning signs with an appropriate truck tilting advisory speed should be considered (figure 6.55).
- The introduction of raised intersections may lessen the conspicuity between road space and pedestrian space, particularly when proposed platforms are flush with adjacent land. Additional delineation such as contrasting colored pavement marking and/or white curbside linemarking may be considered to improve the conspicuity of the raised intersection (figures 6.56 through 6.58). These visual enhancements of intersections can also contribute to a driver's recognition of intersections.

Figure 6.52: Raised intersection with stop sign.

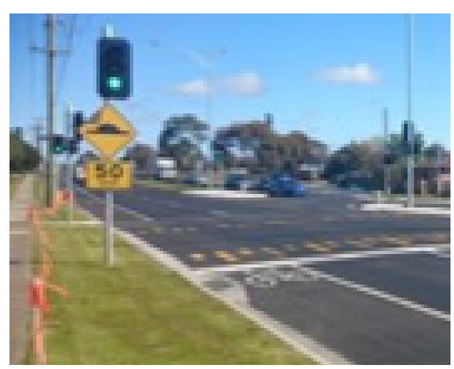


Source: © City of Albuquerque.

Figure 6.53: Raised intersection with crossing sign.

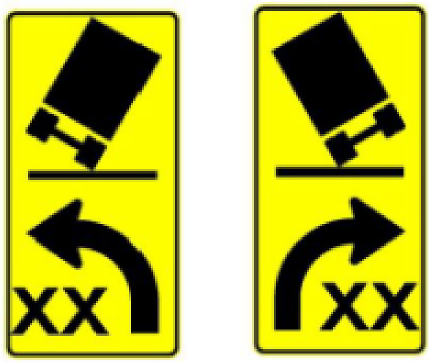
Source: © City of Albuquerque.

Figure 6.54: Warning signs with a recommended advisory speed.



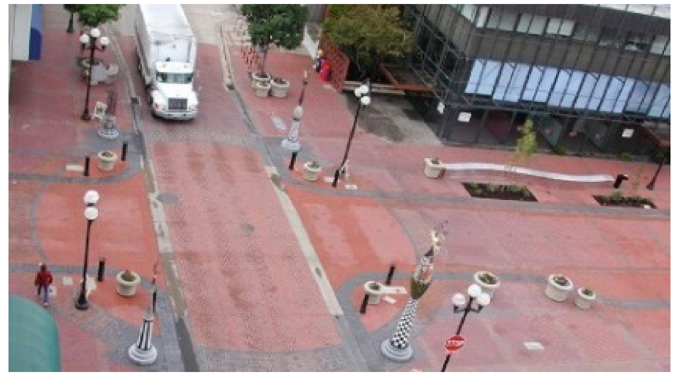
Source: Vicroads.

Figure 6.55: Truck tilting warning signs with advisory speed.



Source: Vicroads.

Figure 6.56: Low cost marked intersection.

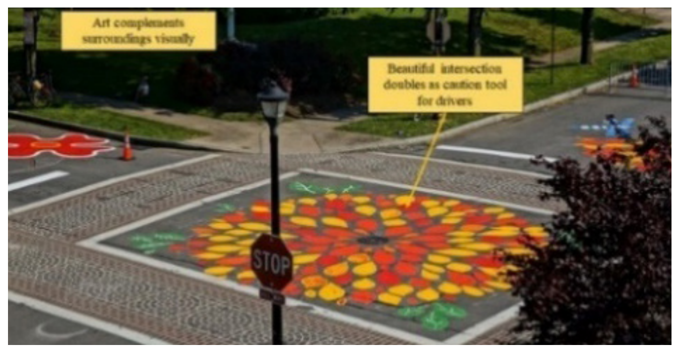


Source: NACTO.

Figure 6.57: Colored, raised intersection with line markings.

Source: Vicroads.

Figure 6.58: Marked intersection with artistic design to attract more driver's attention.



Source: Northeastern University.

Measures for higher speed roads

To achieve appropriate speed reduction for vehicles approaching an intersection on a higher-speed road environment (≥ 80 km/h), it is not practical to use raised intersections alone. Therefore, consideration shall be given to adopting supporting treatments such as, but not limited to:

- Speed reduction in stages (e.g., multiple platforms with appropriate ramp profiles);
- Permanent speed limit reduction (supported by other treatments including platforms and speed cameras when required);
- Additional warning signs (e.g., flashing warning signs);
- Speed calming line marking;
- Transverse rumble strips; and
- Gateway treatments.

Further Reading

- Austroads. 2019. Guide to Traffic Management Part 6.
- NACTO. 2019. Urban Street Design Guide. https://nacto.org/publication/urban-street-design-guide/.
- FHWA. 2017. Traffic Calming ePrimer. https://safety.fhwa.dot.gov/speedmgt/traffic_calm.cfm.
- Vicroads. 2019. Road Design Note: Raised Safety Platforms. https://www.vicroads.vic.gov.au/-/media/files/technical-documents-new/road-design-notes/road-design-note-0307--raised-safety-platforms-rsp-version-c2.ashx.

6.5. Channelization (including turn/slip lanes)

General description

Channelization is the provision of dedicated traffic lanes for different movements at intersections. It aims at improving the performance and safety of intersections by separating traffic flows (either through road marking or physical islands) and making driving patterns and right-of-way rules transparent. Such channelization can reduce the area of conflict as well as improve intersection angles. It may also be added to increase capacity, improve the visibility of traffic control devices, and reduce crashes. It can be included in all types of intersections, irrespective of layout or control.

Channelization can be included on both/or side roads and main roads. Separation of movements can be with traffic islands, medians, or road markings, together with auxiliary lanes or designating lanes for specific movements such as left-turn, right-turn, or U-turn.

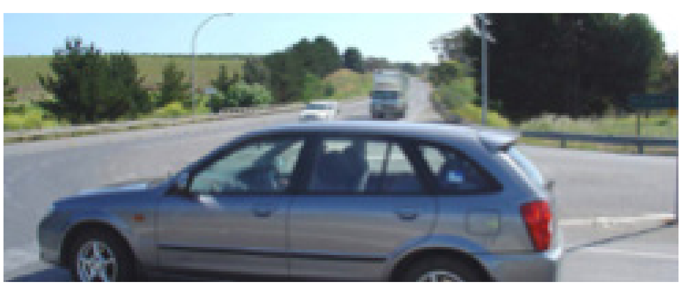
These lanes can also be referred to as turn lanes or slip lanes. In some countries, turn lanes refer to the offside channelized turning lane that provides a waiting area for turning traffic while they wait for a suitable gap in the opposing traffic. Slip lanes to the nearside turning lane provide a dedicated deceleration facility that removes the slowing traffic from the through traffic. These may be free-flow or required to give way to other traffic once the side road is reached.

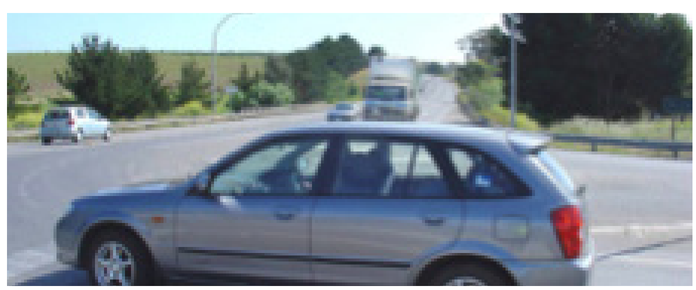
The tapered area of these lanes on the approaches to intersections function as storage lanes for turning traffic. Associated auxiliary lanes can also serve as a useable shoulder for emergency use and to accommodate stopped vehicles. Normally these lanes should be installed as separate lanes (not overtaking lanes) from traffic which is going straight ahead at an intersection, so that this traffic can pass vehicles which are waiting to turn.

Large-scale channelization is not a solution for every problem. Improper or excessive channelization can reduce safety and capacity. Many times the addition of a turning lane, median, or island is sufficient to accomplish the desired improvements. With the added conflict of railroad traffic, care must be taken to ensure that channelization provides guidance and control, not confusion.

Inappropriately designed channelized turning lanes can result in not increasing capacity very much and making crossing difficult for cyclists and pedestrians. A channelized near-side lane (deceleration slip lane) is primarily aimed at improving efficiency. From a safety perspective it is contrary to safe system principles if it allows through traffic to increase their speed through the intersection and creates high-speed, large radius slip lanes, rather than through traffic slowing behind the slowing, turning vehicle. In addition, if the slip lane (deceleration lane) is not adequately separated from the through traffic, there is a high risk that vehicles using that lane could mask or hide vehicles in the through lane. This is sometimes referred to as the "shadowing effect" or "dynamic visual obstruction" and represents a significant increase in risk for a vehicle turning out of the side road (figure 6.59).

Figure 6.59: Shadowing effects (dynamic visual obstruction)—a large vehicle in the slip lane hiding a vehicle in the through lane.





Source: Woolley, J., Stokes, C., Turner, B., and Jurewicz, C. 2018. *Towards safe system infrastructure: a compendium of current knowledge* (No. AP-R560-18).

Safety implication

- A primary goal of intersection design is to limit and/or reduce the severity of potential road user conflicts.
- FHWA clarifies that the basic principles of intersection channelization that can reduce conflicts are:

1. **Separate points of conflict.** Separation of conflict points can ease the driving task while improving both the capacity and safety at an intersection. The use of exclusive turn lanes, channelized right turns (for those driving on the right), and raised medians as part of an access control strategy are all effective ways to separate vehicle conflicts. (see section 6.6 on Left-in left-out/right-in right-out).
2. **Define desirable paths for vehicles.** The approach alignment to an intersection as well as the intersection itself should present the roadway user with a clear definition of the proper vehicle path at risky locations with complex geometry or traffic patterns, such as highly skewed intersections, multi-leg intersections, offset T-intersections, and intersections with very high turn volumes. Clear definition of vehicle paths can minimize lane changing and avoid “trapping” vehicles in the incorrect lane.
3. **Discourage undesirable movements.** Designers can utilize corner radii, raised medians, or traffic islands to prevent undesirable or wrong-way movements, including restriction of turns and designing approach alignment to facilitate intuitive movements.
4. **Encourage safe speeds.** On low-speed roads with pedestrians, turning speeds should be lower by smaller turning radii, narrower lanes, and/or channelization features (figure 6.60). On high-speed roads with no pedestrians, speeds for turning vehicles should be comparable with straight through speeds to remove turning vehicles from the through traffic stream as quickly and safely as possible. This can be accomplished with longer, smooth tapers and with associated deceleration length to corner at a slower speed.
5. **Facilitate the movement of high-priority traffic flows.** Accommodating high-priority movements at intersections addresses both drivers’ expectations and intersection capacity. The highest movement volumes at an intersection define the highest priority movements, although sometimes route designations and functional classification of intersecting roads should be considered. In low density suburban and rural areas, giving priority to motor vehicle movements may be appropriate; however, in some urban locations, pedestrians and cyclists at times may be the highest priority users of the road system. Separating movements by channelization can reduce crossing widths for pedestrians and increase their opportunity to cross busy roadways.

Figure 6.60: Angle of slip lane transformed from wide (left picture) to tight (right picture

Source: Javus, A. et al. 2012. Safety evaluation of right-turn smart channels using automated traffic conflict analysis, *Accident Analysis & Prevention*, Volume 45, March 2012, pages 120–130.

6. **Facilitate the desired traffic control scheme.** Visibility of signs and markings at intersections can be maintained by channelization. Other equipment at the intersection should not block sight distance and should facilitate preventive maintenance by field personnel. Intersection layout should be designed for simultaneous left-turning movements and potential U-turning movements. Operational impacts and the design of pedestrian facilities should be taken into account during the intersection's design.
7. **Accommodate decelerating, slow, or stopped vehicles outside higher-speed through traffic lanes.** Speed differentials between vehicles in the traffic stream are a primary cause of crashes. Speed differentials at intersections are inherent as vehicles decelerate to facilitate turning. The provision of exclusive left- and right-turn lanes can improve safety by removing slower-moving turning vehicles from the higher-speed through traffic stream and reducing potential rear-end conflicts. In addition, through movements may experience lower delays and fewer queues. However, care is needed not to induce higher speeds for through and turning traffic and obscure the view for side-road traffic
8. **Provide safe refuge and way finding for cyclists and pedestrians.** Intersection channelization can provide refuge and/or reduce the exposure distance for pedestrians and cyclists within an intersection without limiting vehicle movement.

- Channelization separating through and turning lanes may constitute a hazard because of its placement when a raised treatment is applied, especially on high-speed roads.[148]
- Channelized offside turn lanes can make speed on intersection approaches slower than non-channelized nearside turn lanes.[149]
- Several studies from high-income countries confirm that the provision of turn lanes has been found to reduce crash rates.[150], [151], [152]

Some studies proved the effectiveness of channelization.

