Part IV

Tools and Technologies for Vision Zero

Road Safety Analysis

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Contents

Abstract

Road safety analysis can be used to understand what has been successful in the past and what needs to be changed in order to be successful to reduce severe road trauma going forward and ultimately what's needed to achieve zero. This chapter covers some of the tools used to retrospectively evaluate real-life benefits of road safety measures and methods used to predict the combined effects of interventions in a road safety action plan as well as to estimate if they are sufficient to achieve targets near-term and long-term. Included are also a brief overview of methods to develop boundary conditions on what constitutes a Safe System for different road users. Further to that, the chapter lists some arguments for the need

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of high-quality mass and in-depth data to ensure confidence in the results and conclusions from road safety analysis. Finally, a few key messages are summarized.

Keywords

In-depth data · Real-life evaluation · Boundary conditions · Combined benefits · Safety gaps · Target setting

Introduction: Why Is Road Safety Analysis Necessary?

Road safety analysis is an area of profound importance in Vision Zero planning and implementation. It has commonly been used to understand the real-life benefits of road safety measures, to guide future implementation of interventions and to facilitate the development of action plans and strategies. Road safety analysis could be said to include more specifically in the context of Vision Zero – gaining detailed insights into crash and injury mechanisms, investigate boundary conditions for what constitutes a safe system and building confidence in innovative solutions by setting up quality management systems and evaluation frameworks. Going forward, road safety analysis is essential to understand future trauma residuals and what it might take to ultimately eliminate fatalities and serious injuries. Road safety analysis is also an important ingredient in target management as it can be used to inform what constitutes ambitious but achievable long-term and near-term targets, both in terms of trauma targets and targets for system transformation, namely Safety Performance Indicators (SPI).

In summary, road safety analysis can be used to understand what has been successful in the past and what needs to be changed in order to be successful to reduce severe road trauma going forward and ultimately what’s needed to achieve zero.

Road safety analysis is made up from numerous elements of data of crashes and injuries, information of the system state as road assets, vehicle and driver characteristics, statistical methods and models, in-depth investigations as well as other analytical tools. As with all analytics, the quality of the outputs and the confidence in the results are products of the input data, the approach used when generating hypothesis and the methods adopted when testing them. Over the past decades, road safety analysis has benefited from increased data quality and coverage as well as new and improved methods for evaluation, forecasting, and scenario development.

This chapter will cover some of the tools used to retrospectively evaluate real-life benefits of road safety countermeasures and methods used to predict the combined effects of interventions in a road safety action plan as well as to estimate if they are sufficient to achieve targets near-term and long-term. Included are also a brief overview of methods to develop boundary conditions on what constitutes a Safe System for different road users. Further to that, the chapter will also list some arguments for the need of high-quality mass and in-depth data to ensure confidence in the results and conclusions from road safety analysis. Finally, a few key messages are summarized.

Retrospective Analysis

Real-Life Evaluation of Road Safety Countermeasures

With the Vision Zero approach it is imperative to constantly evaluate implemented countermeasures in real-life conditions, thus providing valuable feedback to the designers of the road transport system. The basic idea is to compare two different crash populations:

- The treated population, that is, one involving the countermeasure to be evaluated
- The untreated population, that is, one without the countermeasure

An example could be the evaluation of newly installed median barriers on a road. In its simplest form, the analysis would compare the number of crashes occurring on the new roads with median barriers with the number of crashes on the same road, before it was rebuilt. Such an approach is normally called before-and-after study. In other words, the treated and untreated crash populations come from the same road, in different time periods. However, such a simple approach would not handle possible confounders. For instance, it is conceivable that during the studied period there may be seasonable or even long-term variation in traffic volumes, or other changes in driving patterns due to weather, roadworks, or increased police enforcement, that would reasonably affect the overall crash rates on the analyzed road. In order to handle this issue, it is recommended to use the “before-and-after” approach with at least one so-called control group, that is, an untreated crash population from another road during the same time period. Clearly, several control groups can be used, as done by Transport for London (2007).

Further, even more advanced approaches could be used, that is, empirical Bayes (EB) methods, which also account for abnormal crash rates in short study periods by shrinking such estimates toward the mean, depending on the amount of data available. It should be noted, however, that EB require a certain level of statistical tools. While explaining such tools goes beyond the aim of this chapter, further details can be found in Hauer (1997), Elvik (2013), and OECD/ITF (2018).

Regardless of study design, it is important to understand that it is possible to perform real-life evaluations with limited data, as long as the data have a sufficient degree of detail and are analyzed with robust methods. A few recommendations are outlined below.

