Urban Road Design and Keeping Down Speed

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Abstract

This chapter examines the opportunities available to a range of professions that directly or indirectly influence urban settings, to achieve Vision Zero safety outcomes. Starting with how we want our urban areas to be, the chapter examines options to eliminate the systemic risk of deaths and serious injuries on urban roads from three separate but related viewpoints; managing the threats to life and health posed by the energy embedded within the road transport system, the potential for crashes to occur and the exposure of those who use the system to severe injury risk from crashes. In urban settings, it is sometimes possible to eliminate or minimize vehicular traffic on selected roads and streets but, in general, it is either impractical or undesirable to do so. By physically separating vehicles from other vehicles, and from highly vulnerable road users, we risk creating the types of cities and towns that do not support our high level aspirations of highly liveable and healthy societies, with sustainable and equitable urban transport systems. Where physical separation is not viable, it becomes necessary to manage transport system energy to ensure risk remains below the levels we set for Vision Zero outcomes – no one being killed or seriously injured. The main focus of this chapter therefore is on the means by which we can manage kinetic energy, primarily through compatible combinations of infrastructure design and speed limit setting, to protect all who use urban roads. Vehicle technology and structural design are important considerations for system performance as a whole.

Keywords

Active transport · Crash types · Cyclists · Infrastructure · Injury risk · Kinetic energy · Pedestrians · Roundabouts · Safe System · Speed limit · Sustainable Development Goals (or UN SDGs) · Systemic risks · Traffic signals · Urban areas · Vision Zero

Introduction

While references to significant publications are provided at selected places throughout this chapter, these references should not be regarded as providing comprehensive coverage of the literature. Rather, these references should be viewed as sources for further reading, which will often lead to more comprehensive coverage of publications in the field of relevance.

The starting point for considering how to achieve Vision Zero conditions in urban areas is to contemplate what kinds of cities and towns we want for our future, and for the futures of young and coming generations.

Much of what defines our future aspirations is captured in the United Nations Sustainable Development Goals (reference: https://www.globalgoals.org/). “In 2015, world leaders agreed to 17 goals for a better world by 2030. These goals have the power to end poverty, fight inequality and stop climate change. Guided by

Fig. 1 Representation of the global goals for sustainable development

the goals, it is now up to all of us, governments, businesses, civil society and the general public to work together to build a better future for everyone."

Of the 17 goals depicted in Fig. 1, the following are most directly relevant to traffic safety and to Vision Zero:

Goal 3: Good health and well-being
Goal 11: Sustainable cities and communities
Goal 13: Climate actions

If we think about the types of cities and towns that we want for the future, liveability, equality, personal security, sustainability, and environmental-responsibility are high priorities. They align with and promote healthy living, free of avoidable threats to life and health. Creating cities and towns that do not tolerate today's ongoing loss of life and long-term health, while contributing to sustainable, liveable, and economically prosperous urban areas presents a challenge for present-day urban planners and designers, and their counterparts in transport planning and design.

Regarding relationships between population health and well-being, and the transport system, it is well-established (e.g., Mueller et al. 2015; World Health Organization 2013b, 2018; Hammer et al. 2014; Tranter 2010; Catford 2003) that:

- Walking and cycling, known as the active forms of transport, promote both physical and mental well-being.
- Traffic noise diminishes general health, causes loss of hearing, and interferes with the abilities of students to learn.

- Road transport is a source of harmful emissions that contribute to respiratory illness, global warming, and, ultimately, climate change.
- Traffic can restrict people, especially those with mobility impairments and other health issues, in their abilities to interact fully with society and local communities. Social isolation and diminished mental health often result.

Within this broad context, consideration is now given to how an urban road transport system can be designed and operated to be free of road deaths and severe injury, while supporting the higher-order societal goals of achieving sustainable, secure, healthy, liveable, equitable, and environmentally responsible cities and towns.

Eliminating Severe Road Trauma in Cities and Towns

This section addresses the challenge of defining what is required under the Vision Zero goal of eliminating deaths and serious injuries in traffic. It is acknowledged that an agenda of eliminating the risks of severe road trauma is not of high priority among all individuals and stakeholders. However, governments are in unique and privileged positions of having a clear moral responsibility to act in the best interests of society, especially when the individuals comprising society may not be fully informed and/or intuitively motivated to act for the greater good. That is, action by governments is needed, above and beyond what individuals can achieve operating independently, and with limited information and understanding of the systemic nature of our road safety problems and the potential for lasting solutions.

The Safe System

In the early 2000s, the Safe System strategic approach to preventing deaths and severe injury on roads was formulated. The Safe System is regarded as international best practice by many countries, including the Netherlands and Sweden, both of which have consistently led the world in reducing and sustaining reductions in death and serious injury. Global organizations such as the United Nations, the World Health Organisation, the European Union, the European Transport Safety Council, and the Organisation for Economic Co-operation and Development (OECD) also strongly endorse the Safe System approach. The Safe System has been interpreted by individual jurisdictions with varying emphasis but, in essence, it differs from historical approaches to road safety in the following respects:

- It strives to eliminate deaths and serious injuries, rather than simply to reduce them. That is, the Safe System aspires to eliminate severe harm.
- It is accepted that human error cannot be completely eliminated and, therefore, crashes will continue to occur.

- The kinetic energy involved in crashes must be managed more effectively to ensure that the energy levels experienced during a crash do not exceed the human threshold for severe injury or death.
- The road designer and system operator must design and operate the road transport system to accommodate human error in all foreseeable crash types. This professional duty of care builds on the assumption that road users will comply with key rules, such as not speeding, wearing seat belts/restraints and helmets, as applicable, and not driving while impaired by alcohol, drugs, fatigue, or distraction. Where adequate compliance is not being achieved, the designer must take further steps to safely accommodate foreseeable human error.
- There are five pillars defining the Safe System:
  - Safe Roads and Roadsides
  - Safe Vehicles
  - Safe Humans
  - Safe Speeds
  - Post-crash response and care

Road and roadside design must be undertaken as part of a total system, in which vehicle and human capabilities, and vehicle travel speeds interact with the physical environment in a way that avoids severe harm to system users. While a vital element of the Safe System, the post-crash response and care pillar is not covered in this chapter.

Systemic Risk vs. Crash History

World-leading countries are in a state of transition from “chasing fatal and serious injury crashes” around the network to addressing systemic risk. Chasing crashes has been a partially successful approach, at least as far back as the 1970s (i.e., accident black spot programs) but once the locations with clear and reliable high crash concentrations have been identified and treated, identifying high-risk locations and road sections/segments, using historical crash records, becomes less reliable. Instead, it has become essential to focus on systemic risk.

In practical terms, focusing on systemic risk means addressing foreseeable risks in all parts of the system, rather than the isolated treatment of risks that have eventually been revealed through a recent history of crashes. When moving from being reactive to being proactive to safety problems, the emphasis naturally shifts to the prevention of severe harm, drawing on a knowledge of, and insights into, the circumstances that elevate crash risk, but more importantly, the risk of severe injury.

Traditionally, a history of multiple crashes has been required at a location or over a short section of road to give confidence to traffic authorities that there is actually a problem. However, the precise locations of past crashes are not reliable indicators of the locations of future crashes. By definition, systemic risk involves a recurring pattern of crashes with like-characteristics that occur in foreseeable circumstances, rather than necessarily at predictable locations. Spatial mapping of historical crash locations reveals that crashes are highly dispersed, with only minimal spatial clustering evident.

Much care has been exercised globally in writing and refining legislation to make it legally clear what road users must and must not do; however, this is not fully effective in achieving perfectly performing humans on our roads. Focusing on systemic risk makes it clear that design philosophies based on geometric parameters alone are insufficient to prevent severe road trauma. When it is acknowledged that humans are imperfect and that the loss of life or long-term health is an unacceptable consequence of everyday errors, new opportunities based on vehicle kinematics and kinetic energy management begin to reveal themselves. These new opportunities can progressively be integrated into existing design philosophies to ensure the process of building unsafe infrastructure can be disrupted, thereby bringing an end to the need to retro-fit safety, at high cost to life, health, and public finances, in the years ahead.

In urban areas, there are several forms of systemic risk to road users (an example from Australasia is included in Turner et al. 2016). While the relative frequency of each form of risk is dependent on local conditions, such as traffic volumes, transport mode profiles, vehicle fleet characteristics, speed environments, population age (and health) profiles, and the form of physical infrastructure, the main systemic crash types can be summarized as follows.

Vehicle to Vehicle Collisions at Intersections

Most commonly, these involve:

- Side-impact crashes
- Turn-against oncoming traffic crashes

Pedestrian Collisions

These are usually more severe and involve pedestrians being struck while negotiating intersections or crossing roads between intersections. Also of concern is the problem of pedestrians suffering injuries, even death, without the involvement of a vehicle. Pedestrian falls in public spaces are common and often go unreported in the official records of traffic collisions. However, hospital and other medical records have shown that the problem can be large, severe, and costly. Older people and people with mobility limitations are at particular risk, especially where footpaths and roadways act as tripping hazards and are not well-maintained (e.g., ITF 2011; World Health Organization 2013a). While not causing immediate death, falls among older pedestrians may result in bone fractures, which can be a catalyst for serious health problems, eventually leading to death, sometimes beyond the standard period for such events to be recorded as traffic-related fatalities.

Cyclist and Motorcyclist Collisions

It is common for motorists to fail to give way to cyclists and motorcyclists at intersections, especially motorists who are turning across the path of riders. Cyclists and motorcyclists can also be involved in rear-end, lane-changing and side-swipe crashes, where all road users are generally heading in the same direction.

As noted above for pedestrians, single-cyclists and single-motorcyclists falling from their two-wheelers is more common than indicated by official traffic crash records. Such events may be found in hospital and other medical records, or go unreported and, therefore, overlooked as a problem. Poorly maintained surfaces, which may include loose material on roads and paths, contribute to risks for the riders of two-wheelers (Dozza and Werneke 2014). The Swedish Transport Administration promotes good maintenance of cycle (and pedestrian) paths by road operators to reduce cyclist injuries, using its Management by Objectives program to drive the Vision Zero agenda for cyclists (Trafikverket 2019). The presence of poor surfaces, in combination with directional changes, for example, around curves or distinct turns, causes instability for two-wheelers. The presence of hard surfaces and sharp or rigid structures nearby (e.g., trees, rigid poles, sign posts and guardrails) can increase the severity of subsequent falls involving these inherently vulnerable road users.