- The provision of median islands on the approach to an intersection can assist drivers to identify the location of the intersection and raise their alertness to select their travel path through the intersection. Median islands provide some protection for turning vehicles when a turning lane is provided to take the turning vehicle out of the through lane. This treatment can achieve a reduction in head-on, rear-end, and right-turn type crashes by 20 percent. If the median island is placed through the intersection, thereby removing the cross-movement, head-on, right-turn and right-angle type crashes can be eliminated.
- For wider medians (generally more than 5.4 m [18 ft]), offsetting the turn lane provides the following safety benefits:

1. Better visibility of opposing through traffic;
2. Decreased possibility of conflict between opposing left-turn movements within the intersection; and
3. More left-turn vehicles served in a given period of time, particularly at a signalized intersection.[153]

- The provision of indented turn lanes with painted

148 Vicroads. 2019. Road design notes: Raised Safety Platforms (RSPs).

149 FHWA. 2014. Handbook for Designing Roadways for the Aging Population: Accessed at https://safety.fhwa.dot.gov/older_users/handbook/.

150 Staplin, et al. 1997. National Highway Traffic Safety Administration.

151 Gluck, J., H. S. Levinson, and V. Stover. 1999. National Cooperative Highway Research Program Report 420: Impacts of Access Management Techniques. NCHRP, Transportation Research Board, Washington, DC.

152 Elvik, R., Hoye, A., Vaa, T., and Sorensen, M. 2009. The Handbook of Road Safety Measures, Second edition . Emerald Group Publishing Limited. ISBN 978-1-84855-250-0.

153 Harwood, D. W., M. T. Pietrucha, M. D. Wooldridge, R. E. Brydia, and K. Fitzpatrick. 1995. National Cooperative Highway Research Program Report 375: Median Intersection Design. NCHRP, Transportation Research Board, Washington, DC.

islands can achieve a 20 percent reduction in opposing turn and rear-end crashes; and with a median island, reductions of 40 percent in rear-end, 30 percent opposing turn, and 20 percent loss-of-control crashes can be achieved.[154]

- An Australian meta-analysis shows a reduction range from 22 percent to 36 percent of crashes. This reduction is for channelization where it is not clear whether it is a splitter, median, or both. Five studies of splitter islands again showed an overall reduction of about 30 percent; two studies of reductions due to median islands showed a reduction of about 20 percent. These benefits may be captured as part of other attributes, such as turn lane provision and delineation.
- Crashes at signalized intersections where a right offside turn lane (in right-hand traffic) was added, in combination with and without a right-turn separate signal phase, were reduced by 36 percent and 15 percent, respectively. At non-signalized intersections with marked channelization separating the right offside turn lane from the through lane, crashes were reduced for rural, suburban, and urban areas by 50, 30, and 15 percent, respectively. When raised channelization devices were used, the crash reductions were 60, 65, and 70 percent in rural, suburban, and urban areas, respectively. Consistent findings were reported in Hagenauer et al. (1982),121 McFarland et al. (1979),122 and FHWA (2014). Handbook for Designing Roadways for the Aging Population. Accessed at https://safety.fhwa.dot.gov/older_users/handbook/.

Good design practice/ treatments/solutions

- Raised channelization with sloping curbs is recommended over channelization accomplished through the use of pavement markings alone (flush) for left- and right-turn lane treatments at intersections on all roadways with operating speeds of less than 20 km/h. (*AASHTO 2009. Highway Safety Manual*).
- Raised islands should be semi-mountable curbs. Barrier curbs and other profiles are not favored for use on islands. Depressed islands can also be outlined using curbs, provided that adequate definition and delineation of the island can be achieved by other means (e.g., berm behind the curb).
- Prohibited turns should be blocked by channelizing islands, wherever practical.
- Islands/medians should be conspicuous to approaching drivers. Rural sites with few constraints will have relatively large islands (e.g., ≥ 100 m2 for a splitter island on an important approach to an arterial road), whereas an unsignalized urban intersection may have a small island (Austroads 2017. *Guide to Road Design Part 4 A Unsignalised and Signalised Intersections*).
- Island noses should be offset from the edge of the adjacent traffic lane to provide additional clearance to the curb to enhance comfort for approaching drivers and prevent any tendency for them to shy away from the curb.
- As a general guide, the island nose should be offset by 0.2 m per 10 km/h of approach speed, but this is not used by all jurisdictions. On narrow islands where an offset to the approach nose is not practicable, a fully mountable nose may be provided, which requires a smaller offset and nose radius than a curb. However, where this cannot be achieved because of limited visibility to intersections that are located on crests or relatively tight curves, raised median islands in the major road can be used to improve driver perception of the intersection. In such cases the island nose should be designed to a length that carries it over the crest or around the curve to a point where it can be easily seen (see section on Median).
- Curbed islands are sometimes difficult to see at night because of the glare from oncoming

154 Austroads. 2012. Effectiveness of road safety engineering treatments, AP-R422-12.

headlights or from distant luminaires or roadside businesses. Curbed islands generally should not be used in rural areas and at isolated locations unless the intersection is lighted and curbs are delineated, such as with curb-top reflectors.

- Channelization at lower cost is the placement of painted islands/medians to narrow the lanes and reduce approach speeds. This is supplemented by rumble strips within this median and along the outside of the edge lines of the pavement (see section 3.2 on Speed compliance and traffic calming).
- An auxiliary lane should be of sufficient width (including that of shoulders adjacent to auxiliary lanes) and length to enable a driver to maneuver a vehicle into it properly, and once in it, to reduce speed for turning at the intersection.
- The storage length should be sufficient to avoid turning vehicles stopping in the through lanes waiting for a signal change or for a gap in the opposing traffic flow. A longer lane should be considered in situations where there is a high volume of trucks turning, a grade, or a high design speed. The inability of turning vehicles to access turn lanes can adversely affect the capacity of an intersection and result in vehicles encroaching onto medians and causing maintenance issues.
- However, the taper length should not be too long to ensure that the commencement of the auxiliary lane is well-defined, and drivers do not inadvertently enter the lane during inclement weather or on a horizontal curve.
- The design should allow for an occasional large truck to turn by swinging wide and encroaching on other traffic lanes without disrupting traffic significantly.
- Where curbing is to be used adjacent to the auxiliary lane, an appropriate curb offset should be provided to be able to accommodate vehicles.
- Parking should be restricted for a distance in advance of the right, nearside turning radius to avoid encroachment on adjacent spaces of the turning lanes.
- For arterial street design, adequate radii for vehicle operation should be balanced against the needs of pedestrians and the difficulty of acquiring additional right-of-way or corner setbacks. Because the corner radius is often a compromise, its effect on both pedestrians and vehicular movements should be examined.

Figures 6.61 through 6.65 show some good and bad examples of delineation for turning movements.

For vulnerable road user safety:

- Install a raised island of adequate size to provide refuge where pedestrian crossings are expected (figure 6.66). Islands used for channelization should not interfere with or obstruct cycle lanes at intersections.
- Drivers should not be suddenly confronted with an unusable area in the normal vehicle path. Islands first approached by traffic should be indicated by a gradually widening and marking or a rumble strip on each side.
- Place the crosswalk in the center of the turning roadway (further away from the intersection corner) perpendicular to the direction of travel (without making it an inconvenient detour for pedestrians), and use landscaping, etc., to prevent pedestrians from crossing elsewhere (figures 6.67 and 6.68). In addition, the crosswalk and curb ramp should be kept a distance equivalent to one or two car lengths (i.e., usually 6 m or 12 m) back from the holding line so that the crossing is coincident with a space between queued cars, which will allow drivers on the approach leg to look for and yield to pedestrians before reaching the intersecting roadway and scanning for gaps in traffic.
- Adequate stopping sight distance should be provided to pedestrians, particularly to crossings of slip lanes where speeds are higher than locations with smaller corner radii. Other situations where special consideration of cyclists and treatments is required to assist access and safety include on approaches where the skew of an intersection necessitates provision of a slip lane on the corner of a roundabout

Figure 6.61: No marking slip lane in Tanzania.

Source: World Bank.

Figure 6.62: Poor delineated slip lane in Ghana.

Source: Graphic Online. https://www.graphic.com.gh/news/general-news/accra-chokes-heavy-traffic-slows-business-field-day-for-okada-operators.html.

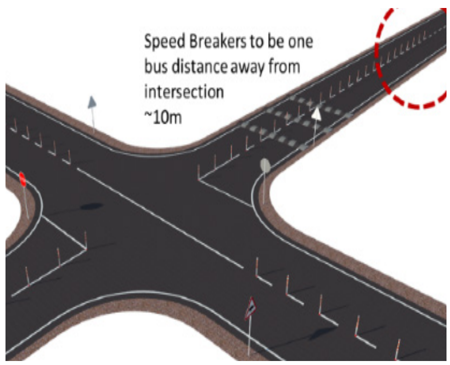
Figure 6.63: Slip lane with zigzag pavement marking in Singapore.

Source: Google street view.

Figure 6.64: Large urban intersection with pavement marking delineation for turning movements

Source: © Google Earth.

Figure 6.65: Minor road treatment with flexible poles.



Source: Indian Institute of Technology, Kharagpur. 2019. Report on Road Safety Audit of SH-11 During Operation Stage, India.

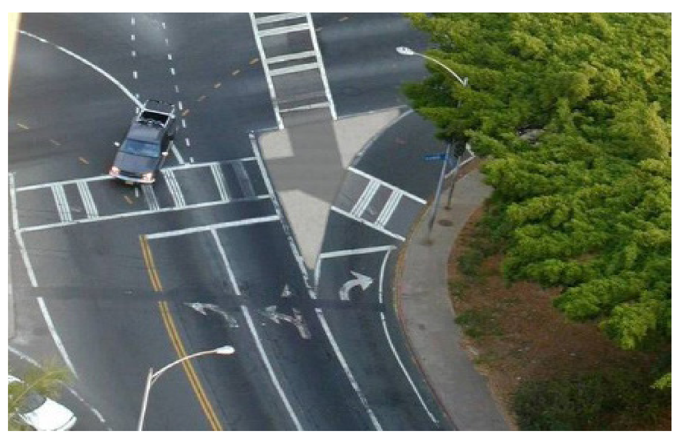
Figure 6.66: Pedestrian refuge and cyclist way finding

Source: FHWA

Figure 6.67: Wide-angled slip lane with poorly aligned crossings and lack of crossing.

Source: Un-Habitat. .

Figure 6.68: A well-designed right turn slip lane at a complex intersection.



Source: Designing for Pedestrian Safety.

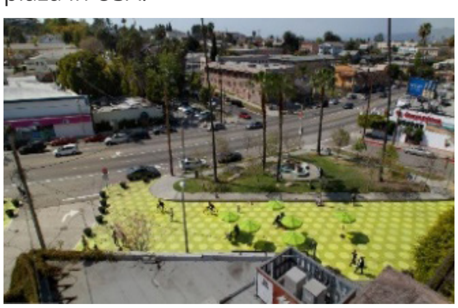
Figure 6.69: Raised crosswalk on slip lane with ghost island markings and crosswalk signs.

Source: The State of Queensland. .

(e.g., marked cycle lanes). The driver may not see (cognitive and physical) cyclists crossing the road the driver wants to turn into (potentially due to driver distraction, or cyclists speed misjudged).

- Whenever feasible, signal and other utility poles and signs should be placed outside of paved pedestrian walkways and landing areas. Care should be taken to avoid placing these objects in conflict with future pedestrian facilities.
- Providing a buffer space whenever sidewalks are constructed adds separation between pedestrians and the travelled way.
- Appropriate cycle treatments, including line marking and signs for drivers using the slip lane to watch for cyclists, may be required adjacent to the island forming slip lanes.
- Priority at crossings should be clear for all road users (i.e., whether motorists, pedestrians, or cyclists have priority).
- At intersections with channelization, lighting systems should be installed for illuminating islands, diverge and merge locations, turning roadways, and pedestrian crossings.
- A refuge island for pedestrians at or near a crosswalk or cycle path that aids and protects pedestrians and cyclists who cross the roadway should be provided with slip and turn lanes.
- Raised curb corner islands and center channelizing or divisional islands can be used as refuge areas. Refuge islands (for pedestrians and cyclists crossing a wide street, for loading or unloading transit riders, or for wheelchair ramps) are used primarily in urban areas.
- Where pedestrians and cyclists are expected to cross a slip or turn lane, low vehicle speeds should be encouraged at the crossing point.
- Using physical devices (e.g., road hump or special marked [such as a wombat]) crossing on slip and turn lanes can reduce vehicle speeds and improve visibility of crosswalks (figure 6.69).
- During recent years in some countries such as the US and Australia, inappropriately designed slip lanes have been converted to a space for pedestrians or cyclists, because these slip lanes can be harmful for safety (figures 6.70 through 6.72). For example, a short slip lane (no safety devices for pedestrian on crosswalks) that carves up the sidewalk only so drivers can take turns faster is dangerous. Many cities converted to pedestrian plazas.

Figure 6.70: Transformation to mini plaza in USA.