Single-Vehicle Crashes Within the Roadside

Crashes involving a single-vehicle are common in both urban and rural settings, even though speeds tend to be lower in cities and towns. When a driver or rider leaves the road in an urban setting, there is considerable potential for a collision with a roadside tree or service/utility pole. Such impacts typically produce severe injuries, even at legal speeds in modern vehicles, largely because of the tendency for narrow, rigid objects (trees and poles) to intrude into the passenger compartments of the striking vehicle.

Rear-End Collisions at and Between Intersections

Because of the greater tendency for interrupted flow of vehicles along busy urban roads, there is an increased risk of rear-end collisions. Often, these types of crash are related to the presence of intersections, especially where traffic signals operate. Stopping motorists from potentially high speeds, in response to a red signal every 1–2 min, establishes conditions for motorists to collide with the rear of vehicles they are following.

The Need for Innovation

These key systemic crash types may vary in proportionate terms between cities and towns but, when viewed over an extended period, remain the most prevalent sources of severe trauma. The preponderance of systemic crash types will change little while the design and operational practices that created them continue to be widely used. The following quote, attributed to Albert Einstein, underscores this important point: “We can’t solve problems using the same kind of thinking we used when we created them.” Without innovation, we will continue to create the same systemic risks of past decades. We must learn from our experiences and strive for continuous improvement. Failing to innovate has high financial and economic consequences, but the real losses are to human life and health, and the traumatic stress exacted on families, friends, and first-responders and medical teams in the post-crash phase.

Eliminating Crash and Injury Risk

A number of conceptual models, aligned with the Safe System, have been developed to represent the management of kinetic energy in various key crash types that too often lead to death and serious injury (Corben et al. 2005; Logan et al. 2019; Turner et al. 2016). Within these models, there are three main options for contributing to the elimination of systemic risk of death or serious injury:

- Reduction in exposure to crash potential
- Reduction in crash likelihood
- Reduction in injury risk, in the event of a crash

Each is now discussed in greater detail.

Exposure to Crash Risk

Exposure to crash risk is measured by the numbers of road users passing through an intersection, along a particular route or through an area or region. The more road users, the more opportunities exist for road crashes to occur. The numbers of opportunities for crashes do not necessarily change in direct proportion to the numbers of road users; interactive effects and the differing nature of road user types that characterize urban areas result in complex relationships. Logically, shifting road users to non-road-based public transport (e.g., trains, air, and ferries) will reduce exposure to crash possibilities compared with road-based modes, such as the use of private car, trucks, cycling, or motorcycling. In fact, the recommendations of the Academic Expert Group (AEG) formed for the Third Global Ministerial Road Safety Conference in Stockholm in February 2020 (Swedish Transport Administration 2019) recommended as follows "In order to achieve sustainability in global safety, health and environment, we recommend that nations and cities use urban and transport planning along with mobility policies to shift travel toward cleaner, safer and affordable modes incorporating higher levels of physical activity such as walking, bicycling and use of public transit."

While substantial mode shift is a vitally important policy option, reducing exposure to such an extent as to eliminate deaths and serious injuries from urban roads is believed unrealistic in the foreseeable future. As the world's populations and urbanization grow (ITF 2016), a high and growing exposure to road crash possibilities is expected into the long-term future, but the adverse effects on safety, sustainability, and liveability can be moderated through policies directed at supporting public transport and the other active modes.

Crash Risk

The traditional focus of last century's approach to road safety has been on preventing crashes, primarily by trying to create the perfectly performing human. This has been, and continues to be, attempted through initiatives such as regulation, education, training, and enforcement. The focus on behavior change has resulted in sizeable reductions in deaths and serious injuries in countries that have lead with these measures over the past 50 or so years, but a large and severe residual problem remains, indicating that a more comprehensive approach is needed. Much of today's problems of deaths and serious injuries on all road classes can be traced to risk-taking behavior, simple human errors, and predictable lapses in road user performance (ITF 2016). This, however, does not mean that the most effective solution continues to require consistently perfect performance.

Roman philosopher Marcus Tullius Cicero is quoted as saying "It is the nature of every person to error, but only the fool perseveres in error" (https://www.brainyquote.com/quotes/marcus_tullius_cicero_156305). Unsurprisingly, the many professional disciplines involved in road safety have been only partially successful in eliminating human error. Indeed, human error is strongly evident in virtually every other aspect of life, including among our most highly skilled and intensively trained sportswomen and men. Even the very best are unable to sustain high performance when competing. Fatigue, stress, overconfidence, anxiety, and misjudgment can cause occasional failures.

When human error occurs in the road transport system, and the impact speeds are beyond the human tolerance to energy exchange in any specific crash type, severe injuries, even death, are likely. Often, legal travel speeds produce impact speeds that exceed the critical values for survivable outcomes. Allowing foreseeable loss of life and health to continue, as a consequence of systemic flaws in design and operation, is in conflict with professional obligations. It is contended that, while crash risk and/or exposure continue to be substantial, all decision-makers and professions must continually strive to eliminate injury risk.

When the means to eliminate human error have been created, today's levels of kinetic energy may become acceptable but, for the coming years (potentially decades), exposure and crash likelihood will remain unacceptably high.

Injury Risk

Vision Zero seeks to address injury risk, given our inability as a profession to reduce today's unacceptably high levels of exposure and crash risk. Addressing injury risk successfully requires the effective management of kinetic energy of individual road users and, hence, of the system as a whole, in order to avoid severe injuries when crashes inevitably occur. More specifically, the kinetic energy of vehicles involved in crashes must be kept below the levels known to threaten the survivability of the most vulnerable road users in any given crash scenario. These levels are referred to here as the Vision Zero boundary conditions and exist for each of the main systemic crash types (ECMT 2006; ITF 2016).

Because speed is the primary determinant of kinetic energy, and vehicle mass of secondary importance, speed management is critical to success. Energy can be managed in two main ways: first by minimizing the amount of energy at impact and, secondly, by managing the transfer and dissipation of energy during impact (Corben 2005).

The primary and most effective means for minimizing kinetic energy at impact is to minimize speed. Because kinetic energy (KE) is proportional to the second power of speed (KE = ½ mv^2, where m is the mass of the vehicle and v its velocity), even a small reduction in speed delivers a disproportionately larger reduction in energy. That is, reducing speed by 10% reduces kinetic energy by 19%. Smaller mass vehicles also result in less kinetic energy; however, a 10% reduction in mass leads to a 10% reduction in energy.

Figure 2 shows the relationship between kinetic energy and travel speed, for a vehicle of approximately 1250 kg. The increasing gradient of the kinetic energy curve with increasing speed highlights the second-power relationship between kinetic energy and speed. Compared with a travel speed of 50 km/h, the same vehicle traveling at 60 km/h (20% faster) has 44% more kinetic energy. This disproportionate increase in kinetic energy, which is intrinsic to the movement of all objects on Earth, presents a serious challenge to those responsible for the safe operation of the road transport system.

Reducing vehicle mass, while contributing to a reduction in the threat to life and health of the occupants of a struck vehicle, has other practical effects, including a

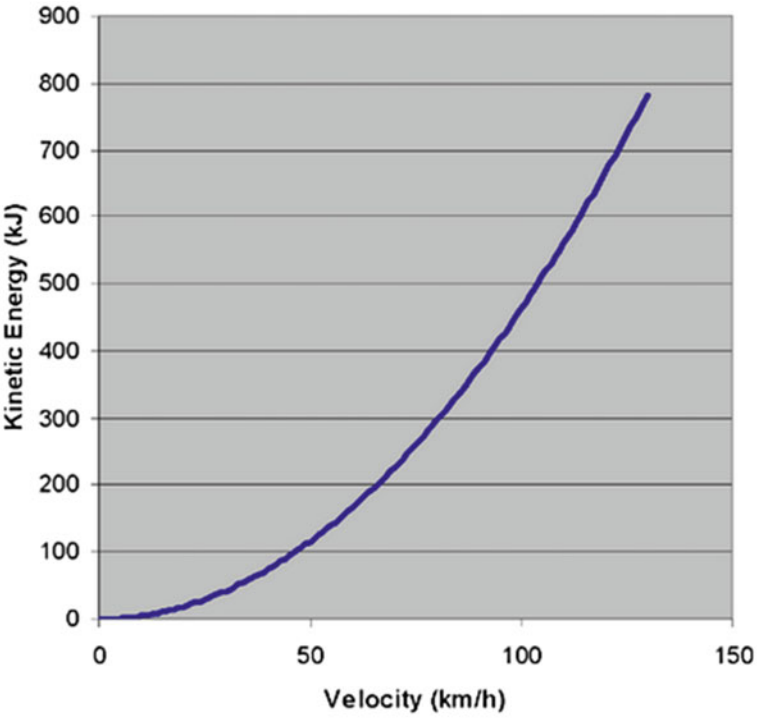

Fig. 2 The relationship between kinetic energy and travel speed

greater threat to the occupants of lower mass vehicles. To avoid this negative safety effect for the occupants of lower mass vehicles, a universal reduction in vehicle mass across the fleet would be needed.

The second option for the safe management of kinetic energy concerns its dissipation during the crash phase. Vehicle design has made a major contribution to the safer dissipation of kinetic energy in a crash, through features such as seat belts and seat belt pre-tensioners, front, side, center and curtain air bags, structural design, especially in the sides and fronts of vehicles, active head restraints, and side- and rear-underrun barriers on trucks (https://www.euroncap.com/en). Overall, these developments have been valuable but are of limited effectiveness when the threshold energy levels common in crashes, even at legal speeds, are exceeded (i.e., the Vision Zero boundary condition speed is violated). Vehicle crashworthiness limitations and aggressivity levels need to be considered, as part of a cohesive system, in determining the Vision Zero boundary conditions for various crash types and road user combinations.

At this point in human existence, road user errors will continue to occur and therefore crashes will also continue. Exposure can be managed to reduce the extent to which system users are exposed to crash potential but because societies need and wish to move about, exposure reduction will offer only a partial solution, even if sizeable shifts from private cars to public transport occur. Managing injury risk through road design is an underdeveloped and underutilized option for eradicating deaths and serious injuries.

Impact Biomechanics and Injury Risk

The biomechanical thresholds for severe injury have been the subject of considerable research over past decades. Despite the continual improvement in research methods, including data collection and crash reconstruction tools, productive debate continues among road safety experts as to the validity of the various risk curves that have been developed for a number of key crash types. Because consensus on scientific method is unlikely to be reached in the near future, practical, maximum tolerable impact speeds that align with the Vision Zero aspiration of eliminating death and severe injury have been defined and adopted for each of a number of systemic crash types. The difficulties inherent in establishing scientifically robust mathematical relationships linking the risks of death or of serious injury with impact speed should not impede efforts to avoid preventable severe injuries and loss of life. Research efforts will likely continue to achieve greater scientific rigor. In the meantime, the general shape of the risk curves can be used to guide the establishment of a boundary condition impact speed for each major crash type, above which the risk of death begins to rise rapidly with increasing impact speed.

These challenges are discussed in the recommendations of the AEG, formed for the Third Global Ministerial Road Safety Conference in Stockholm in February 2020 (Swedish Transport Administration 2019). It is concluded that "… to protect vulnerable road users and achieve sustainability goals addressing livable cities, health and security, we recommend that a maximum road travel speed limit of 30 km/h be mandated in urban areas unless strong evidence exists that higher speeds are safe." This recommendation seeks to present a practical, evidence-based perspective that will deliver benefits broadly across the Sustainable Development Goals (SDGs).

The very nature of seeking to define a single impact speed that represents the biomechanical threshold for each crash type is, in itself, questionable. There are many variables that influence the notion of a threshold impact speed in real-world collisions. These include the age, stature, and health status of pedestrians and other unprotected road users, the mass and frontal design features of the impacting vehicle, and the physical surroundings of the crash site (e.g., into which a pedestrian, cyclist or motorcyclist may land after impact). These variables can lead to many combinations of crash conditions, resulting in a distribution of risks of death (and serious injury) as a function of impact speed. By adopting maximum tolerable impact speeds that align with the best available research, and also with real-world experience, valuable progress can be made. As new, more robust evidence comes to light, the maximum tolerable impact speeds can be adjusted up or down, as appropriate. Experience with emerging vehicle safety technologies, such as Autonomous Emergency braking (AEB) and vehicle connectivity, will provide valuable new opportunities to manage speeds to avoid severe injury across all systemic crash types.

The mathematical definition of risk as a function of impact speed is important for reliably estimating the potential savings in severe trauma. However, accurate mathematical relationships are less important to defining the impact speed that should not be exceeded for each major crash type, if severe injury is to be avoided. A pragmatic approach that reflects real-world experience and outcomes is essential while research continues to inform us.

In the context of the above discussion, the following maximum tolerable impact speeds have been adopted to achieve alignment with Vision Zero principles. Drawing upon the results of past research (Swedish Transport Administration 2019), impact speeds that coincide with the point on the risk curves where the risk of death rises sharply with increasing impact speed have been found to provide valuable practical guidance for road designers and system operators. These speeds each correspond with an approximate 10% likelihood of death in the event of a crash (ITF 2016; SWOV 2006):

- 30 km/h for **impacts with pedestrians, cyclists, and motorcyclists**
- 30 km/h for **side-impacts of passenger cars into narrow rigid objects** such as roadside trees and utility poles
- 50 km/h for **side-impacts** between passenger cars of similar mass
- 50 km/h for **frontal-impacts into narrow rigid objects** such as roadside trees and utility poles
- 70 km/h for **head-on impacts** between passenger cars of similar mass – the corresponding threshold impact speed is even lower for narrow offset head-on crashes

These maximum tolerable impacts speeds will be much lower if a criterion of avoiding serious injuries is strictly applied, or where one or more of the impacting vehicles is large, such as a truck, bus, or tram, or when older road users are involved (e.g., 65 years or older).

The Relationship Between Impact Speed and Travel Speed

The relationship between impact speed and travel speed is not always clear; however, it is known that in a substantial number of road deaths and serious injuries, no braking by the driver of the impacting vehicle took place (e.g., Anderson et al. 1997; Kusano and Gabler 2011). This means that, often, the travel speed becomes the impact speed.

Today's five-star vehicles are equipped with technology capable of detecting a potential crash and, by braking automatically, sooner than is typically possible by a human, either avoiding the impact entirely or shedding speed prior to impact – that is, reducing the speed at impact, and hence the risk of death or severe injury.

It has been established that impacts with pedestrians of 30 km/h can produce serious injuries and, in some circumstances, death. Some researchers (e.g., Ashton 1980; Anderson et al. 1997 and Ministry of Transport and Communications 1997) have concluded that at 30 km/h, approximately one in ten pedestrians will die if struck by a vehicle. Other researchers (e.g., Rosén and Sander 2009; Rosén et al. 2011; Davis 2001) have found that higher impact speeds correspond with an approximate 10% risk of death to the struck pedestrian. As noted earlier, this lack of consensus has led to the adoption of a Safe System boundary condition speed for pedestrians of 30 km/h, in the knowledge that an impact at this speed causes unacceptable outcomes for the individual and for society, irrespective of the accuracy of the alternative risk curves describing the pedestrian-vehicle conflict.

To avoid impacts causing severe injury or death to a pedestrian (or other unprotected road user), it is proposed that vehicle travel speeds be limited to 30 km/h, or less, and for vehicle technologies to reduce travel speeds by around 20 km/h when a collision occurs. Technologies such as AEB are capable of detecting pedestrians on a collision trajectory and automatically braking the vehicle earlier than is possible by a typical driver. The resultant shedding of vehicle speed before impact dramatically alters injury risk.

Autonomous Emergency Braking (AEB)

This section examines the role of AEB (https://www.euroncap.com/en/vehicle-safety/the-rewards-explained/autonomous-emergency-braking/) in preventing severe trauma to pedestrians, by comparing vehicle performance with and without AEB. While the focus is on pedestrians, largely because of their high prevalence in urban areas, the same or significant benefits can be expected for other urban road users.

For a typical vehicle, not fitted with AEB, traveling at 30 km/h and being driven by a person with a 1.3 s perception-reaction time, the vehicle's stopping distance will be around 16 m, should the driver need to brake to avoid a pedestrian, or other road user, on a conflicting path ahead. The stopping distance trajectory is calculated from the following basic equation of kinematics, found in textbooks on classical mechanics:

$$v^2 = u^2 + 2as,$$

where:

v = the final speed of the vehicle
u = the initial speed of the vehicle
a = the acceleration of the vehicle (equal to μg, where μ is the coefficient of friction between the tire and the road surface, and g the gravitational constant ($9.8\ m/s^2$))
s = the distance traveled at any point along its trajectory

Stopping distance profiles for an average passenger vehicle are shown in Fig. 3, for a range of driver perception-reaction times of 0.65, 1.30, 1.50, 1.70, 1.90, and 2.10 s. These estimates assume a coefficient of friction of 0.7, which is reasonably typical for urban roads, though will vary considerably across the globe, especially for countries with poorly maintained or unsealed road surfaces. For roads with lower values of the coefficient of friction, the risks of severe injury to pedestrians and to other unprotected road users will be even greater than described in this comparison.

For the pedestrian who is located just 10 m ahead of the approaching vehicle when the driver perceives the need to brake, the impact speed without AEB will be around

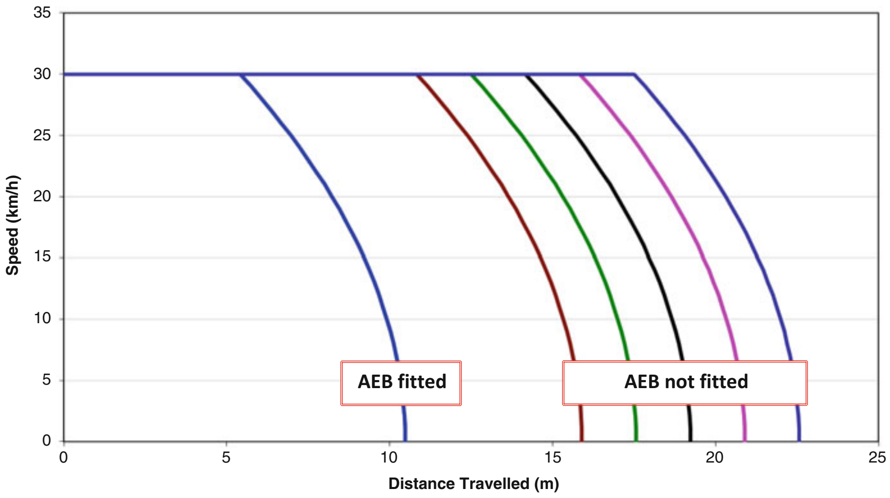

Fig. 3 Stopping distance profiles for an average passenger vehicle, for perception reaction times of 0.65 (AEB fitted), 1.30, 1.50, 1.70, 1.90, and 2.10 s (AEB not fitted). Note: assumed value of coefficient of friction is 0.7

30 km/h. This is because the vehicle travels about 11 m before the driver is able to initiate braking. If we are to design according to Vision Zero principles and, therefore, to virtually eliminate the risk of death to an unprotected road user, in this case a pedestrian, impacts at 30 km/h are unacceptable and much lower speeds at impact are required.

Under the same scenario described above, a vehicle fitted with AEB will be capable of braking earlier than is possible according to an average driver's "perception-reaction time." If the time for an average driver to react can be halved (i.e., 0.65 s for AEB c.f. 1.30 s for the driver), the impact speed would reduce to around 10 km/h. At this vastly reduced impact speed, the kinetic energy of the vehicle at impact would be almost 90% lower than at 30 km/h. The risk of a serious injury to a pedestrian would rapidly approach zero, other than for older/frail pedestrians who need only fall to sustain a potentially life-threatening injury. Present-day AEB systems are activated when the driver has failed to brake sufficiently early to avoid a collision. Should a pedestrian step into the path of an approaching vehicle equipped with AEB, at a distance greater than the vehicle braking distance, it should be possible to avoid an impact provided the pedestrian is detected immediately and that braking commences instantaneously. If, however, the pedestrian steps into the path of an approaching vehicle equipped with AEB, within the vehicle's minimum braking distance, there will be a collision (assuming that the pedestrian is unable to clear the path of the vehicle before it arrives). Under this scenario, the impact speed will depend on the distance of the pedestrian from the vehicle when the pedestrian is detected by the AEB system, which has been designed to initiate maximum braking much more quickly than a human driver. Therefore, for many pedestrian crash scenarios, impact speeds will clearly be within the range required to transform the risk profiles faced by pedestrians and other unprotected road users. Where AEB results in impact speed reductions of 15–20 km/h from 30 km/h, as a result of halving the typical time required to commence braking, risks will align with the Vision Zero aspiration.