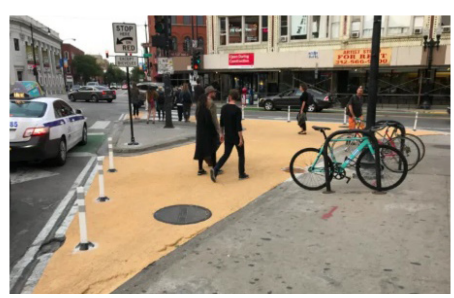


Source: LADOT people St (CC BY-ND 2.0).

Figure 6.71: Transformation to street cycle lane in the US.

Source: Google streetview.

Figure 6.72: Transformation to footpaths in the US.



Source: John Greenfield/Streetsblogusa.

Further Reading

- AASHTO. 2018. Green Book (GDHS-7). Must read chapter 2, Design controls and criteria; chapter 5, Local roads and streets; chapter 6, Collectors in urban areas; chapter 7, Arterial road.
- FHWA. 2014. A Report on the Development of Guidelines for Applying Right-Turn Slip Lanes. Must read chapter 2, Literature review.
- Austroads. 2017. Guide to Road Design. Must read Part 4A, Unsignalised and Signalised Intersections.
- Austroads. 2015. Road Geometry Study for Improved Rural Safety. Must read chapter 6, Design elements for improved rural road safety.
- Rune Elvik. 2009. The Handbook of Road Safety Measures, Second edition. Must read Part II, Road Safety Measure.

6.6. Left-in Left-out/Right-in Right-out

General description

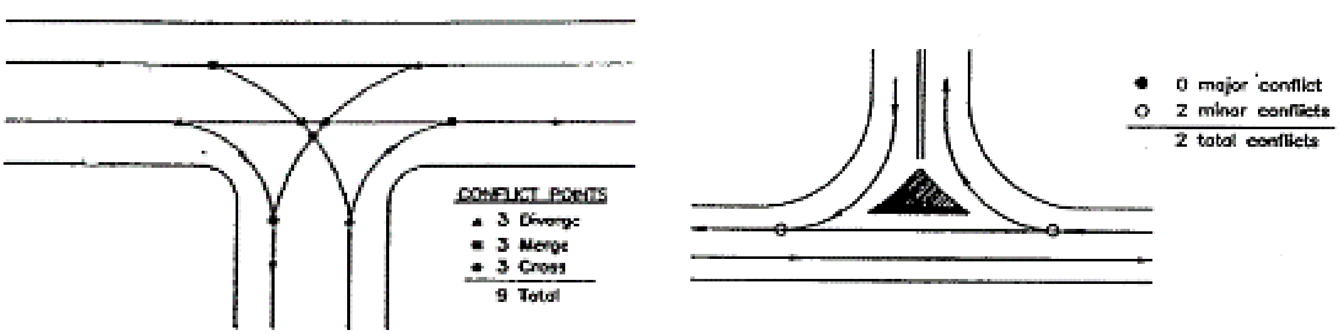
Left-in/left-out (LILO) and right-in/right-out (RIRO) refer to a type of three-way road intersection where turning movements of vehicles are restricted. RIRO is typical when vehicles drive on the right, and LILO is typical where vehicles drive on the left. This is because minor roads usually connect to the outsides of two-way roads.

A LILO permits only left turns and a RIRO permits only right turns. "Right-in" and "left-in" refer to turns from a main road into an intersection (or a driveway or parcel); "right-out" and "left-out" refer to turns from an intersection (or a driveway or parcel) to a main road. They are implemented to prevent the turning maneuver across opposing lanes of traffic.

Safety implication

- RIRO/LILO configurations generally improve road traffic safety and efficiency by reducing the number of conflict points between vehicles (figure 6.73). In particular, they eliminate the high severity risks of turning traffic versus through traffic. Turning movement restrictions are a type of access management strategy used to improve the safety of stop-controlled intersections and driveways. Restricted and prohibited turn movements reduce the number of turning conflict points at intersections, which are generally known to reduce crash risk.[155]
- According to the literature, 74 percent of driveway crashes involve offside turn maneuvers where

Figure 6.73: Sketch of change in conflict points with RIRO arrangement.



Source: Oregon Department of Transportation, 1998.

Three-way intersection before restriction

RIRO intersection

155 Simodynes, T., Welch, T., and Kuntemeyer, M. 2000. Effects of Reducing Conflict Points on Reducing Accidents (abstract), Third National Access Management Conference, p. 141, Federal Highway Administration, Washington, DC.

Figure 6.74: RIRO junction with too close offset right turn in Ukraine.

Source: © Google Earth.

Figure 6.75: Urban LILO Brunei with insufficient space for safe lane change to offside right turn.

Source: © John Barrell.

emerging vehicles have to cross opposing traffic lanes.[156]

- RIRO/LILO are only effective where this turning maneuver is effectively prevented, usually by a physical barrier or raised island. Legal restrictions on turning maneuvers (those without physical restrictions) are much less effective and open to abuse. Therefore, they are most common where there is a divided carriageway and no median crossing.
- There is some evidence that RIRO without physically preventing left turn movements can result in higher crash rates than those with a physical prohibition.[157]
- A RIRO/LILO configuration may improve safety and operations at one intersection while consequently worsening them at another intersection upstream or downstream.
- Crash migration is a potential issue related to restricted turning movements at a given access point. This occurs when crashes at a treated site shift to another site. While RIRO/LILO operations eliminate turns across opposing flows at the subject location, U-turn movements and related crashes potentially increase at the next intersection downstream that allows U-turns.
- They also introduce additional collision patterns as vehicles attempt to cross the main running lanes and merge with traffic in opposing directions (figures 6.74 and 6.75). As such, at a full movement

156 National Highway Institute. 1992. Access Management, Location and Design: Participant Notebook, NHI Course No. 15255, U.S. Department of Transportation, Federal Highway Administration, Washington, DC.

157 Sarath Chandra Gorthy. 2017. Analysis of Right-in, Right-out Commercial Driveway Safety, Operations and Use of Channelization as Compliance Countermeasure. MSc Thesis, Clemson University.

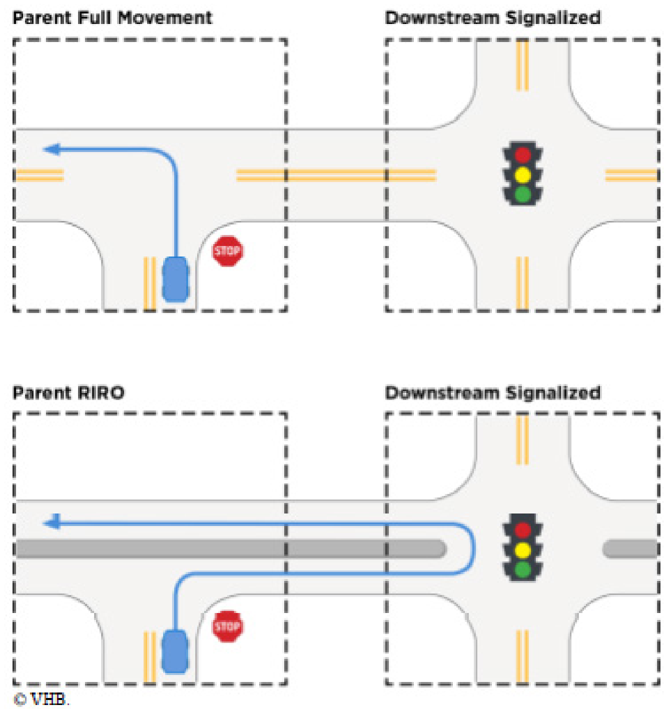
signalized intersection within a corridor, there could be an increase in U-turn movements from both directions along the main line if the stop-controlled intersections are converted to RIRO along the corridor.

- RIRO junction with offset right turn too close and insufficient weaving length between movements (also incorporates pedestrian crossing and public transport stop). Turning and storage needs to accommodate all vehicles, including heavy goods vehicles (HGVs).

Good design practice/treatments/solutions

- RIRO/LILO intersections should be designed with a physical median in the mouth of the junction that is effective in preventing an unauthorized turn.
- Single lane approaches are most effective in preventing this unauthorized turn.
- Where the main highway is a single carriageway, a physical barrier is also needed on the main highway.
- Where the main highway is a dual carriageway, the intersection should be designed as though the deceleration lane were an off-ramp and the acceleration lane an on-ramp, with physical separation between the decelerating/accelerating traffic emphasizing the intersection and converting the turn movement into a merge. This philosophy is similar to the examples shown in the next section.
- The ability to undertake the prohibited maneuver at the RIRO/LILO intersections needs to be possible at the next available intersections. As these are effective U-turns into the offside of the opposing traffic stream, they must be made under controlled conditions with higher quality turning facilities—either a signal control or at a roundabout (figure 6.76).
- The use of an offset median crossing merely transfers the merge problem to another location.

Figure 6.76: Illustration of replaced turning movement at downstream junction.



Source: FHWA, 2012.

- Wherever this turn is allowed, it should be at a sufficient distance from the RIRO/LILO to allow emerging traffic to safely cross the main traffic lanes and allow approaching vehicles to anticipate vehicles slowing for the offside turn.

Further Reading

Ahmet Aksan, Robert Layton. 1998. Right-In Right-Out Channelization Discussion Paper No. 13 prepared for Oregon Department of Transportation presented at the 3rd National Conference on Access Management Transportation Research Board Fort Lauderdale, Florida, October 4–7, 1998.

FHWA. 2012. Safety Evaluation of Turning Movement Restrictions at Stop-Controlled Intersections. FHWA Publication No. FHWA-HRT-17-065.

Mn/DOT Access Management Manual. 2008. Must read chapter 3, Guidelines and Public Street and Driveway Connections.

6.7. Acceleration and Deceleration Lanes

General description

Acceleration/deceleration lanes (also known as speed change lanes) provide drivers with an opportunity to speed up or slow down in a space not used by high-speed through traffic (figure 6.77).

Merging can occur at on-ramps to freeways or multilane highways, or when two significant facilities join to form a single traffic stream.

Merging vehicles often make lane changes to align themselves in lanes appropriate to their desired movement.

Diverging occurs when one traffic stream separates to form two separate traffic streams. This occurs at off-ramps from freeways and multilane highways, but can also occur when a major facility splits to form two separate facilities. Again, diverging vehicles must properly align themselves in appropriate lanes, thus indicating lane changing; non-diverging vehicles also make lane changes to avoid the turbulence created by diverge maneuvers.

Figure 6.77: Illustration of acceleration and deceleration lanes.

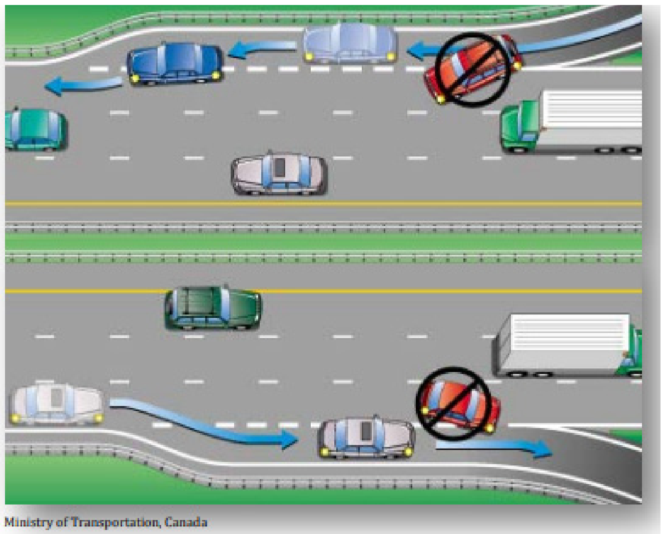


Figure 6.78: Deceleration lane approach tight exit radius—Brunei.

Source: © John Barrell.

Figure 6.79: Well defined acceleration lane—Brunei.

Source: © John Barrell.

On freeways and some major streets, the speed change between the main lanes and the adjacent streets can be substantial and cause stop- and-go traffic and more collisions for the main vehicle flow.

While these speed change lanes are most often associated with high-speed roads, they can be included as part of lower speed RIRO/LILO junctions where capacity requires side road traffic to enter high-volume roads.

Dedicated acceleration lanes allow vehicles that have turned onto the main road to speed up to match the flow of traffic. Deceleration lanes allow vehicles leaving the high-speed main road to slow down to match the side road traffic or negotiate a tighter road alignment at exit.

Figure 6.80: Offside diverge lane—Brunei—narrow median and lane requiring additional space beyond turn.

Source: © John Barrell.

Figure 6.81: Additional barrier to offside diverge—Brunei—to control entry and turning area beyond far carriageway for ALL vehicles, adding additional merge after crossing opposing traffic.

Source: © John Barrell.