While this comparison shows great promise in dramatically reducing impact speeds and hence the levels of kinetic energy experienced by struck pedestrians, its success relies on drivers being compliant with the 30 km/h speed limit. Geo-fencing is a technology that limits vehicle speeds to the speed limit through which the vehicle is passing, or potentially lower if desired. Geo-fencing technology utilizes a vehicle's GPS-based location co-ordinates to determine the applicable speed limit which, to meet Vision Zero principles, should be set to accommodate the significant foreseeable crash types. For densely populated cities and towns, Geo-fencing can be deployed to require drivers to stay at or below the threshold speed deemed appropriate to the systemic risk profile, in this case, 30 km/h to protect pedestrians, cyclists, motorcyclists, and users of personal mobility devices, such as e-scooters, e-skateboards, mobility scooters, and the like.

As a further "line of defense" against severe injury to unprotected road users, the frontal design of vehicles plays an increasingly valuable part. Vehicle frontal design continues to evolve to allow impact energy to be dissipated more effectively by the vehicle structure, so that less of the kinetic energy at impact is shared with the struck pedestrian or other unprotected road user.

The combination of:

- 30 km/h speed limits
- AEB technology with shortened reaction times (around, say, 0.5 s)
- Geo-fencing technology to support driver compliance with 30 km/h speed limits in high risk areas
- Good energy absorbing properties of vehicle fronts
- Has the potential to dramatically reduce risk profiles for the most vulnerable of road users commonly using urban roads and streets

An example of pedestrian passive safety protection devices under development is shown in Fig. 4 (https://www.autoliv.com/products/passive-safety/pedestrian-protection). They comprise:

- Pedestrian Protection Airbag to mitigate head impact to hard structures such as the A-pillars and windscreen frame
- Active Hood Lifters to mitigate head impact with structures beneath the hood, such as the vehicle’s engine, suspension tower, and battery

In summary, vehicle technology and structural design, in combination with 30 km/h urban speed limits where pedestrians are prevalent, supported by

Fig. 4 Example of pedestrian passive safety protection devices (https://www.autoliv.com/products/passive-safety/pedestrian-protection)

technology and infrastructure to achieve high levels of compliance with speed limits, indicate that “Vision Zero” is feasible in the future for unprotected road users in urban areas. Automotive technology manufacturers are, today, developing and testing external airbags and bonnets that lift to absorb the kinetic energy in a collision with an unprotected road user.

However, the safety benefits derived from vehicle technology and structural design will be relatively slow to penetrate jurisdiction vehicle fleets, even in the most advanced nations, where fleets typically require 20–30 years to be largely replaced. Therefore, in the intervening years, the achievement of low-risk vehicle speeds, through appropriate speed limit setting practices and supportive infrastructure design, remains critical to protecting citizens who use urban roads and streets. To give credence to the potential of creating low risk cities and towns for unprotected road users, the Norwegian capital of Oslo reported a fatality-free year in 2019 for pedestrians and cyclists (and other active travellers), and just one fatality to a vehicle occupant for the entire year (https://www.smh.com.au/national/nsw/oslo-cut-road-deaths-to-one-in-2019-can-sydney-do-the-same-20200111-p53qmz.html).

Vision Zero Design and Operation for Urban Roads and Streets

Safety and Environment

In urban areas, there are multiple modes of travel, ranging typically from pedestrians, cyclists, scooter-riders, and motorcyclists, through to passenger cars, trams, buses, and trucks. Electric personal mobility devices, sometimes referred to a micro-mobility devices, for example, e-scooters, e-skateboards, and e-bikes, are emerging rapidly in some parts of the world, presenting challenges for regulators, road designers, and system operators to integrate these relatively new devices safely and functionally into existing systems. In the various and changing settings that characterize urban areas, it is important to be able to assign different priorities to the movement of individual modes in order to create efficient, liveable, and sustainable cities and towns. In this context, it is contended that two ethical imperatives should apply:

- All road user groups, whether assigned higher priority or not, must not only *feel* safe but also *be* safe.
- Future changes to the road transport system should not detrimentally affect population health or the environment and, ideally, should reduce traffic-related impacts, such as noise and emissions. Furthermore, existing levels of social inequity, resulting from the way in which the road transport system operates, should not be worsened and, wherever possible, should be improved.

In the case of safety, designing and operating to assure the safety of vehicle occupants will not necessarily address safety for unprotected road users, namely, pedestrians, cyclists, motorcyclists, or the users of the variety of innovative personal mobility devices on urban streets. The riders of e-skateboards, e-scooters, e-bikes, and scooters for the mobility-impaired are all effectively unprotected in traffic and share similar injury risks to pedestrians. However, by designing to ensure the safety of society's most vulnerable road users, namely, children and older pedestrians, vehicle occupants and other unprotected road users are also naturally accommodated. Thus, under Vision Zero, designing for pedestrians and cyclists becomes the ethical and scientific benchmark for urban areas. That is, assuring the safety of unprotected road users should be the default position for cities and towns. This means that travel speeds higher than the biomechanical tolerance level of humans should only be possible where truly effective separation has been provided.

Separation Versus Managing Kinetic Energy

In cities and towns, effective separation can take the forms of overpasses, bridges, tunnels, elevated roads and the like; however, while these types of infrastructure have a place in modern cities, they are typically very costly and sometimes not in keeping with the aims of good place-making. A common example in some parts of the world is shown in Fig. 5.

For pedestrians and cyclists, overpasses and tunnels may also be inconvenient to use, often requiring substantial detours and/or changes in levels, which can be difficult for people with health or mobility concerns. While it is highly desirable to design these structures to include features that prevent pedestrians or cyclists from interacting with high-speed traffic at street level, this can be difficult to achieve in practice. If it is found that pedestrians and/or cyclists continue to mix with vehicles traveling at high speeds, further steps must be taken to assure effective separation or to manage speeds to below the boundary conditions described above.

Fig. 5 Pedestrian overpass of a high-volume, high-speed urban road (Melbourne, Australia)

Other commonly used devices (e.g., traffic signals, and pedestrian and cyclist crossings) are often described as providing separation, albeit time-based separation. Regrettably, experience has shown that separation is only partially effective, despite the existence of comprehensive, detailed regulations specifying how traffic signals and other traffic control devices are to be used. Too many drivers, pedestrians, cyclists, and other road users fail to comply fully with red traffic lights, flashing lights, zebra crossings, and an assortment of other devices designed for full compliance. When such system failures occur, legal travel speeds in many urban areas produce collisions far outside the Vision Zero boundary conditions for unprotected road users, and often for vehicle occupants as well. Traffic control devices, as used in many countries today, fail to accommodate the requirements of effective energy management when the inevitable human error occurs.

The example shown in Fig. 6 illustrates how speed platforms can be used to achieve reduced risk where pedestrians cross busy urban roads.

Effective physical separation is needed, otherwise speeds must be managed to ensure foreseeable impacts do not exceed the boundary condition for the main systemic crash types. Designing expressly for speeds within the relevant Vision Zero boundary condition is needed to prevent serious harm.

Fig. 6 Speed platforms in advance of pedestrian crosswalks along busy urban roads (Dubai, UAE)

The Practical Application of Kinetic Energy Management Principles

Unprotected Road Users

Pedestrian Collisions

Broadly speaking, pedestrian collisions can be categorized as occurring at intersections or between intersections. Because the previous section addresses pedestrian risk at intersections, this section focuses on risk along roads and streets between intersections.

Exposure

In keeping with the Global Goals for Sustainable Development, in particular:

Goal 3: Good health and well-being
Goal 11: Sustainable cities and communities

the opportunities available through exposure modification to reduce deaths and serious injuries to pedestrians are limited by the need to encourage the active modes of travel, especially walking, cycling, and public transport use. More walking, cycling, and public transport use helps to create healthy, sustainable cities and towns. While it is undesirable to limit pedestrian exposure for these reasons, there may be opportunities to restrict pedestrian access to roads and streets where walking is high-risk or otherwise undesirable.

Limiting exposure to crashes by limiting walking is generally undesirable; however, the exposure of pedestrians to crash opportunities can be substantially reduced by limiting vehicle access to busy pedestrian streets and areas. Options could include preventing vehicle access entirely or limiting access to low risk times of day and days of week. Pedestrian malls and car-free streets, sometimes operated with time-based restrictions, are increasingly common examples of exposure reduction measures that help to assure the safety of unprotected road users in cities and towns. Figure 7 illustrates the opportunities that are presented to enhance urban settings where streets can be made car-free.

Restricting vehicle access is often not a viable option and therefore other options must be considered.

Crash Likelihood and Injury Risk

Given the limited opportunities to protect pedestrians through exposure modification, other possibilities will often be necessary to support the safety of pedestrians. The combination of reducing crash likelihood and injury risk offers considerable scope.

A common circumstance in which pedestrians are injured, even killed, is when they are attempting to cross from one side of a road to the other, without the assistance of a traffic control device. In this everyday situation, pedestrians are required to choose a safe gap in traffic, a task that may sound simple when expressed in a traffic regulation but, in practice, can be extremely challenging, especially when

Fig. 7 Opportunities to enhance liveability in car-free streets (Stockholm, Sweden)

traffic speeds are high. The main factors that contribute to crash risk include (Corben et al. 2008; Walk This Way 2012):

- the speed of traffic
- the width and number of traffic lanes to be crossed
- the number of directions of traffic to be negotiated
- the volume of motorized traffic
- the capabilities of the pedestrian to make good decisions and execute their decisions successfully, for example, the experience and maturity, physical agility, and judgment of the pedestrian making the crossing

Sometimes, though not normally, pedestrians may be provided with traffic control assistance, such as a zebra crossing, traffic signals, school crossings, or similar devices. While the majority of drivers and pedestrians comply, full compliance is not assured. Drivers are known to run red lights, deliberately or unintentionally, typically at speeds that will result in severe injury or death to the pedestrian, should a crash occur. Pedestrians, too, will often cross against red signals or at nearby, high-risk locations, rather than wait for the green pedestrian signal (refer to Fig. 8).

There is a long history of the traffic engineering profession attempting to improve compliance, through signage, pavement markings, more conspicuous signals and shorter cycle times. While these efforts are commendable, failure by both drivers and pedestrians to comply fully continues at unacceptable levels, suggesting more effective methods are needed.

Of the above list of main factors contributing to pedestrian crash and injury risk – there are many more – speed plays a vital role. Travel speeds not above 30 km/h are essential to achieving the lowest practical risk levels for several reasons:

Fig. 8 Pedestrian and driver compliance with signals is challenging (Melbourne, Australia)

- In a highly complex traffic setting, as is often encountered in urban areas, drivers and riders are more likely to reach the threshold of their information processing capabilities when traveling at higher speeds. At 30 km/h or lower, decisions can generally be made in a more timely fashion.
- Driver willingness to give way to pedestrians on crossings increases with reductions in travel speed. Thus, the frequency of conflict between motorists, and pedestrians and cyclists, can be reduced further at lower travel speeds compared with legal speeds commonly encountered today (Johansson 2004).
- Vehicle stopping distances are substantially reduced with lower travel speeds (refer to Fig. 3).
- Past research on pedestrian safety (Anderson et al. 1997) shows that in about half of all pedestrian fatalities, no braking occurred and therefore the travel speed is too often the impact speed. This is likely to be true for cyclists as well.
- A review of research on the biomechanical tolerance of humans to various vehicle impact speeds (Logan et al. 2019) shows a rapid rise in the risk of a pedestrian (or cyclist) fatality above an impact speed of around 30 km/h. For serious injury risk, the corresponding threshold impact speed is likely to be much lower. Risk is even more acute when the striking vehicle is a tram/light rail vehicle or other large vehicle and/or when children and older people are involved.
- ITF (2016) also discussed the lack of clarity with research in the field and recommended the adoption of 30 km/h as the target Safe System speed, until

> more robust research comes to light. The ITF report notes that "Whilst there is, and will continue to be, considerable debate on safe impact speeds and the shape of various fatality risk curves, precise definitions are not possible or meaningful in reality. They represent some form of population average over a sizeable number of cases but there is considerable variability in outcomes, and hence risk, among individuals due to uncontrollable factors such as the type and size of the vehicle, the age and health status of the road user, the point of impact, etc. There is a certain randomness about these factors that is often beyond the control of the system designer or operator. Because of this variability in the incidence and circumstances of real world crashes, a conservative position should be adopted concerning risk so as to account for a broad range of population, vehicles and conditions. We must also be cognisant that the use of fatality risk curves, and the tenth percentile value to determine safe impact speeds, is by definition permitting the incidence of some deaths and serious injuries, notwithstanding the commitment to eradicating deaths and serious injuries from road crashes."

In support of the importance of assuring low risk speeds for pedestrians (and other road users), the AEG formed to make recommendations in the context of a Third Ministerial Conference on Road Safety, held in Stockholm in February 2020, recommended as follows (Swedish Transport Administration 2019): "In order to protect vulnerable road users and achieve sustainability goals addressing livable cities, health and security, we recommend that a maximum road travel speed limit of 30 km/h be mandated in urban areas unless strong evidence exists that higher speeds are safe."

Given the need for a pragmatic decision on the boundary condition for pedestrians and cyclists, 30 km/h is regarded as an appropriate, practical threshold, until such time as more reliable estimates emerge. In reality, a lower threshold could legitimately be considered to accommodate the greater vulnerability of older people, young children and people with disabilities, or where the striking vehicles are large and/or have unforgiving frontal designs (e.g., trucks, trams, and utilities fitted with "bull bars").

Powerful opportunities to reduce pedestrian deaths through speed moderation are illustrated in Fig. 9, which shows the long-term trends in pedestrian deaths in the Australian state of Victoria. From an annual average of 146 pedestrian deaths during the 1980s, an unprecedented step-drop in deaths occurred in 1990, following the introduction of a large-scale automated speed enforcement program during 1989. The number of fatalities fell to just 93 in 1990 from 160 in the previous year, and settled below this level over subsequent years. Another large step-drop was experienced in 2002, compared with 2000, when Australia's default urban speed limit was reduced to 50 km/h from 60 km/h and enforcement tolerance levels were reduced in 2002. A number of other measures were also introduced in 2001 and 2002, such as the provision of new speed enforcement technology and random breath-testing (Cameron et al. 2003).

Following each of these step-changes in annual pedestrian fatalities, the long-term trend line has settled at new lower and generally declining levels. This four-

Fig. 9 The long-term trends in pedestrian deaths in Victoria, Australia (1980–2019)

decade history is indicative of the power of lower travel speeds to reduce pedestrian fatality risk. The drop that occurred in 1990 was very likely the result of improved driver and rider compliance with existing speed limits (rather than reductions in speed limits), again underlining the potential power of lower limits to cut unprotected road user deaths when introduced in busy pedestrian settings.

A number of other road safety interventions, not involving speed moderation, were being implemented during the period shown in Fig. 9. However, none is likely to explain the step-drop observed in pedestrian fatalities.

To achieve vehicle speeds not exceeding 30 km/h in densely populated urban areas, greater use of speed-moderating design forms is needed. There is also an ongoing need for design innovation to create a wider range of measures that suit or can be adapted to different urban settings. The evolution of modern and future vehicle technologies is highly likely to interact with safe infrastructure design, which highlights the potential value of road/traffic engineers collaborating with their automotive engineering counterparts to optimize system-based designs for the protection of pedestrians, cyclists, and other unprotected road user groups (Strandroth et al. 2019).

For pedestrians crossing roads and streets between intersections, effective separation, or speed moderation is needed to assure their safe passage. For high-speed and/or high-volume roads, serving an important traffic movement function, separation may be more appropriate than speed moderation. Also, in high-density urban settings, such as shopping centers, public transport interchanges, and major commercial land uses, high investment in separation can be more readily justified. Figure 10 shows how full separation has been achieved in central Stockholm, where rail, shopping, and other commercial activities predominate. The choice will be influenced by the type of urban setting through which a road or street passes. For

Fig. 10 Grade-separation of pedestrians from city center motorized vehicles (Stockholm, Sweden)

roads that serve an important vehicle movement function, a variety of design forms, such as pedestrian bridges or tunnels, elevated roadways or tunnels for vehicles are used to achieve separation (Austroads 2020). Banning pedestrian access to freeways is generally seen as reasonable, but preventing or limiting access across other urban road classes is typically not desirable for cities and towns.

Full separation is often difficult to achieve and can impact unfavorably on the urban surroundings, involves high costs, and offers only a limited number of locations at which pedestrians can cross safely. In particular, pedestrian tunnels create feelings of personal insecurity for pedestrians (and cyclists) who might use them, unless they are designed exceptionally well. Pedestrian bridges linking buildings can prove safe and convenient if located on the pedestrians natural desire line; however, requiring pedestrians to walk long distances and/or undergo significant changes in levels is inconvenient and potentially highly restrictive for people with mobility impairments. Moreover, restricting pedestrian movements to a relatively small number of locations does not support the high-order goals of social equity and of sustainable cities and communities.

Measures that help to achieve travel speeds not exceeding 30 km/h include:

- 30 km/h speed limits (or lower) along busy pedestrian routes or throughout dense urban areas

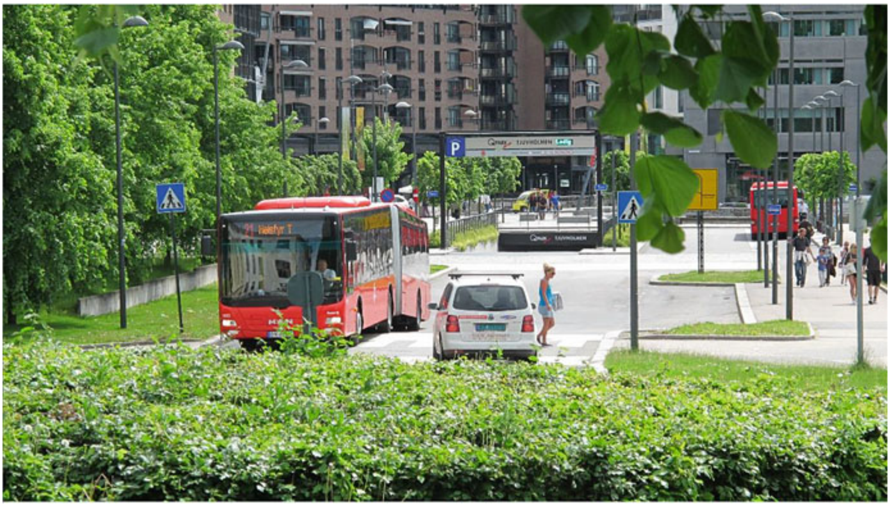

Fig. 11 Pedestrian crossings on speed platforms (Oslo, Norway)

- Pedestrian signals or crossings positioned on speed platforms designed to elicit 30 km/h speeds or lower (refer to Fig. 11)
- Road narrowing that permits only a single lane of traffic at a time
- General traffic-calming along a street to ensure 30 km/h travel speeds
- Plateau intersections separated by distances that achieve travel speeds up to 30 km/h
- Shared spaces requiring speeds not greater than 10 km/h
- Various forms of tactical urbanism, which has been described as introducing low-cost, temporary changes to the built environment, usually in cities, intended to improve local neighborhoods and city gathering places (Pfeifer 2014). Tactical urbanism techniques are being used increasingly in cities and towns, especially in North America, to accelerate the pace of change (refer to Fig. 12).

Cyclist Collisions

Cyclists are among the most vulnerable of road users when involved in a crash. They face similar risks of severe injury as pedestrians when struck by a vehicle but are characterized by differing forms of conflict and levels of exposure to crash potential.

Exposure

There is a wide range of levels of cycling in cities and towns across the world. In car-dominated societies, cycling is at relatively low levels, but in many places these levels are increasing quite rapidly, often in response to concerns about the high costs of car ownership, traffic congestion, climate change, and personal health. As with walking, cycling is a sustainable mode that delivers a wider array of benefits beyond being a convenient and effective mode of transport. Cycling is healthy, does not pollute, and is spatially compact when compared with motorized transport,

Fig. 12 Tactical urbanism (New York, USA)

especially when parking requirements are considered. Cycling can also interface well with public transport, either through the provision of parking at rail and bus stations or by being able to travel on some public transport modes, although these options may often need to be restricted to low patronage times. In essence, cycling has many positive features and the use of bicycles as a meaningful transport mode should be encouraged along suitable urban road classes. Use on freeways and motorways, where the speeds and volumes of motor vehicles are high, will be an obvious exception, unless separated cycling paths can be provided alongside these types of urban corridor. This leaves limited scope to address cyclist safety through exposure reduction, other than along roads that are highly unsuited to this mode.