Safety implications

- Acceleration and deceleration lanes may be blocked by parked or stopped vehicles.
- Drivers using acceleration lanes have a narrow angle of vision with the main road flow.
- Drivers merging in a stream of vehicles may have difficulty in watching both the vehicles on the main stream and those that are merging.
- Those wishing to leave the multilane highway into a speed change lane need ample warning to move safely into the nearside lane in sufficient time to enter at the start of the lane.
- Congestion, if the number of vehicles goes beyond the capacity, can increase collisions as vehicles slow or stop unexpectedly.
- If lanes do not have sufficient capacity for all vehicles, then queues can back onto the main carriageway causing additional rear-end collisions.
- Where speed change lanes are included on multilane highways, the lane changing of vehicles within the main streams can reduce free flow capacity.
- Late entry and early exit from a speed change lane can increase the risk of collisions.
- The spacing between merge and diverge speed change lanes can result in disruption to main line flow and result in excessive sideswipe and rear-end collisions.

Good design practice/ treatments/solutions

- Good visibility should be maintained for both emerging and approaching traffic.
- Clear signing and marking of lanes are crucial to safety.
- Visibility in the night can be enhanced by using reflective road studs of different colors.
- In the case of a perpendicular approach to merging lanes, the line of sight should be kept free from street furniture, barriers, and road signs.
- To avoid obstruction on the lanes, parking restrictions should be implemented and strictly followed.
- Speed change lanes should be kept free in case of congestion. Therefore, the capacity of the main road and volume of merging traffic need to be calculated to allow free flow conditions under all circumstances. When queues develop, the effective length of the lane is reduced.

- Similarly, the upstream capacity of the main road is a major consideration when large amounts of traffic need to use the deceleration lane off a multilane highway and relative speeds and lane changing will be an issue.
- Length of the lanes should be long enough to accommodate all the traffic if traffic volume is very high on the main stream. Where intersections with speed change lanes are close together, sufficient weaving length is needed to maintain stable flow conditions between intersections.

Further reading

- G. T. Wall, and N. B. Hounsell. 2004. A Critical Review of the Standards and Design Processes for Motorway. Must read chapter 2, Evolution of standards for motorway diverges; chapter 3, Introduction to the diverging flow-region diagram; chapter 6, Critical review of the diverging flow-region diagram.
- Diverges in the UK School of Civil Engineering and the Environment University of Southampton Southampton, UK.
- Markos Alito Atamo. 2012. Safety Assessment of Freeway Merging and Diverging Influence Areas Based on Conflict Analysis of Simulated Traffic. PhD Thesis, University of Colorado. Chapter 2, Literature review.

6.8. Grade Separation and Ramps

General description

Most crashes happen at intersections. The best way of stopping conflicting intersection movements is placing the intersecting roads at different levels, or grade separating them. This can be done with overpasses or interchanges.

An overpass is a simple grade separation of two roads whereby there is no actual link between them and hence no exchange of traffic is possible (figure 6.82). Overpasses are typically used when a minor road crosses a major road, and where a rail line crosses a road.

Interchanges are grade-separated intersections where

Figure 6.82: A simple overpass with no connection between the two routes—Ethiopia.

Source: © John Barrell.

traffic from one main road is connected to another main road via free flow connecting roads.

An interchange allows traffic to move between two or more roads that are grade separated. Interchanges vary from simple arrangements with ramps and intersections at the minor road to complex layouts where two or more freeways (major highways or motorways) connect.

Overpasses and interchanges are very costly and are usually built as part of a freeway system where large traffic flows justify the cost. Occasionally, interchanges and overpasses are built on busy urban highways when justified by road safety and traffic flow improvements.

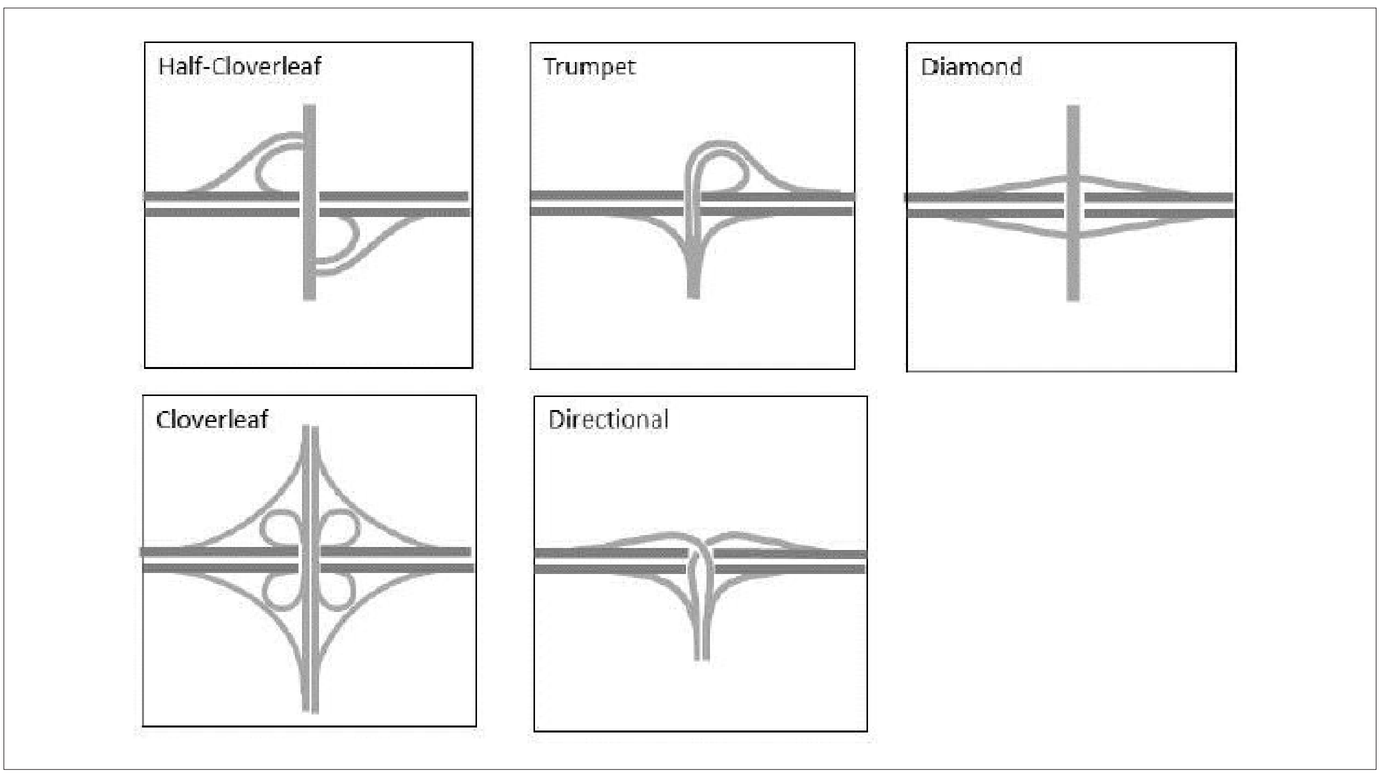
In full grade-separated interchanges, with separate lanes for all streams of traffic, all movements that require crossing other streams of traffic are removed and reduced to changing traffic lanes.

Various forms of interchanges have been developed, such as diamond interchanges, trumpet interchanges, and full or partial cloverleaf interchanges (figure 6.83). These interchanges differ with respect to the types of ramps that are built for turning traffic.

Partial grade-separated intersections (figure 6.84) are those where there is no at-grade connection between two main roads, but where the connections between ramps and main roads are at grade (instead of acceleration/deceleration lanes).

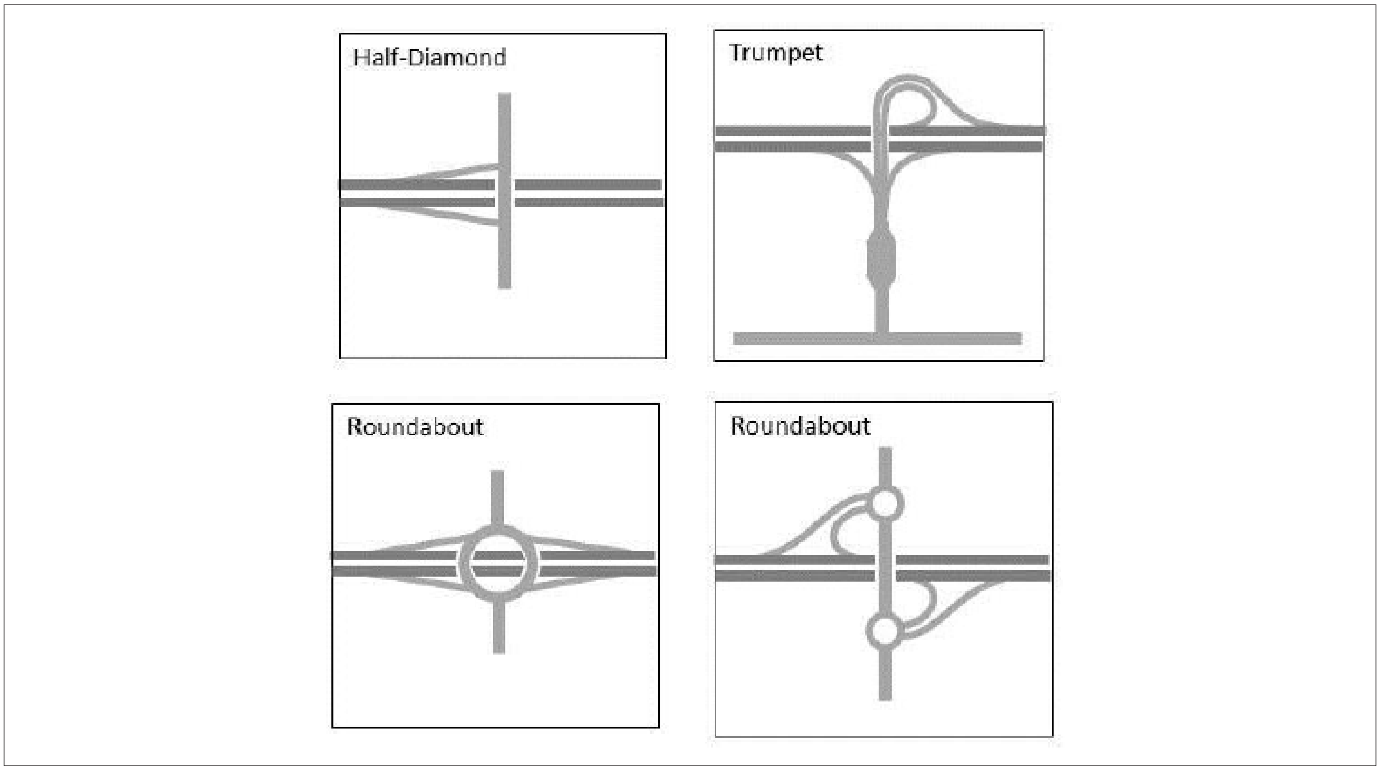
Ramps joining one of the intersecting roads may be in the form of an at-grade intersection such as priority intersection, signalized intersection, or roundabout.

Figure 6.83: Typical full grade-separated interchange layouts.



Source: © John Barrell.

Figure 6.84: Typical partial grade-separated interchanges layouts.



Source: © John Barrell.

Safety implications

- According to research,[158] the crash rate is lower at grade-separated junctions than at at-grade junctions. The largest differences have been found in four-way intersections. At these, the reduction of the number of injury crashes is larger than the reduction of the number of property-damage-only crashes.
- The crashes around grade-separated intersections include crashes on ramps, but not crashes on comparable stretches of road immediately before and after at-grade junctions. If these crashes were included in the calculation of the effects on crashes, still larger reductions of the number of crashes on grade-separated junctions would probably have been found. However, ramps are a new road element when grade-separated junctions are constructed, and their effects on safety should be included in the effects of grade-separated junctions.
- Partly grade-separated junctions have been found to be less safe than grade-separated junctions, but safer than at-grade four-way intersections. When at-grade four-way intersections are equipped with speed cameras, these are safer than partly grade-separated junctions without speed cameras. No significant difference has been found between partly grade-separated and signalized junctions.
- Diamond interchanges (simple and comprehensive, with straight ramps, and with minor roads running above the main road) appear to be the safest form of grade-separated interchanges.
- Diamond interchanges have lower crash rates than

158 Elvik, R., Hoye, A., Vaa, T., and Sorensen, M. 2009. The Handbook of Road Safety Measures, 2nd ed., Emerald Group, United Kingdom.

most other types of interchanges. Most differences are only small and not significant. Diamond interchanges are most favorable in comparison with trumpet interchanges and junctions with direct access ramps. There are several factors that make diamond interchanges relatively safe: the layout is relatively simple and thereby reduces confusion or errors among drivers. Ramps in diamond interchanges are straight, and crash rates are smaller on straight ramps than on curved ramps or loops.

- The studies have found that there are more crashes in curves with a smaller radius than in curves with a larger radius.[159]
- It is possible that the higher speeds on motorways on the approach to loops may be a contributory factor to crashes, particularly on diverge loops.
- HGVs are particularly susceptible to rollover incidents on curved ramps or loops due to the tight radius and potential for high speed.
- Short or frequent spacing between intersections can result in short weaving lengths between associated merge/diverge/speed change lanes.