Crash Likelihood

While the vulnerability to injury in a crash is similar for pedestrians as for cyclists, their interactions with traffic differ considerably. Cyclists share the road with the full range of motor vehicles, from other cyclists and motorcyclists to passenger cars, trams, buses, and trucks. The major conflict types involve drivers failing to give way to cyclists at intersections, commonly leading to side-impact crashes and crashes involving motorists turning across the paths of cyclists riding along the same road or street.

Crash likelihood is affected by factors such as the speeds and speed differentials between vehicles and cyclists on conflicting trajectories, the sightlines between drivers and cyclists, and the natural tendency for drivers not to see riders even though they are in plain view. This effect of “looked but did not see” is recognized as a crash risk factor for motorcyclists and cyclists, alike. It has been hypothesized that this difficulty in perceiving an approaching cyclist (or motorcyclist) is exacerbated by their small physical size relative to other traffic, and the resultant greater difficulty in perceiving and judging their approach speeds. The presence of other vehicles (e.g., queued or moving slowly) can obscure cyclists from the view of surrounding motorists, as can the structure and size of left-turning trucks (right-turning for countries where traffic travels on the right-hand side of the road). A number of countries experience serious crash problems caused by turning truck drivers being unable to see a cyclist approaching from behind and traveling in the same direction as the truck, largely because of the height and physical design of the truck cabin. Very severe injuries, including death, commonly result, even for trucks turning at relatively low speed.

Given the types of factors affecting crash likelihood for cyclists, it is generally preferable to provide physical separation for riders. Separated cycling facilities may lead to a rise in exposure to crash potential, due to increasing numbers of cyclists – a desirable consequence from the perspective of supporting healthy, sustainable transport – with any increase in exposure likely be offset by reduced crash likelihood.

As noted above, a substantial proportion of severe trauma between cyclists and motor vehicles occurs at intersections, often involving turning maneuvers by drivers. While conjecture exists as to whether roundabouts assist cyclists, it is contended that roundabouts offer substantial safety benefits for cyclists because of the natural tendency of roundabouts to reduce vehicle speeds and conflict angles at locations of concentrated conflict, and to also simplify the pattern of conflicts. Further research may be needed to determine the effects of roundabouts on cyclists, in terms of crash likelihood and injury severity risk. In a study undertaken in 2009 (Scully et al. 2009), it was found that motorcyclists experienced the same magnitude of reductions in casualty-producing crashes from roundabout construction, as did vehicle occupants (around 80–85%).

Where physical separation of cyclists from motor vehicles is impractical or undesirable, speed management is required to reduce crash risk and to ensure impact speeds between cyclists and vehicles remain within the Vision Zero boundary condition for severe harm.

Injury Risk

Cyclists share similar risk profiles for severe injury as pedestrians. Though not mandatory in many countries, the wearing of helmets moderates the risk of head injuries sustained by cyclists who fall or are involved in collisions with vehicles (or other road users). Further, riders are generally positioned at greater heights than pedestrians when struck, which may contribute to a larger vertical component in their speeds at impact with the ground. The dynamics of these crashes tend to be complex and difficult to interpret reliably. Suffice to say that cyclists mixing with traffic should not be subjected to vehicle travel speeds greater than 30 km/h. For the same reasons explained for pedestrians, impact speeds of 30 km/h are known to cause severe injury and therefore are unacceptable under a Vision Zero approach to protecting humans in traffic. Vehicle technology, particularly AEB, will prevent crashes or enable impact speeds to be reduced from 30 km/h by around 15–20 km/h, resulting in a substantial reduction in impact speed and therefore the risk of death or severe injury. Geo-fencing and energy-absorbing frontal design of vehicles will make additional valuable contributions to the compliance of drivers with 30 km/h on roads and streets used by cyclists, and to injury severity in the event of a cyclist-involved collision, respectively.

Vehicle Occupants

Intersection Collisions

Intersections concentrate conflict. The more traffic entering, the greater the extent to which vehicle and other road user paths intersect. This leads to more opportunities for crashes. If the speeds of vehicles on conflicting paths are high, then the chances of severe injury, when crashes occur, will also be high.

Exposure

Exposure to potential conflicts is generally growing as populations and road use increase. While crash likelihood can be minimized, it is inevitable that crashes will occur as a result of lapses in human performance or intentional risk-taking. It is therefore necessary to manage the energy transfer between roads users at intersections to avoid exceeding the boundary conditions for the various combinations of road user types that conflict at intersections.

Crash Likelihood

There are large differences in the kinetic energy levels for different forms of intersection design and operation. For example, for an intersection within a 60 km/h speed zone, the kinetic energy levels of entering vehicles will potentially be more than double for conventional traffic signal design or regulatory signing, compared with a well-designed roundabout. This twofold difference has a vast effect on the ability of the designers to keep vehicles separated and, more importantly, to ensure the energy dissipation in any resulting collision will not lead to death of serious injury.

Injury Risk

The boundary condition for side-impacts between passenger vehicles at intersections is 50 km/h, indicating that the risk of death to an occupant of the struck vehicle rises rapidly above this impact speed. For pedestrians and cyclists, the boundary condition is around 30 km/h. As noted earlier, it is not possible or meaningful to set a precise value for the various boundary conditions, as crash circumstances vary by vehicle type and mass, and road user age and health condition, as well as the exact point of impact on the struck vehicle.

A well-designed roundabout constrains vehicle travel speeds to 40 km/h or lower, depending on the local design philosophy of the road authority, and therefore will be successful in reducing both crash likelihood and injury severity, given a crash between conflicting vehicles. However, even for a 40 km/h design speed, pedestrians, cyclists, motorcyclists, and the riders of personal mobility devices will remain exposed to impact speeds beyond their biomechanical tolerances to the impact forces experienced in a crash. This means that, if we are to eliminate deaths and serious injuries, we must design for the most vulnerable of the road users found at urban intersections. These will typically be pedestrians and cyclists, as well as motorcyclists and the riders of various types of personal mobility devices – this group of highly vulnerable road users will now be referred to as unprotected road users.

In many countries today, only a minor proportion of vehicles are capable of detecting unprotected road users on a conflicting path at intersections. However, it is expected the five-star rated vehicle of the future will have this capability as a standard feature. Leading vehicle manufacturers and automotive technology suppliers are optimistic that the next generation of five-star vehicles will be able to avoid many potential collisions with unprotected road users at intersections or shed up to 20 km/h prior to impact, and so turn life-threatening incidents into low severity injury events at worst. However, in the case of older pedestrians, severe injuries occur even at 10 km/h impact speeds. With aging populations, designers and system operators must be mindful of such risks.

We can manage energy more effectively at intersections when we design to keep impact speeds below the boundary condition for unprotected road users. Because travel speeds are quite often the impact speeds in vehicles without automatic braking technology (e.g., Anderson et al. 1997; Kusano and Gabler 2011), speed limits and road design features need to elicit travel speeds not exceeding the respective boundary condition speeds.

Urban roundabouts have proven highly successful in achieving speeds within the boundary conditions for vehicle occupants and for unprotected road users. This is because roundabouts integrate several essential design features that affect crash and injury risk simultaneously:

- **Reduced crash likelihood**, as a result of lower travel speeds and a large reduction in possible conflict points within the intersection – just four main conflict points compared with 32 in a standard four-leg cross road.
- **Reduced injury severity in a crash**, as a result of lower travel speeds and more favorable impact angles – the combination of lower speeds and acute angles markedly diminishes the lateral component of force to the struck vehicle in an impact between vehicles that would otherwise occur at around 90°. The occupants of a struck vehicle are at the greatest risk when the impact angle is 90°, as vehicle structures are able to offer only limited protection in this common scenario. When the impact angle is 30° instead of 90°, the lateral component of both force and impact speed are halved and the effective kinetic energy level reduced to a quarter of the value in a 90° collision. Good geometric design can change fundamentally the physics of crash likelihood and injury risk.

Well-designed roundabouts are an ideal default design form for urban intersections. In their basic form, they can be designed to operate at low risk for vehicle occupants but need explicit attention for unprotected road users. For pedestrians, the integration of pedestrian crossings on speed platforms helps in ensuring the boundary condition speed of 30 km/h is not exceeded. Figure 13 illustrates a number of desirable safety attributes of urban roundabouts.

Fig. 13 Urban local street roundabout with elevated pedestrian crossings (Melbourne, Australia)

Fig. 14 Urban signalized intersection with speed platforms for cyclists and pedestrians (The Netherlands)

For cyclists, it is desirable to provide separation from motorized traffic when more than one circulating lane is required. This can be achieved through the use of off-road cycle paths that enable cyclists to negotiate intersections without the need to share traffic lanes. Instead, cyclists can cross intersecting roads in a similar manner to pedestrians, with the benefit of cyclist crossings on 30 km/h speed platforms. Figure 14 shows a Dutch example of speed platforms at traffic signals to reduce both crash and injury risk to pedestrians and cyclists.

Fig. 15 Semi-urban turbo-roundabout (The Netherlands)

In the Netherlands and some other European countries, turbo-roundabouts have been trialed to address safety issues of this type on multi-lane roundabouts. Both safety and operation have been found to improve, with a 10–15% increase in vehicle throughput at turbo-roundabouts compared with conventionally designed roundabouts. Figure 15 shows a turbo-roundabout in a semi-urban area of The Netherlands.

In summary, for urban intersections to perform according to the Vision Zero aspiration, vertical and/or horizontal deflection would ideally be designed into the intersection layout to achieve travel speeds within the boundary condition for unprotected road users. That is, the basic design elements of horizontal and/or vertical deflection are essential features for safe intersection operation, unless vehicle speeds can otherwise be controlled to low risk levels. Technologies such as Geo-fencing offer this possibility but their widespread use is considered unlikely in the next 10–15 years, and therefore there is an ongoing need for road design and system operation that produce safe travel speeds.

Lane Departure Collisions (Head-On and Single-Vehicle)

It is commonplace for urban roads and streets to be lined with trees, utility poles, lighting poles, and other objects that can present a hazard to a vehicle occupant or rider who leaves the road at speeds outside their respective boundary conditions. The often narrow and rigid nature of trees and poles explains why vehicle occupants suffer severe injury and death in impacts with these objects, even when traveling at legal speeds.

Communities value trees, and other road and street vegetation, because they provide shade and can offer considerable aesthetic and environmental value. Trees make an important contribution to cleaning the atmosphere of air and water-borne pollutants, so common in modern cities, and help to make city streets more walkable.

Utility poles carry electricity to homes, industry, and businesses (and more) and enable modern-day telecommunications services to operate throughout urban areas and beyond. These essential services in modern cities can, in some circumstances, be located underground within road reserves. To date, however, this has proven impractical and/or costly, and seemingly beyond the abilities of utility and telecommunications companies to achieve. While new, safer, and more aesthetic means of delivering these essential urban services to the world's cities and towns should continue to be sought, current conditions are unlikely to change markedly in the short- to medium-term future.

Urban areas are often characterized by the presence of street lighting, mounted on utility poles or columns specifically designed for the purpose. Progress has been made over recent decades with designing frangible/energy absorbing columns to reduce the risk of severe injury to the occupants of vehicles which collide with these frequently encountered hazards. Poles serving a street lighting function are typically found in roadsides and medians, depending on the cross-section of the road, and often within just a few meters of the traffic lanes.

So while trees, utility poles and street lighting represent a substantial source of risk for many road users, they are fundamentally important to today's urban life. This is unlikely to change in the medium-term future.

Exposure

As with other systemic crash types, the loss of life and the incidence of severe injury as a result of collisions with roadside hazards can be reduced by moderating exposure. However, this will make only a limited contribution to eradicating trauma involving lane departure collisions. Finding ways to shift vehicle occupants onto public transport, for example, will reduce exposure to this type of risk. Where practical, encouraging traffic to roads that are inherently less hazardous, in terms of the outcomes of lane departure collisions, will also make a contribution. The degree of success with using exposure reduction methods will be defined by the magnitude of the shift that can be achieved.

Crash Likelihood

There is also a range of measures that have been used with varying degrees of success to reduce the likelihood of crashes involving vehicles leaving their lanes and colliding with roadside hazards or with oncoming traffic. This is a particularly common crash type in rural areas where higher travel speeds, corresponding with disproportionately higher levels of kinetic energy, play a key role in the severity of injury outcomes. Measures that reduce crash likelihood include:

- Reconstruction to create larger radius curves.
- Improvements in the quality of delineation of road and lane alignments, using for example, curve warning and delineation signs, enhanced marking of center, lane

and edge lines (i.e., with audio and/or tactile feedback when a vehicle's tires traverse them).
- The introduction of new, or the widening of existing, clear zones – this measure tends not to reduce the incidence of vehicles leaving their lanes, and may even increase this risk due to the higher travel speeds that can result from wider roadways. Clear zones also reduce the likelihood of an object being present on the trajectory of a vehicle which has entered the roadside.
- The removal of such hazards, especially in the vicinity of sharp curves.
- The use of high-friction surfacing to heighten the chances of vehicles remaining on the road while negotiating curves, especially where there may be unfavorable cross-fall.
- Reduction in speed limits.

The above sample of measures used to reduce crash likelihood are, in themselves, insufficient where travel speeds are above the Vision Zero boundary condition speed for impacts with trees and poles, or for head-on collisions with oncoming vehicles. The boundary condition speed for collisions with trees and poles is around 50 km/h when the impact involves a frontal collision, and around 30 km/h for side-impacts. For head-on collisions, severe injury, even death, may occur at around 70 km/h.

Injury Risk

Crashes involving passenger cars into trees and poles produce severe injury, sometimes death, at impact speeds between 30 and 50 km/h. On this basis, travel speeds above 50 km/h increase the likelihood of severe injuries from crashes above the boundary condition for collisions with narrow, rigid objects. That is, the crashworthiness of modern vehicles does not provide adequate protection to occupants above the boundary condition speeds. As with other systemic crash types, the travel speed is often the impact speed, given that factors such as alcohol, drugs, distraction, and drowsiness are commonly present in lane departure events.

For roads and streets with speed limits above the boundary condition speed for an impact with a tree or rigid pole, it is necessary to provide energy absorbing barriers (or similar systems) to prevent the transfer to vehicle occupants of levels of kinetic energy that exceed human tolerance to severe injury. Modern vehicles have the capability to remain within their lanes, provided the lanes are effectively delineated at all times of day and in all weather conditions. In addition, AEB technology, as described in earlier, will also assist with crash avoidance and injury mitigation in potential collisions with median and roadside hazards.

Unfortunately, only a small proportion of vehicles comprising today's vehicle fleets are fitted with these features. This proportion is likely to vary considerably between high- and low-income countries but will grow significantly over the years ahead, as older vehicles are replaced with new vehicles. This means that for a period of some 20–30 years, a substantial proportion of vehicle occupants will be exposed to unacceptable risks due to roadside hazards when speed limits are set above the boundary condition.

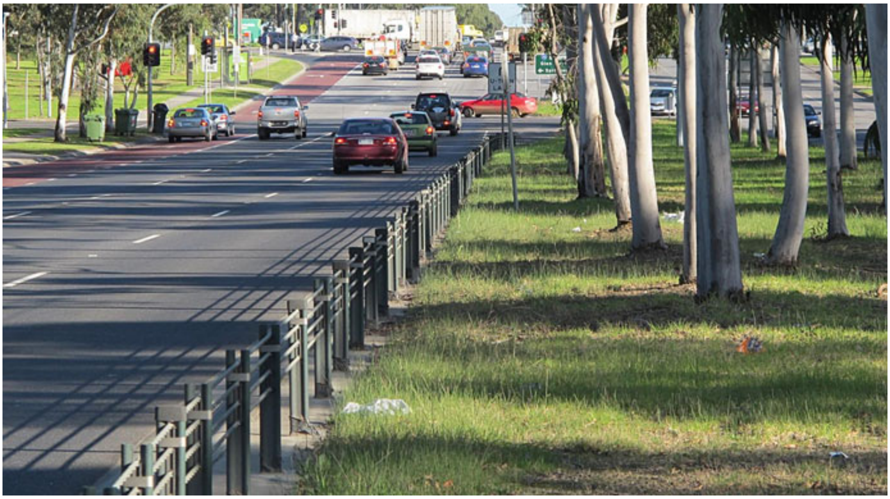

Fig. 16 Continuous flexible barrier systems to manage kinetic energy in lane departure crashes along high-speed, high-movement roads (Melbourne, Australia)

Given that exposure management can exert only a modest (but, nevertheless, worthwhile) effect on the potential for lane departure crashes, and measures that address crash likelihood will offer only limited reductions, a sizeable residual risk remains unaddressed. To tackle this problem in ways that are aligned with Vision Zero principles, either energy absorbing infrastructure is needed on roads with speed limits above 50 km/h, until such time as key vehicle safety technologies have penetrated the vast proportion of vehicle fleets, or speeds must be constrained to 50 km/h or lower. At these speeds, and below, side-impacts with narrow rigid objects, which have a boundary condition speed of around 30 km/h, become less likely. This is largely because, at lower travel speeds, loss of control through loss of surface adhesion or uncontrolled vehicle dynamics is less likely than at higher speeds.

Figure 16 highlights the opportunities along some urban roads, where it is desired to allow high travel speeds, to use flexible barriers to manage the high energy levels of errant vehicles. Without such barriers, much lower speeds are needed to meet the Vision Zero aspiration.

Rear-End Collisions

Rear-end collisions are among the most common crash types, though, on average, they tend to produce less severe injuries than other systemic crash types. Rear-end crashes are more prevalent along busy roads where traffic does not flow freely. Intersections are among the sources of interruption to smooth traffic flows, with traffic signals being a substantial generator of rear-end collisions, both at signal-controlled intersections and also upstream. The onset of a red signal display, typically every 1–2 min, sets up the conditions for rear-end collisions, as drivers traveling at the speed limit are required to respond to the closing yellow/red signals. Some drivers have a natural propensity to try to get through an intersection when presented with a yellow/red signal, while others endeavor to stop if they can do so safely. When a driver with the latter tendency is being followed in the same lane by a driver with the former tendency, the potential for read-end impacts is heightened. Heavy vehicles have also been found to be more highly represented in rear-end collisions at traffic signals than traffic generally, which can lead to more severe outcomes because of incompatible vehicle masses, structures, and/or geometry. Many other factors and incidents can lead to rear-end collisions along roads and streets, especially in urban areas where roadside activity tends to be much higher than in rural settings. In fact, in large cities, where intense interactions occur between the movement of traffic and the human activities underway in the places through which the traffic passes, there is an inherent potential for rear-end collisions.

Exposure

The reduction in exposure is a universally applicable approach, though far from sufficient in itself. Exposure reduction can include network-level shifts from the use of motor vehicles to public transport and/or rail-based freight movement. Other options that encourage use of roads less prone to rear-end collisions can also be employed; however, these approaches are unlikely to make large-scale gains in safety, other than if implemented to a significant degree, with a view to lasting change. Where possible and well-aligned with the SDGs, exposure reduction opportunities should always be considered and assessed as a means of supporting active travel and the more sustainable modes.

Crash Likelihood

To date, the elimination of rear-end crash risk has proven elusive for the road safety, policing, and road design and traffic engineering professions. This is because crashes happen as a result of speed differentials between vehicles in the same traffic stream, and drivers and riders being unable to respond in a consistent and timely way to prevent collisions with slowing or stationary vehicles ahead. Excessive speed differentials, together with inherent limitations on human perception-reaction times, the tendency to follow too closely, to be distracted or inattentive, to speed or to be tired or otherwise impaired while driving, all contribute to the risks of rear-end collisions. It has not proven possible to modify human performance in traffic to eliminate these risk factors and there is little potential to do so without the aid of modern vehicle technology. Features such as active cruise control (ACC), AEB, Intelligent Speed Assist (ISA), and Geo-fencing offer considerable potential but, today, too few vehicles are fitted with these technologies. This will, of course, change gradually over the years ahead as more and more new car sales will include vehicles with these features fitted as standard.