Good design practice/ treatments/solutions

- Several features and issues are common to all types of interchanges. These items are important to consider in all contexts.
- Common elements include:
  1. Clear sight lines (vertical and horizontal),
  2. Interchange form—appropriate for traffic types and patterns,
  3. Appropriate horizontal/vertical geometry,
  4. Adequate speed change lanes,
  5. Driver expectancy/positive guidance—adequate perception/reaction distances for typical maneuvers and all exits/entrances to the right of through traffic,
  6. Design vehicle offtracking,
  7. Adequate storage for vehicle queues, and
  8. Adequate accommodation for signing.
- Interchanges should be located such that merging and diverging areas are sited on straight or near straight alignment with gentle gradients.
- Where feasible, it is preferable to provide exit slip roads on uphill gradients to facilitate deceleration, and conversely, entry slip roads on downhill gradients to facilitate acceleration. As such, it is generally not advisable to locate grade-separated intersections at a hilltop due to unfavorable gradients. Drivers are also more likely to be affected by bright sun glare on the approach.
- Grade-separated intersections should be relatively simple, with a minimum number of decision points which are spaced well apart. They should enable all drivers to readily identify the direction with minimal need for lane changing. Where more complex road connections are unavoidable, notably within cities and at their peripheries, every effort should be made to simplify the layout and provide adequate and well-designed directional signing.
- Ramps generally have lower design speeds than the main line, but the difference should not be excessive. It is important that changes to a lower design speed are predictable and obvious to drivers, and there is adequate distance for deceleration.
- Loops are ramps which turn through more than 120 degrees on a small radius curve. They are typical of grade-separated intersections in the trumpet or cloverleaf layout. Loops should not consist of more than one lane per direction.
- Measures to maintain safety are necessary, and measures to consider include:
  1. Provision and maintenance of clear visibility

159 Rune Elvik, Handbook of Road Safety Measures, p. 236.

over the whole of the loop on the approaches, especially beyond an underbridge or other structure,

2. Advisory speed limits and/or bend signs and "chevron" warning signs,
3. Widening of lanes on the loops as appropriate for lower radii,
4. The provision of vehicle restraint systems on the outside of curves,
5. Physical separation of opposing traffic streams,
6. Lighting, and
7. High skid resistant surfacing.

- Cyclist and pedestrian movements must be accommodated through interchanges, even in rural locations. In urban or suburban areas where sidewalks are in place, the existing accommodations may not be suitable for current needs. It is equally important to develop the design for bikes and pedestrians, as well as vehicles. Some interchange configurations (such as the single point or diverging diamond) require multistage crossings and refuge islands. Occasionally it is necessary to provide separated facilities through complex interchanges.
- Grade-separated interchanges are complex highway elements, and every discipline involved in the design (geometry, traffic, structure) needs to coordinate to ensure the needs of various users are met.

Further Reading

- Oregon Department of Transport Highway Design Manual. 2012. Must read chapter 9.
- Transport Infrastructure Ireland (TII) Layout of Graded Separated Junctions DN-GEO-0303 2009. Must read chapter 4, Geometric standards and chapter 5, Layout options.

6.9. Rail Crossings

General description

Rail networks are defined corridors where vehicles move on defined and immovable rails. They are commonly situated in dedicated corridors with only limited and controlled interaction with other forms of land transport (cars, vans, motorcycles, cycles, and pedestrians) on the highway network.

In previous centuries rail transportation was also common on the streets of major cities in the form of trams or streetcars. In many cities that had abandoned these systems, they are now being reintroduced, either on streets or in separate dedicated corridors.

They all share the requirement—to varying degrees—to positively cross the running carriageway of general traffic. These, whether for conventional heavy rail or urban tramway/light rail systems, all include rail crossings to varying degrees.

All these interactions must be undertaken under controlled conditions.

Rail crossings are intersections where a highway crosses a rail track at grade and are the physical intersection of two very different vehicle-carrying surfaces and areas approaching the physical intersection. Within the crossing area, physical design characteristics of each structure, i.e., rail and highway, may have to be specifically adjusted to accommodate the other transportation mode smoothly and safely.

Some international rules have helped to harmonize level crossings, for instance, the 1968 Vienna Convention which requires standard warning signs and lines, and potential barriers. This has been implemented in many countries, including countries which are not part of the Vienna Convention.

Early crossings had a flagman in a nearby booth who would, on the approach of a train, wave a red flag or lantern to stop all traffic and clear the tracks.

Gated crossings became commonplace in many areas, as they protected the railway from people and livestock trespassing, and they protected the users of the crossing when closed by the signalman/gateman.

In the second quarter of the twentieth century, manual or electrical closable gates that barricaded the roadway started to be introduced, intended to be a complete barrier against intrusion of any road traffic onto the railway.

Automatic crossings are now commonplace, although each of the systems described above are still used in some LMICs. Full, one-half, or no barrier crossings superseded gated crossings, although crossings of older types can still be found in places.

In rural regions with sparse traffic, the least expensive type of level crossing to operate is one without flagmen or gates, with only a warning sign posted. This type has been common across North America and in many developing countries.

Safety implications

- Level crossings constitute a significant safety concern internationally. On average, each year around 400 people in the European Union and over 300 in the United States are killed in level crossing crashes.
- Collisions can occur with vehicles as well as pedestrians; pedestrian collisions are more likely to result in a fatality.[160] Among pedestrians, young people (5–19 years), older people (60 years and over), and males are considered to be at high risk[161] due to their attitude to risk or lack of general awareness.
- Rail crossings can be dangerous if:
    1. There is poor sight distance to a signal display, or to approaching trains,
    2. Traffic control is inadequate,
    3. Vehicles queue across tracks due to congestion or nearby intersections,
    4. There is a lack of pedestrian facilities,
    5. Either road or rail pavement is not maintained,
    6. Signaling equipment is located too close to the road that can result in unnecessary damage by passing vehicles, and
    7. Vertical profile of road over rail crossing results in grounding of road vehicles.
- Signalized intersections at or near grade crossings possess added concerns over intersections that are stop controlled. If traffic signals are not properly coordinated with railroad operations, severe crashes can occur.
- When a highway-railroad grade crossing is located near a signalized intersection, it is possible that queues from the intersection could extend over the grade crossing and potentially cause stopped vehicles to become trapped on the tracks.
- Similar situations can occur at uncontrolled intersections close to rail crossings where long vehicles can block the crossing.
- When a long-wheelbase or low-ground-clearance vehicle negotiates a roadway having a high vertical profile, such as a highway-railroad grade crossing, roadway crown, or driveway entrance, the vehicle may become lodged or stuck on the "hump." A somewhat common occurrence is one in which a railroad is on an embankment and a low-ground-clearance vehicle on the crossing roadway becomes lodged on the track and is subsequently struck by a train.

160 Australian Transport Safety Bureau. 2004. "Level crossing accident fatalities."
161 Lloyd's Register Rail. 2007. "Study of pedestrian behaviour at public railway crossings." Public Transport Safety Victoria.

Good design practice/treatments/solutions

- Trains have a much larger mass relative to their braking capability, and thus a far longer braking distance than road vehicles. With rare exceptions, trains do not stop at level crossings and rely on vehicles and pedestrians to clear the tracks in advance.
- Level crossings (figures 6.85 through 6.88) are controlled through either passive or active systems. Passive control systems provide warnings through signs and line markings. They do not react to the presence of an approaching train. Active traffic control systems warn road users of approaching trains.
- Adequacy of sight distance is critical at passive crossings; however, even where active devices are present or will be provided, sight distance is beneficial to confirm the ability to cross the tracks.
- The US Traffic Control Devices Handbook (2nd edition)[162] indicates three zones within the approach to a crossing where drivers make decisions about their movements in relation to the crossing. It identifies three zones of visibility as well as the respective sight distance associated with each, and MTCD refers to the “minimum track clearance distance”

Figure 6.85: Rail crossing UK.

Source: Archant. Hunt Post. https://www.huntspost.co.uk/news/final-plan-for-offord-cluny-s-new-rail-crossing-to-5013974.

Figure 6.86: Automatic signal controlled crossing—Dubai tram.

Source: © John Barrell.

Figure 6.87: Rural rail crossing—Zimbabwe (passive).

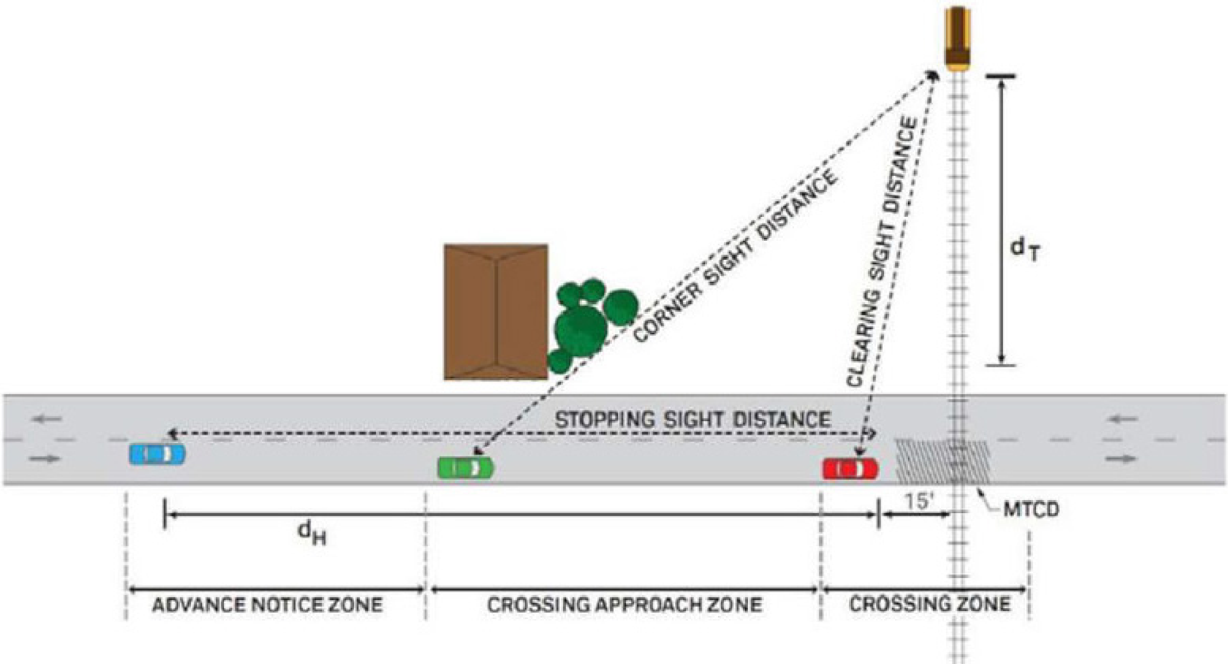
Source: © John Barrell.

Figure 6.88: Rural rail crossing—Australia (active).

Source: Department of Transport and Main Roads, Queensland Government.

162 Seyfried, R. K., and P. E., PTOE. 2013. Traffic Control Devices Handbook (2nd edition). Washington, DC: ITE.

Figure 6.89: Visibility zones approaching a passively controlled rail crossing.



Source: FHWA, 2019. Ogden, B. D., and Cooper, C. 2019. Highway-rail crossing handbook (No. FHWA-SA-18-040). United States. Federal Highway Administration.

at the crossing, which should be clear of vehicles when a train is approaching. It also indicates for each zone the desired roadway user response, depending upon whether a train is visible or not (figure 6.89).

- Warnings at active controlled crossings consist of flashing lights and sounds (combined with static controls such as signs and pavement markings) which are triggered by a train.
- As with passive crossings, adequate visibility of these devices is necessary for approaching road users.
- Another level of active control is achieved by placing a barrier between vehicles or pedestrians and trains. This is done with electro-mechanical devices such as pedestrian gates and vehicle boom barriers used in combination with other active and passive controls.
- Intersections near highway-railroad grade crossings require special attention to coordinate the movements of vehicle, train, and pedestrian traffic.
- To avoid queues from an intersection blocking a crossing, traffic signals located near highway-railroad grade crossings need to be synchronized when trains approach in order to clear vehicles off the tracks before the train arrives. This synchronization is normally achieved through an electrical interconnection circuit between the railroad grade crossing warning system and the highway traffic signal controller assembly. The geometric design of any signalized intersection near a highway-railroad grade crossing should consider interconnection and synchronization.
- Sufficient space is needed to ensure that waiting vehicles can wait safely to clear a crossing.
- Approach to rail crossings therefore needs to be as flat or straight as possible to allow clearance for long wheelbase vehicles.
- Opportunities should be considered to close low-volume crossings where a viable alternative exists.
- Several assessment tools exist for the determination of risk at rail crossings (e.g., ALCRM in the UK and ALCAM in Australia and New Zealand).

Further Reading

- Texas Department of Transportation. 2000. Design Guidelines for At-Grade Intersections Near Highway-Railroad Grade Crossings. Must read chapter 3, Interconnection.
- Manual of Uniform Traffic Control Devices for Streets and Highways (MUTCD) 2nd edition. 2009, with 2012 updates. US Department of Transport Federal Highways Administration. Must read part 8, Traffic Control for Railroad and Light Rail Transit Grade Crossings.

7. DESIGN TOOLS FOR SAFE OUTCOMES

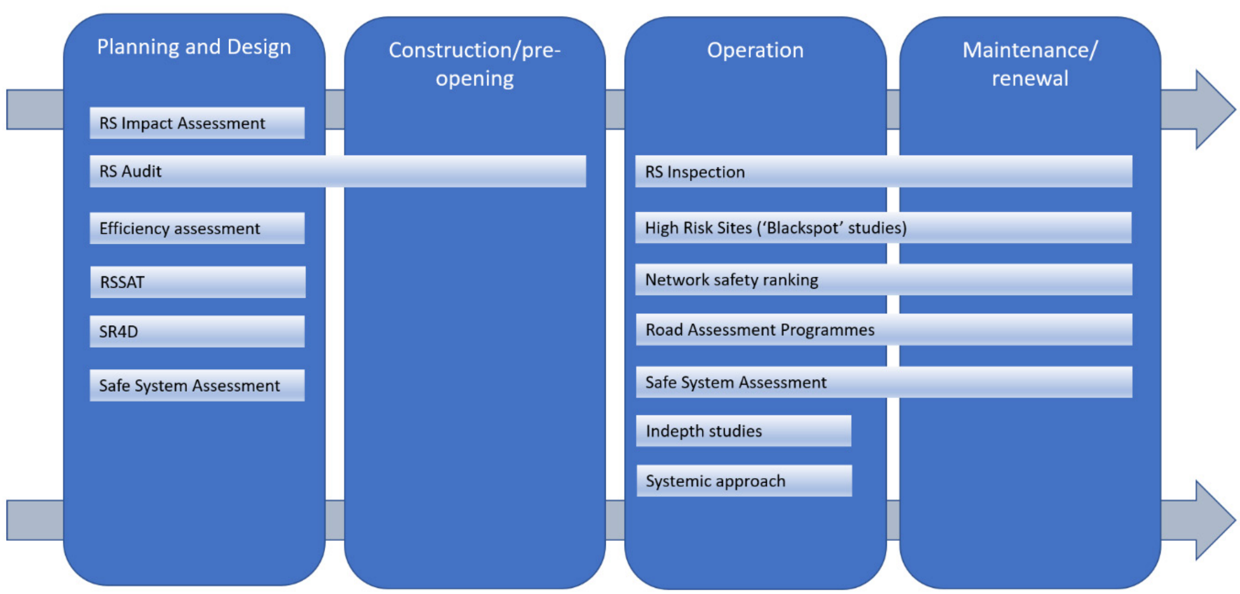
7.1. Introduction

As identified in section 1.3, existing road design guides are generally technically sound and are essential for the design process, but they will not enable designers to achieve safety outcomes on their own. Even designing strictly to existing guides will result in designs that allow death and serious injury. It is therefore very important that additional tools and processes be used to ensure that road safety objectives are met through the life cycle of a road or network. In response to knowledge on this issue, various approaches have been developed over time to help ensure safety is adequately considered throughout the life cycle of a road.

The comprehensive approach to the safe design, operation, maintenance, and use of roads is generally referred to as Road Safety Infrastructure Management. This is described in the EU standard, the EU Directive 2008/96/EC,[163] as well as the PIARC Road Safety Manual,[164] among other sources. The objective of road safety management is to integrate all road safety activities throughout the design and operation of an individual road or network such that a systematic approach is taken to reducing death and serious injury.

Examples of safety techniques used at each stage of the road life cycle are provided in figure 7.1, while details for these are provided in section 7.3.

Figure 7.1: Road safety techniques for different stages of the road life cycle.



Source: Adapted from Elvik 2010. Elvik R. 2010. Assessment and applicability of road safety management evaluation tools: Current practice and state-of-the-art in Europe, Institute of Transport Economics (TØI), Oslo, Norway.

163 EU Directive 2008/96/EC Directive of the European Parliament and of the Council of November 19, 2008 on road infrastructure safety management.

164 https://roadsafety.piarc.org/en/planning-design-operation/infrastructure-management.

The strategies implemented in road traffic safety management can include both reactive and proactive approaches.

- A reactive approach to road safety is associated with the identification of locations experiencing safety problems (screening), problem definition (diagnosis), and the identification and implementation of countermeasures (cure) from a detailed examination of crash data. Road safety improvements are proposed in response to identified safety problems brought to light by crashes that have occurred after the road has been designed, built, and opened to the travelling public.
- A proactive approach to road safety is associated with the prevention of safety problems before they manifest themselves in the form of a pattern of crashes focusing on what is known about the impact of different situations, road features, and treatments on road safety injury or crash outcomes. The proactive approach applies this knowledge to the roadway design elements or to improvement plans on existing roads to diminish the likelihood and severity of crashes.

Years of experience in crash analyses and treatment of crash locations has improved the understanding of the road and roadside elements that contribute most to crash risk, and the amount that each of these elements contribute to that risk, making the proactive approach more generally applicable. The reactive and proactive approaches are often used in combination with the emphasis shifting from one to the other, depending on the maturity of the overall safety management processes in an organization or nation, or even in different road environments.

As an example, for a rural route with high numbers of run-off-the-road crashes, it is desirable that all potential high severity locations be treated, regardless of whether crashes have happened there yet or not (the route-based approach is described in later sections of this guide). This is in contrast to a crash-based analysis that addresses just those points on the road where crashes have previously occurred. Equally risky locations (in terms of road and roadside features) should not be ignored.

Whichever approach is used, it is necessary to identify safety deficiencies that need to be investigated to diagnose safety problems, and then identify and implement countermeasures or design improvements to remedy the deficiencies before they create serious harm to road users.

In order for these deficiencies to be addressed effectively through the design process, there must be some form of performance measure of the effectiveness of the design to achieve safety outcomes, in the same way as key performance indicators (KPIs) are applied to other design aspects.

7.2. Road Infrastructure Safety Performance Indicators

Road Infrastructure Safety Performance Indicators (SPIs) are any measurement that is causally related to crashes or injuries, and can be used in addition to the figures of crashes or injuries in order to indicate safety performance or understand the process that leads to crashes. Road Infrastructure SPIs aim to assess the safety hazards by infrastructure layout and design (e.g., percentage of road network not satisfying safety design standards).

The inclusion of performance indicators is common practice within major infrastructure projects. They are quantifiable measures of performance over time and provide targets for teams to aim for, milestones to gauge progress, and insights to help organizations make better decisions.

"What gets measured gets done."

Managing with the use of performance indicators includes setting targets (the desired level of performance) and tracking progress against that target. Historically, specific performance indicators to reflect safety outcomes have seldom been applied in road design. At best, phrases such as "improved safety outcomes" are used when defining project objectives, but these are not measured in any tangible way. With the development of better assessment techniques for safety in design, and even the quantification of safety impacts from design decisions, there is now the ability to better specify safety outcomes in design.

A recent survey by the World Road Association (PIARC)[165] highlighted that there are four categories of performance indicators that are typically used to improve safety for road infrastructure projects. These are:

- The number or percentage of the network that was subject to a road safety audit or inspection (for example, South Africa has an objective based on the extent of the network assessed).
- The international Road Assessment Programme (iRAP) targets (for example, percent of travel on three-star roads or better; see below for information on targets 3 and 4 from the voluntary road safety targets relating to road infrastructure).
- Targets relating to provision of additional safe infrastructure by length of road (for example, Estonia has targets from kilometers of infrastructure installed for central and roadside barriers and centerline rumble strips).
- Provision of additional safe infrastructure as a percentage of the network (for example, Norway set targets to 2018 for the percentage of motor vehicle traffic on national roads with speeds of 70 km/h or higher with median barriers).

For many years, the conduct of a road safety audit has been specified as part of the road design process in many countries to assess road safety of a scheme from the perspective of all road users. This is especially the case for larger projects. This process requires designers to consider safety improvements without any quantifiable objective. However, with the advent of models that quantify safety outcomes, including from design, it is now possible to specify safety outcomes in a more objective manner. The models (some of which are outlined later in this section) can provide reasonably accurate accounts of likely safety outcomes in terms of fatal and serious injuries (the key crash types that need to be eliminated under the Safe System approach). These models can also be used to set a threshold level in regard to crash risks. In theory, it is possible to specify that design should not result in death or serious injury.

In recent years, a large number of models have been developed to help assess the impact of designs on road safety outcomes. Some of these have been developed for specific countries or environments, while others have more general application. Some have been devised for specific application in low- and middle-income countries (LMICs) or can be adapted or readily used in these countries. The earlier such tools can be applied in the design process the better. Changes to design are likely to be more feasible and will generally be at lower cost if they are incorporated before the design is completed.

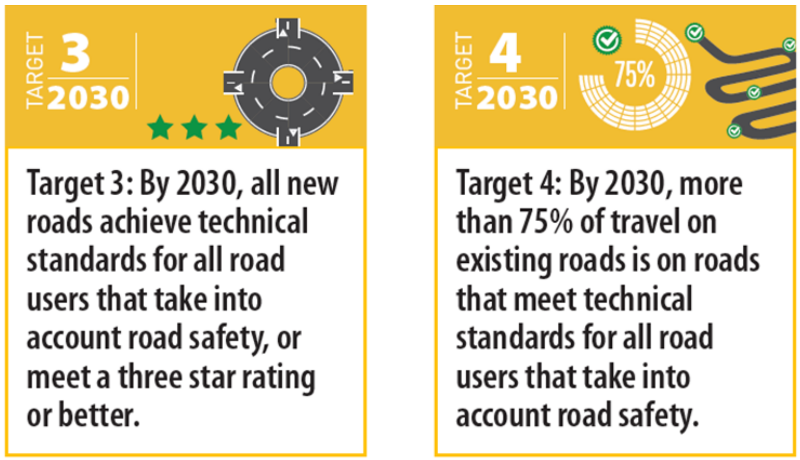
In 2016 the UK Transport Research Laboratory (TRL) identified and reviewed 21 such models used internationally for identifying affordable and appropriate engineering-based solutions to improve road safety on rural road networks,[166] while some of the more recent models are included in the descriptions that follow.

Alternatively (or in addition), the types of safety provisions to be included in designs for different road types can be specified. For instance, it may be that for high-speed, high-volume roads vehicles travelling in different directions must be separated by an appropriate central barrier system. Some countries are now developing safe cross sections for new roads, and as part of upgrades that embed this type of thinking, so as to provide safe infrastructure outcomes. These types of performance indicators (whether based on crash outcomes, infrastructure characteristics, or defined stereotypes) are typically set at country or

165 PIARC. 2019. Implementation of National Safe System Policies: A Challenge. World Road Association, Paris, France.

166 J. Fletcher, B. Mitchell, J. Bedingfeld, and K. Kolody Silverman. 2016. TRL PPR770 Road Safety Models.

Figure 7.2: Star ratings (referred to in Target 3) can be derived using processes outlined by the International Road Assessment Program.



Source: iRAP—see www.irap.org.

regional/state level and should ideally be linked to road safety strategy and funding capability.

Relevant infrastructure-based performance measures have been established globally. Many governments have included road safety targets in support of the Sustainable Development Goals (SDG's), which were adopted by all United Nations member states in 2015. This led to the development of voluntary global road safety performance targets.[167] Two of these targets relate specifically to safe road infrastructure (figure 7.2). Target 3 states that "by 2030, all new roads achieve technical standards for all road users that take into account road safety or meet a three-star rating or better." Target 4 declares that "by 2030, more than 75 percent of travel on existing roads is on roads that meet technical standards for all road users that take into account road safety."

The use of one or more of these types of performance indicators is highly recommended as part of national transport policies as well as at project levels during design. A recent study has identified that application of safety metrics as part of the design process can double the safety benefits (or halve the number of deaths and serious injuries), often at little or no additional cost.[168]

7.3. Infrastructure Tools and Techniques

This section contains introductory information on some of the road safety infrastructure tools and techniques that can be used to assess risks and identify solutions. In general, the earlier such tools can be applied in the design process, the better. Early changes to design are likely to be more feasible and will generally be at lower cost. The tools included are those most likely to be used by road designers. Examples of the most common tools are included as well as information on some promising emerging tools. These are presented in the same order as they appear in figure 7.1.

Road safety impact assessment

Being able to explicitly estimate the impact on road safety that results from building new roads or making substantial modifications to the existing road infrastructure that alter the capacity of the road network in a certain geographic area is of crucial importance if road safety is not to unintentionally suffer from such changes. The same applies to other

167 https://www.who.int/violence_injury_prevention/road_traffic/12GlobalRoadSafetyTargets.pdf.