Injury Risk

On the assumption that rear-end crashes will continue to happen on a substantial scale in the coming 20 or more years, new measures will be required to achieve the very low risks expected from successful deployment of Vision Zero thinking, while modern vehicles with AEB and ACC penetrate urban vehicle fleets. Indicative speed differentials of around 40 km/h (Trafikverket 2014) should not be exceeded if the Vision Zero boundary condition for rear-end collisions is to be met. An even lower speed differential will be necessary to remain within the respective risk levels for avoiding fatal or serious injuries when, for example, trucks, buses, or trams are involved in rear-end crashes with smaller, passenger vehicles.

Given that rear-end crashes often involve the struck (front) vehicle being stationary, and no braking by the driver of the striking vehicle, travel speeds of 40 km/h cannot be exceeded to align with Vision Zero principles. To ensure a high level of compliance with 40 km/h speed limits on urban roads, vehicle technologies such as Geo-fencing and ISA will be needed. These technologies may obviate the long-term need for the deployment of traditional police speed enforcement resources and possibly automated speed enforcement methods as well.

The high degree of incompatibility that exists between the masses and structures of passenger vehicles and trucks illustrates the elevated risk of severe outcomes when these two vehicle types collide in a rear-end configuration. Trucks without under-run protection at the rear can cause especially severe injuries to the occupants of passenger vehicles which strike the truck, even at relatively low impact speeds. Similarly, the front of trucks, trams, and buses often have aggressive structures and geometric features that do not interface well with the structures of passenger vehicles, leading to severe injuries to passenger vehicle occupants.

In the interim, until a high degree of saturation has occurred in urban vehicle fleets with technologies such as ACC, AEB, ISA, and Geo-fencing, urban speed limits of not greater than 40 km/h will be needed to avoid fatalities and severe injuries caused by rear-end crashes.

Barriers to Implementing Safe Urban Speeds

This chapter underlines the vital role of effective management of vehicle speeds, especially in urban settings, in protecting the lives and well-being of citizens. There is a history of resistance to lowering speed limits from some interest groups and individuals in society. Often, the concern expressed is about the impacts of lower speed limits on travel times, with potential harm to economies also sometimes cited as the reason for opposition to lower speed limits. While increases in travel times are an understandable concern, particularly for rural, high-speed travel over long distances, where impacts may sum to minutes, lower urban speed limits do not typically lead to appreciably longer trip times (Haworth et al. 2001).

Along urban roads and streets, other factors such as high traffic volumes, congestion, and traffic signals are influential in determining travel times for urban journeys. The need to create gaps in flow along busy routes using, for example, traffic signals to assist motorists on intersecting roads and streets to cross, leave, or

Fig. 17 Streets that allow walking and cycling prosper commercially (Utrecht, The Netherlands)

join major roads is a chief source of delays. The regulations governing the operation of traffic signals require motorists to stop for durations of around 1–2 min, sometimes longer when the intersecting roads carry high traffic volumes. The durations of these delays are far greater than the impacts of lower speed limits on overall journey time. Other factors, such as motorists entering and leaving parking spaces or waiting in traffic queues, simply because the traffic volumes exceed the physical capacity of roads, also have a dominant effect on travel time. If speed limits were raised in these circumstances, motorists would more likely reach the tail of the traffic queue sooner, while experiencing and imposing increased risk of road trauma, increasing harmful emissions and generally diminishing the liveability of urban areas. In some circumstances, lower travel speeds can actually lead to smoother flow and increased vehicle throughput.

Not only have lower travel speeds in urban areas been proven to save lives and prevent severe injuries, they also contribute to the liveability and sustainability of cities and towns. Where people can walk and cycle, local economies are often found to prosper (refer to Fig. 17).

Achieving Synergies with Other High-Order Goals

In the early part of this chapter, reference was made to the importance of achieving the Sustainable Development Goals (SDGs). Much of the focus of this chapter has been on achieving either separation or travel speeds within the boundary conditions for each of a number of systemic crash types, in order to align with the aspirations and principles of Vision Zero. This has led to the specification of various speed limits for each crash type found to be common to urban roads and streets. The scope has been confined to systemic crash types known to lead to death or severe injury.

On some roads and streets, it has been concluded that speed limits should not exceed 30 km/h, while on others not used by unprotected road users (namely, pedestrians, cyclists, and motorcyclists), speed limits not exceeding 40 km/h are needed to prevent severe trauma from rear-end collisions and speed limits not exceeding 50 km/h are needed to provide protection for vehicle occupants in collisions with each other or with roadside trees, poles, and other like-hazards. Where effective separation of road users from these specific hazards can be achieved, higher travel speeds can be permitted from a safety perspective, though they may not always be desirable from other viewpoints. For example, higher travel speeds may increase traffic noise, vehicle emissions and fuel use, detract from local place-making and diminish feelings of security, and overall liveability of cities and towns.

In closing this chapter, it is valuable to consider the opportunities presented by initiatives aimed at achieving alignment with Vision Zero objectives, as well as to contribute to a number of specific SDGs. Potential contributions are now discussed briefly.

Population Health

The main gains in population health are expected to come from lower travel speeds supporting active travel. Achieving urban travel speeds that align with Vision Zero goals will not only reduce the risks of death or severe injury to pedestrians and cyclists, as well as to public transport users, but will encourage more walking and cycling. The health benefits of more pedestrian- and cyclist-friendly communities are well-established and include:

- Improved health as a result of the increased physical activity
- Reduced traffic noise, leading to reduced stress levels and enhanced abilities to learn
- Lower vehicle emissions, resulting in reductions in respiratory illness
- Greater social connection, especially for older and mobility-impaired citizens
- Greater independence for children in being able to walk or cycle, at low risk, for school trips.

Environment

Benefits to the environment of lower travel speeds and more walkable and cyclist-friendly urban areas include a reduction in traffic congestion, leading to a reduction in the harmful emissions that contribute to the greenhouse effect and to global warming. Lower travel speeds are associated with smoother flow of traffic, reduced acceleration and deceleration, and a further reduction in greenhouse gases and wasted fuel use. When travel speeds are aligned with the Vision Zero boundary condition for lane departure crashes, the need to remove trees as part of clearing the roadside is also obviated. As a consequence, roadside trees can be planted or retained without compromising safety and this, in turn, contributes to cleaner air, especially in more densely populated cities, and to general liveability.

Liveability

The liveability of urban areas is strongly influenced by the ease of access to the various activities defining urban life. The aesthetics of roads and streets, especially in local neighborhoods and places where communities gather to socialize, recreate, shop, and study, are also important factors in defining liveability. Matching travel speeds to the Vision Zero boundary conditions applicable to the main systemic urban crash types, including the intrinsic vulnerability of unprotected road users, helps to ensure that place-making, tree-planting, street-scaping, and the creation of highly walkable environments can co-exist with motorized traffic. The choice of safe, convenient, and secure access to public transport, schools, shops, community facilities, and work locations, by foot, bicycle, micro-mobility, or public transport are among the attributes that characterize liveable communities.

Sustainability

Sustainable living and, in particular, sustainable transport are important long-term goals for society. Aligning the operation of the road transport system to Vision Zero helps to meet sustainability criteria. For example, support for active travel, by virtue of full separation or 30 km/h speed limits will lead to greater levels of walking, cycling and public transport use, and, conversely, reduced reliance on private car travel. This is important to the long-term sustainability and environmental goals of the world's most densely populated cities.

Social Equity

Modern societies are increasingly sensitive to the need to assure social equity, especially in densely populated urban areas where safe and convenient mobility is essential to daily life. Yet assuring equity has proven very challenging as populations and urban density grow. Socially well-placed citizens and visitors to cities and towns enjoy a wide range of mode choices, including the use of private car travel. This enables socially advantaged people full access to opportunities for employment, socialization, entertainment, education, health services, and other activities needed to participate purposefully in modern life.

People who are socially less-well placed, due perhaps to low personal or family incomes, or health concerns, tend to be restricted in their mobility choices. For example, low-income individuals and families are generally only able to afford cars that are older and, therefore, inherently less safe. This exposes the occupants to greater crash and injury risks. Those who do not own cars will often be limited to using public transport and (hence) associated active travel. While active travel is, in itself, good for the individual and for society, and therefore to be supported, travel options are restricted to the places and times offered by these services. In the absence of well-designed infrastructure and low-risk travel speeds, active road users face heightened vulnerability, especially when walking or cycling in fast-moving, busy traffic. Among the gender-based concerns are the limitations on mobility for females who feel insecure (and may well be insecure) in some settings, on particular days of the week and/or during higher risk times of the day.

It is not uncommon for there to be under-investment in infrastructure in cities where socially disadvantaged communities live and work. This can occur because of long-standing political priorities and lead to higher exposure to an inherently unsafe road transport system.

Among the most vulnerable road users are children, and older and mobility-restricted people; they are often unable to enjoy full personal independence, easy access to health and other services essential to urban living, and the social interaction with family and friends that can be so important to a person's well-being. In many of today's cities, people are limited in their mobility by threatening traffic speeds, high and constant flows of traffic, narrow or non-existent footpaths and wide roads to cross. Instead of being able to walk or cycle safely to and from school, it is common for children to be driven, which further exacerbates the exposure to risk and the general congestion around schools. This progressive loss of personal freedom impedes the development of young people and limits their opportunities for social interaction and a level of personal independence appropriate to their ages.

Ensuring that vehicle travel speeds align with the Vision Zero boundary conditions for pedestrians and cyclists allows greater urban mobility, thereby helping to compensate for the social-disadvantage common in our larger cities and towns.

Concluding Comment

Translating the Vision Zero aspiration and principles to real-world practice offers opportunities to create safe, healthy, sustainable, and socially equitable road transport systems. A focus on achieving lasting gains will deliver benefits for today, as well as for future generations.

Cross-References

- ▶ Automated Vehicles: How Do They Relate to Vision Zero
- ▶ Road Safety Analysis
- ▶ Sustainable Safety: A Short History of a Safe System Approach in the Netherlands

- ▶ The Development of the "Vision Zero" Approach in Victoria, Australia
- ▶ Vision Zero and other Road Safety Targets
- ▶ Vision Zero in Norway
- ▶ Vision Zero in Sweden: Streaming Through Problems, Politics, and Policies
- ▶ Zero Visions and Other Safety Principles

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