168 Turner, B., and Ahmed, F. 2018.Evaluation of Safe System Assessments. VicRoads, Australia.

schemes and developments that have substantial effects on the pattern of road traffic. The procedure that has been designed for this purpose is known as road safety impact assessment (RSIA) (Wegman et al. 1994).[169] This procedure is intended to be applied at the planning stage, often proceeding to a definite design for the scheme. A safety impact assessment thus precedes and complements the eventual safety audit of any specific design for the scheme.

A scenario method is used to carry out an RSIA. The starting point is the existing road network, the current pattern of traffic on that network, and the level of reported road injury collisions within the area. Current traffic patterns include usage for all users—motorized and nonmotorized—although nonmotorized travel data are notoriously difficult to access at the same level as motorized data. It is helpful, though not essential, to have all this information represented in a digital form within a geographic information system (GIS).

The information needed relates to a road network which is made up of roads of several types that have different road safety characteristics. Each road consists of junctions and stretches of road between the junctions, with associated traffic volumes for each user group, and the number of collisions and casualties.

Alternative scenarios to this current situation are the possible changes being studied in respect to the physical infrastructure and the associated traffic volumes in the road network in the future. If, for example, a new road is to be added to the existing network, the traffic and transport models can be used to estimate what this will mean for the traffic volumes throughout the network in the future.

The central step is to interpret these changes in terms of the impacts they will have on the numbers of crashes and casualties. To accomplish this, what are needed are quantitative indicators of risk (such as casualty rates per million vehicle-km) for each type of road and user, supplemented, if possible, by corresponding indicators for each main type of junction. One way of obtaining such indicators is to estimate them at a national level and adjust them if necessary, using data for the area in question. In addition, thought should be given to any expected changes over time in the level of risk for each type of road or junction. These kinds of information enable safety impacts to be estimated for the duration of the road's life cycle.

If the various data are accessible from a computer, calculations of safety impacts for a range of scenarios and comparisons between impacts of different scenarios can be made quite readily. The procedure can be adapted to help identify what changes are needed in a given scenario in order to bring the safety impact within some target range.

When implementing this scenario technique, it is important to bear in mind the quality of the information being used. It is also important for the information to be accessible in such a way that calculations for a range of scenarios can be elaborated at relatively modest costs within a short period of time. For this purpose, the traffic and transport models should be set up in such a way that an RSIA module to apply the relevant indicators of risk for future years can be readily linked with them. This requires a higher proportionate investment in safety features in LMIC designs to achieve these comprehensive improvements.

Adopting this sort of methodology of risk assessment allows consideration to be made of future land use changes and the potential for the land use changes to encroach on the road corridor and change the consequent function and safety risk. Additionally, it allows for opportunities to influence road user behavior by introducing cycle ways and footways to encourage sustainable travel modes—many of which are initially lacking in LMICs and need the additional consideration to develop comprehensive networks.

169 Wegman, F. C. M., Roszbach, R., Mulder, J. A. G., Schoon, C. C., and Poppe, F. 1994. SWOV Road safety impact assessment: RIA. Report R-94-20. Leidschendam: SWOV Institute for Road Safety Research.

Road safety audit

Road safety audits have been applied to road design projects for several decades and are a well-established approach in high-income countries (HICs) as well as LMICs. A large number of experts have been trained in the application of this approach, and there is broad industry understanding of the benefits from applying such audits.

The road safety audit (RSA) process involves independent teams of experts assessing designs at one or more stages of project development through a formal process to identify safety-related risks. The sooner that an audit is undertaken in the design process, the greater and easier the safety benefits are to achieve. Road safety audits are not a check of compliance against design standards (as identified in section 1.3, compliance with such standards does not guarantee a safe design). These teams of experts review designs and make assessments on safety impacts for all road users based on experience. Road safety issues are documented, and a priority for addressing these issues is typically given. It is expected that designers would address each of these issues wherever practicable.

Given the broad international adoption of road safety audits, a large number of guidance documents exist on how to conduct audits, including from the UK,[170] Australia,[171] the US,[172] Africa,[173] Asia,[174] and the World Road Association (PIARC).[175] The process outlined in each of these documents is broadly similar.

Assessments of the benefits of road safety audits have identified that the process produces positive outcomes and often for very low costs. For example, benefits of recommendations made through the audit process in a study from Australia found that 75 percent of recommendations implemented had benefits that far outweighed costs by a factor of 10 to 1.[176] The costs for undertaking audits form only a small additional cost, estimated at around 4 percent of total design cost[177] (noting that the design cost is only a small component of overall project costs when compared to construction), while the costs for implementing the recommended changes were also often low (65 percent of recommendations had a cost < US$1,000).

Although road safety audits can lead to substantial road safety benefits, this will only occur if audits are conducted correctly by an experienced team. Audits, especially extensive ones, can also lead to a large number of recommendations which can be difficult for designers to address. However, audit recommendations could be classified under different priorities based on the potential safety risk and the cost of treatment to address them. This prioritization is a decision for the design team, as the audit only deals with safety considerations. Finally, the biggest barrier to successful audit outcomes is that recommendations are often not addressed, and so a strong process is required to ensure that this stage occurs, including that decisions by the design team in response to audits are well documented.

Efficiency assessment

Budgets for transport in general and for road safety in particular should be spent as optimally as possible. Efficiency assessment (EA) tools (e.g., cost-benefit analyses) determine the effects for society of a given investment, for instance in road safety, in order to prioritize investment alternatives.

170 http://www.standardsforhighways.co.uk/dmrb/search/710d4c33-0032-4dfb-8303-17aff1ce804b.

171 https://austroads.com.au/publications/road-safety/agrs06.

172 https://safety.fhwa.dot.gov/rsa/guidelines/.

173 https://www.afdb.org/en/documents/document/road-safety-manuals-for-africa-new-roads-and-schemes-road-safety-audit-51937.

174 https://www.adb.org/publications/carec-road-safety-audit-engineering-manual.

175 https://www.piarc.org/en/order-library/3875-en-Road%20Safety%20Auditsandhttps://www.piarc.org/en/order-library/31994-en-Review%20of%20Global%20Road%20SafetyAudit%20Guidelines%20%E2%80%93%20With%20Specific%20Consideration%20for%20Low-%20and%20Middle-IncomeCountries.

176 Macauley, J., and McInerney, R. 2002. Evaluation of the proposed actions emanating from road safety audits, AP-R209/02, Austroads, Sydney, NSW.

177 Morgan, R., Tziotis, M., Turner, B., and Epstein, J. 2019. Guide to Road Safety Part 6A: Implementing Road Safety Audits, Austroads, Sydney, Australia.

A full cost benefit analysis is an extremely demanding task to perform properly. It requires all significant monetized costs and benefits to be assessed, typically over a scheme's lifetime. It should include annual maintenance costs, all environmental and social impacts, and all costs need to be moved into a single base year value, and GDP growth across the assessment period needs to be taken into account. It is an in-depth process that can require significant effort and so may not be suited to smaller schemes.

The simplest method for carrying out EA is called cost effectiveness (CE). In CE the cost that needs to be expended for each crash saved in alternative and competing schemes is estimated to help with the prioritization of investments. The approach is commonly applied to the treatment of small improvements or high-risk sites and assesses the whole program of design alternatives that are to be applied rather than assessing the cost effectiveness of an individual scheme.

The main parameters required are:

- The number of crashes per year over a fixed period of years; generally for three to five years,
- The estimated effectiveness of each scheme as an expected reduction in crashes after implementation, and
- The total estimated cost of the proposed schemes.

This gives a value which represents the cost required to save a single crash for each proposed scheme. The potential schemes can be ranked by the calculated CEs in descending order, and those schemes with the smallest values should be implemented preferentially.

A First Year Rate of Returns (FYRR) is commonly used for appraising low-cost schemes. In this method crash costings are required in addition to the parameters required to do a CE. The approach requires the treatment cost to be calculated, the average crash cost, and an estimate of savings.

The simplest FYRR will be estimated as:

FYRR = (100* annual casualty saving*casualty cost)/ scheme cost

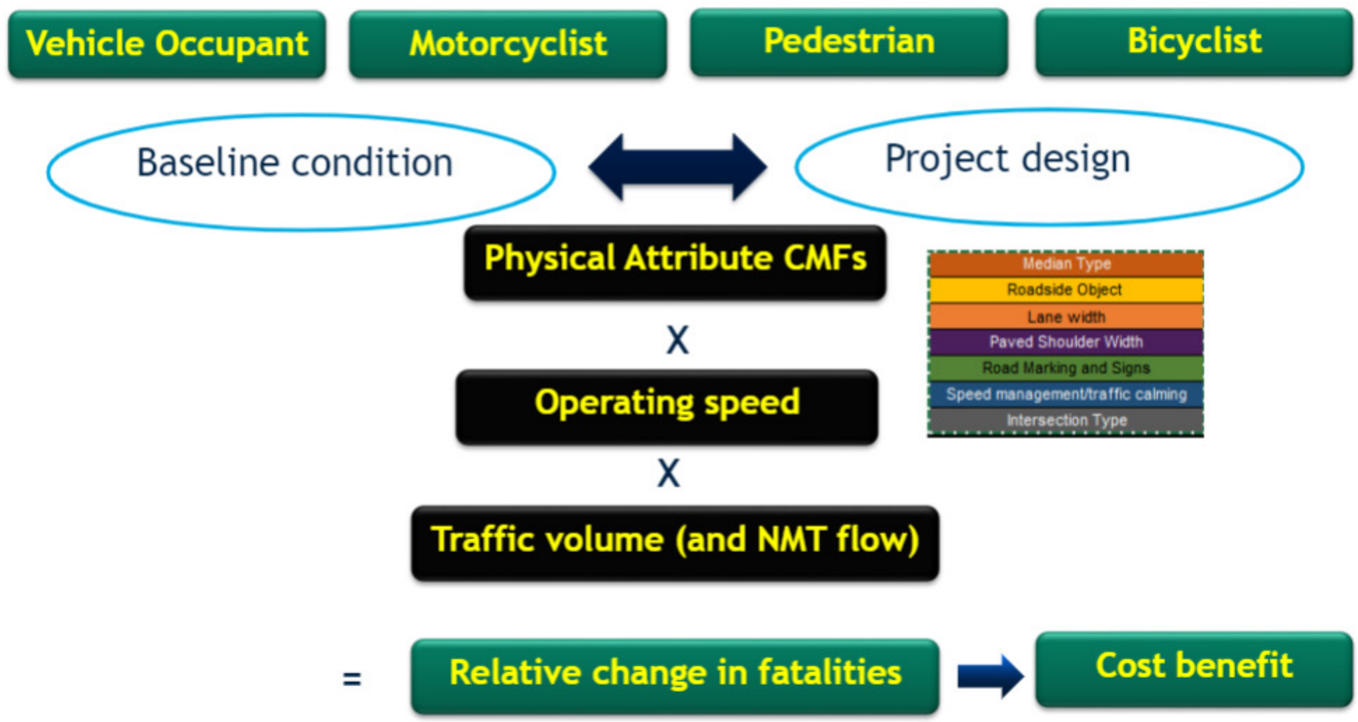
The largest variable is the estimated effectiveness which relies on a robust understanding of the effectiveness of safety interventions.

The effectiveness of any safety interventions that are implemented relies heavily on the appropriate application of those measures to treat a specific problem. This can only be determined through a thorough understanding of the underlying factors determined from intensive examination of crash data and thorough monitoring of each implemented measure. Internationally, this is one activity that is not undertaken as diligently as it should be. Therefore, any potential savings claimed for particular treatments must be taken with extreme caution unless robust evidence of their effectiveness in truly comparable situations is available. Without monitoring and evaluation, much of the claimed benefit could be the result of statistical variation from purely random events.

Road Safety Screening and Appraisal Tool

The World Bank and GRSF have developed a Road Safety Screening and Appraisal Tool (RSSAT) that assesses the road safety impact of projects, both in relative terms (comparing risks with and without project) as well as absolute risk terms. The user-friendly RSSAT produces a metric called Project Safety Impact (PSI), which is the ratio of road traffic fatalities with project to without project. It also assigns a road safety risk level for the existing situation as well as the project scenario based on the number of fatalities, and finally it presents the monetized road safety costs/ benefits over the analysis period of the project. The PSI is generated by taking account of crash reduction benefits from physical attributes, the operating speed, and traffic volumes (including for nonmotorized traffic) as shown in figure 7.3. The RSSAT can be used early during project preparation to test various road

Figure 7.3: PSI process.



For further details please visit the GRSF website. https://www.roadsafetyfacility.org/global-road-safety-tools#tab2.

design scenarios and make an early informed decision on the safest cross-section design.

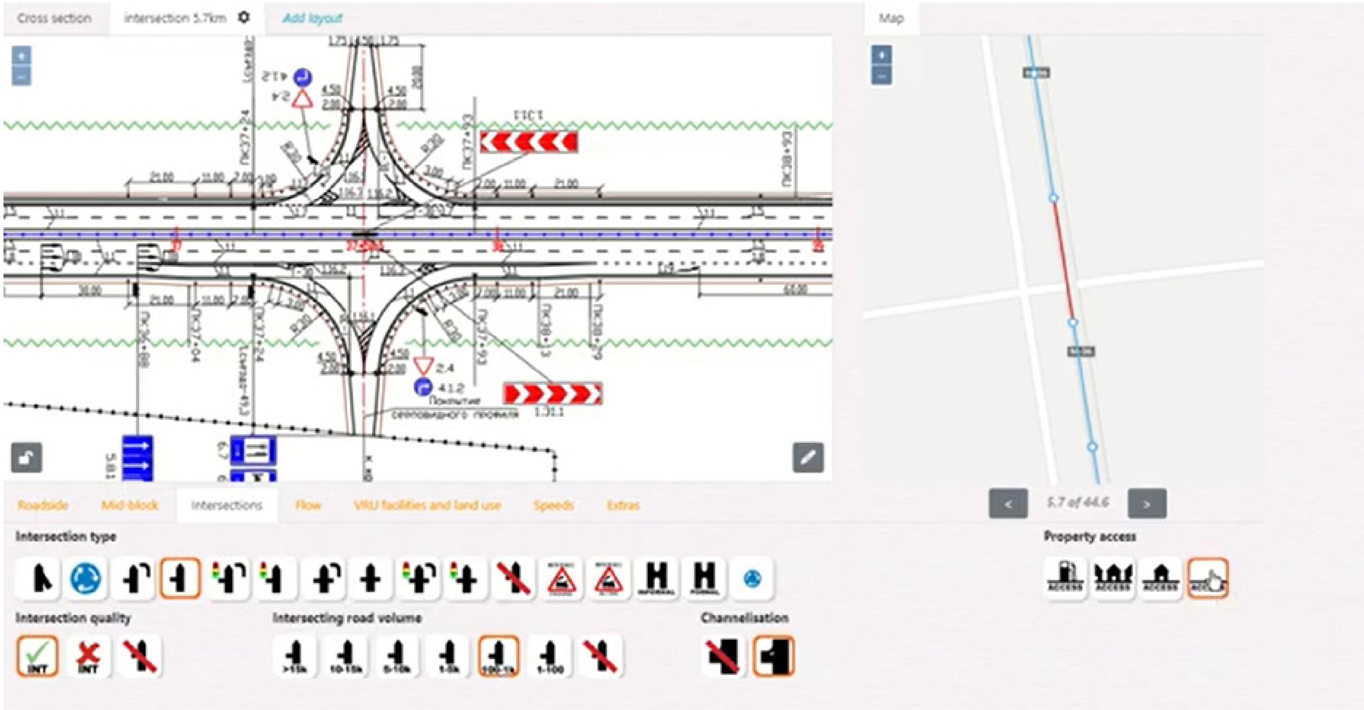
The current version of the RSSAT (v1) is only based on road design features, speed, and traffic flow composition. However, with additional effort this tool can be extended to include other road safety interventions related to road user risk factors (e.g., seat belt use, enforcement compliance, etc.), vehicle safety, and so on. The RSSAT is meant to be used for projects involving maintenance, rehabilitation, or reconstruction/upgrade of existing roads, including lane expansion or change from gravel to paved surface. The RSSAT can be applied for roads that are classified as rural roads, inter-urban highways, access-controlled expressways, and urban roads, including arterials. It is not intended to be used for the construction of new roads (e.g., greenfield projects) nor for mass rapid transit projects (Bus Rapid Transit (BRT), Light Rail Transit (LRT) or Mass Rapid Transit (MRT)).

Star rating for design (SR4D)

The iRAP methodology (described below) can be used to help assess the safety of road designs and to identify ways to improve this design before roads are constructed or upgraded. One of the ways that this can be performed is by using the SR4D web app developed by iRAP with funding support from the GRSF.

The process can be applied by any suitably trained engineer or road safety practitioner and is easily incorporated into the road design process. SR4D provides an objective “star rating” for each road user type (pedestrian, vehicle occupant, motorcyclist, and cyclist) based on different road design elements that are drawn from proposed designs and coded by users. Key design elements are selected with a click from a menu of options.

Figure 7.4: Intersection selection options for SR4D.



For more information see https://www.irap.org/3-star-or-better/?et_open_tab=et_pb_tab_3#mytabs|3.

For example, figure 7.4 shows various options for intersection type, quality, and intersecting road volume. Once design elements are selected, the tool uses the iRAP method to generate a risk score or star rating, an approach that provides repeatable qualification of road user risk. In addition to the star ratings, the method can also be used to produce statistics on various safety-related road attributes (such as percentage of road or design with good quality pedestrian crossings); estimates of the numbers of fatalities and serious injuries associated with the designs, including identification of locations where numbers are likely to be highest and lowest; and Safer Roads Investment Plans (SRIP) that list safety countermeasures that could be viably added to the design to improve safety within a specified budget. Star ratings can be used to set an objective "pass mark" for designs, and their use is consistent with broader performance targets that can be set as part of a wider strategy as described in the previous section above.

Safe System Assessment Framework

The Safe System Assessment Framework (SSAF) is a tool that assesses project designs to determine the likelihood of fatal and serious injury outcomes. The tool is mainly concerned with the safe road and safe speed pillars of the Safe System, but usefully also provides prompts for designers to consider relating to the other pillars (road user, vehicle, and post-crash care) that they may influence to help achieve safe designs. An assessment can be made of projects (or project elements) to determine the impact on fatal and serious outcomes from design decisions. It also helps identify changes that might be applied to bring designs into closer alignment with Safe System outcomes.

The framework breaks designs down into basic elements, comprising the key crash and road user types that result in fatal and serious injury outcomes. These crash types are:

- Run-off-the-road,
- Head-on,
- Intersection,
- Rear-end and other,
- Pedestrian,
- Cyclist, and
- Motorcycle.

Each of these crash types is assessed based on different components of risk, which are

- Exposure,
- Likelihood, and
- Severity.

An estimate is made of the contribution for each of these risk types against each of the key crash types. A subjective scale between 0 and 4 is applied, with 0 indicating that there is minimal contribution, and 4 indicating a high impact on poor safety outcomes.

A matrix is used comprising these crash and risk types as shown in Figure 7.5.

A total score is derived, with a low score indicating high Safe System compliance, and a high score indicating low compliance (and therefore a high chance of a fatal or serious crash outcome from the design). Guidance is also available on suitable interventions to help reach closer alignment with Safe System objectives. The framework has been widely applied in several countries, particularly at concept/early design stage. One study found that application of the framework had a positive impact on designs for road projects. Based on an estimate of crash reduction of designs before and after the assessment was conducted, it was concluded that benefits in terms of fatal and serious injury crash savings can be doubled by applying this approach to infrastructure development, design, and delivery phases.

The framework and guidance[178] can be downloaded from the Austroads website at https://austroads.com.au/publications/road-safety/ap-r509-16.

Figure 7.5: Safe System Assessment Framework matrix.

	Run-off-road	Head-on	Intersection	Other	Pedestrian	Cyclist	Motorcyclist
Exposure	AADT; length of road segment	AADT; length of road segment	AADT for each approach; intersection size	AADT; length of road segment	AADT; pedestrian numbers; crossing width; length of road segment	AADT; cyclist numbers; pedestrians	AADT; motorcycle numbers; length of road segment
Likelihood	Speed; geometry; shoulders; barriers; hazard offset; guidance and delineation	Geometry; separation; guidance and delineation; speed	Type of control; speed; design, visibility; conflict points	Speed; sight distance; number of lanes; surface friction	Design of facilities; separation; number of conflicting directions; speed	Design of facilities; separation; speed	Design of facilities; separation; speed
Severity	Speed; roadside features and design (e.g. flexible barriers)	Speed	Impact angles; speed	Speed	Speed	Speed	Speed

Source: Austroads.

178 Austroads. 2016. Safe System Assessment Framework, AP-R509-16. Austroads, Sydney, Australia.

Road Safety Inspection

A road safety inspection (RSI) is a systematic review of the safety provision on an existing road, in particular in relation to the provision and hazards associated with traffic signs, roadside features, environmental risk factors, and road surface condition. RSIs are based on similar approaches as Road Safety Audits (RSAs). The key difference between RSIs and RSAs is that RSAs are carried out on new or rehabilitation schemes where design teams are in place and RSIs are undertaken on existing roads where no proposals are yet in place for improvement. An RSI is a proactive approach that involves a systematic review of an existing road by driving and walking to identify hazardous conditions, faults, and deficiencies in the road environment that may lead to road user injury.

High-risk sites

Identification and treatment of high-risk sites use crash and road usage data to understand road safety issues. Depending on the quality and details recorded in crash data, several different types of analyses may be undertaken, each with a differing level of granularity:

- Specific site analysis is undertaken to identify locations across the network where a concentration of crashes have occurred. These are then investigated in detail to understand the nature of the crashes, and a site visit is undertaken. A remedial treatment program is then designed and implemented.
- Corridor/route analysis is undertaken to identify stretches of roads that perform badly. These can then be investigated, inspected, and a treatment program developed.
- Area analysis is undertaken to understand the types of crashes occurring in an area which may be more widespread than for a single site or route.

Once identification has been undertaken, sites can be prioritized to maximize casualty reduction for the available budget.

Network Safety Ranking

Network Safety Ranking (NSR) is a method defined in Article 5 of EU Directive 2008/96/EC for identifying, analyzing, and classifying parts of the existing road network according to their potential for safety development and crash cost savings. NSR looks at an existing road network to identify potential safety problems and is thus a possibility for safety development.[179] NSR is based on crash data and draws extensively on a calculation of different parameters, like crashes per km, number of crashes per vehicle km, or crash cost rates.

Depending on the parameters used, additional data, such as traffic or infrastructure data might be necessary. Different sections of a road network can be ranked and prioritized according to the criteria that "investments in road safety will have the greatest impact." It can also lead to further steps like conducting an RSI before costlier (e.g., infrastructural) measures are applied.

A general definition or procedure of how to segment a road network does not exist. Usually one section should have homogenous characteristics, e.g., in terms of geometric design, density of traffic, road users, or adjacent environment. Junctions may have to be considered separately. Which type of indicator is chosen for ranking has to be decided in each case and may also depend on the data available.

Road Assessment Programmes

These involve the collection of road characteristics data which are then used to quantify risk, identify safety deficits, or determine how well the road environment protects the user from death or serious injury when a crash occurs. There are a number of such programs globally, each of which falls under the broad banner

179 Transport Infrastructure Ireland (TII). 2014. Network Safety Ranking GE-STY-01022.

of the international Road Assessment Programme (iRAP).[180]

Star ratings are calculated based on road design and other elements that impact safety outcomes. Star Rating Scores are an indication of the relative risk of death and serious injury for an individual road user, and are based on factors such as crash likelihood, severity, operating speed, and traffic flow. A risk score is generated using an algorithm, and this in turn is based on an international evidence base on crash risk.

A star rating of 1 indicates that the road is of poor quality, while a rating of 5 means that the road is of high quality from a safety perspective with a low chance of death or serious injury to road users. Star ratings for different types of road users (vehicle occupants, pedestrians, cyclists, and motorcyclists) are also generated.

Policy objectives have been set in a number of countries relating to this star rating, including for Sweden, the Netherlands, Malaysia, New Zealand, China, Chile, Australia, and the United Kingdom. As an example, as part of the National Road Safety Action Plan 2018–2020, the Australian government included an action to improve the star ratings across the whole road network, with the aim to achieve 3-star AusRAP ratings or better for 80 percent of travel on state roads, including a minimum of 90 percent of travel on national highways. In order to support these national policy objectives, project designs can be assessed to determine the star rating of individual designs. The iRAP star rating for designs tool (SR4D, see above) has been developed for this task.

Specific design proposals are then developed that can reduce the risk of future injury and collisions. A number of tools are available to assist in the evaluation of risk and potential effectiveness of treatments, including the iRAP software tool VIDA.

Further Reading

Austroads. 2015. Guide to Road Safety Part 8—Treatment of Crash Locations.

Austroads. 2006. Guide to Road Safety Part 7—Road Network Crash Risk Assessment and Management.

African Development Bank. 2014. Road Safety Manuals for Africa:

1. New Roads and Schemes Road Safety Audit
2. Existing Roads—Proactive Approaches
3. Existing Roads—Reactive Approaches

180 www.irap.org.

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- AASHTO 2018. A Policy of Development of Highways and Streets 7th edition.
- Australian Road Safety Engineering Toolkit. https://engtoolkit.com.au/default.asp?p=issue&i=15.
- European Commission. Getting Initial Safety Design Principles Right. https://road-safety.transport.ec.europa.eu/statistics-and-analysis/statistics-and-analysis-archive/roads/getting-initial-safety-design-principles-right_en
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