The first critical step in evaluating a countermeasure is matching the treated and untreated crash populations. Ideally, these should be as similar as possible and only differentiate on the variable under study. However, this may not always be possible, therefore it may be necessary to make assumptions or simplifications. With regard to optional vehicle safety technologies, for instance, it would be preferable to compare the same car models with and without the technology.

The second critical step is to obtain the exposure. Indirect methods are often used, that is, the exposure is derived from the actual crash data (i.e., induced exposure). With this approach, the key point is to identify at least one crash type or situation in which the countermeasure under analysis can be reasonably assumed (or known) not to be effective. Then, the relation between crashes with and without the countermeasure in a non-affected situation would be considered as the true exposure relation. For further reading, please see Evans (1998), Lie et al. (2006), or Strandroth et al. (2012). While sometimes it may be possible to use data based on real exposure (Teoh 2013; HLDI 2013), this may be difficult to obtain and could also include confounding factors. The most obvious advantage of indirect methods is that the analysis can be performed based on crash data only, without any need of other sources. Secondly, the issue of confounding factors may be easier to handle. To elaborate further, an example regarding the evaluation of optional autonomous emergency braking (AEB) on passenger cars is illustrated below.

As long as AEB is not standard equipment in all cars on the roads, it could be argued that drivers choosing AEB are probably more concerned about their safety in the first place, which could naturally lead to a lower crash involvement (i.e., selective recruitment). Further differences between the crash populations could also confound the results, for instance age, gender and use of protective equipment, etc. If crash rates are calculated based on real exposure (i.e., number of crashes divided by number of registered vehicle, or vehicle mileage), it is essential to control for possible confounders, for instance driver age or seat belt use rate, as done in Teoh (2011). However, adopting an induced exposure approach would normally address this issue, as the result is given by the relative differences within the AEB and non-AEB crash populations. Basically, even though a variable is known to affect the overall crash or injury risk (say driver age), the same variable can only confound the induced exposure results by deviating from the overall sensitive/nonsensitive ratio. If this is found to be the case, the treated crash population can be stratified into different subgroups for further analysis. The induced exposure calculations can be adjusted for confounders, as suggested by Schlesselman (1982), for instance by calculating the weighted average of the individual odds ratios.

Nonetheless, it is important to stress that the induced exposure approach is also based on a number of assumptions and limitations. First of all, it should be clear that the basic idea with this method is to calculate the number of crashes that should be included in the data, if the countermeasure under analysis had no effect at all. This approach may be considered as calculating the “missing” crashes in the dataset. Therefore, it is evident that a certain reduction in police reported crashes, for instance, does not necessarily mean that no crashes had occurred at all, or that no slight injuries were sustained in a minor crash that was not reported to the police.

An attempt to address this issue, that is, distinguishing between crash avoidance and reduced crash severity, has been presented in Rizzi et al. (2015). However, it should be noted that this approach is difficult to apply to police-reported crashes, as it requires injury data with good resolution (i.e., hospital records including full diagnoses), which may not be available in all regions of the world.

It is important to stress that the most critical assumption with the induced exposure approach is to determine the nonsensitive crash type. While the main method for selecting nonsensitive crashes is a priori analysis of in-depth studies, as done in previous research (Sferco et al. 2001), the distribution of crash types within the analyzed data may also provide insights into the non-sensitivity of certain crash types. However, it is very important that such assumptions are based on an actual hypothesis, rather than “trial and error” in the analysis steps (Lie et al. 2006). A further reflection is that evaluations of safety countermeasures based on real-life crashes may imply several factors affecting each other, that is, these may not be based on the principle “everything else is constant.” An example is the fitment of “safety packages” on cars, that is, a number of safety features such as low-speed AEB, high-speed AEB, Lane Keeping Assist, and Blind Spot Detection are offered as optional fitments together. It is therefore important to keep this issue in mind in order to differentiate between explanatory variables and confounding variables. If confounders are present as variables that differ between cases and controls, they might be picked up by the effect variable. When selecting possible confounders, it is important that they are based on a hypothesis, and not just invented. If included without any hypothesis, they may pick a variation that is not real. In other words, it is important to distinguish between possible correlation and causation.

Risk Factors and Boundary Conditions

Road safety research has traditionally had a significant focus on identifying risk factors which could be explained as factors correlating with increased crash or injury risk (Stigson 2009). Certainly, in some areas of road safety it is crucial to gain insight into risk factors. The development of driver support systems is one area where an understanding of driver distraction and impairment are important when selecting treatment strategies (Tivesten 2014). However, it has been found repeatedly that severe injuries and fatalities can be prevented without deep knowledge of the specific crash causation. Median barriers, speed reduction, airbags, and restraint systems are all interventions that act independently from driver-related errors. Despite the fact that they do not prevent crashes they are nonetheless effective in preventing injuries or mitigating injury outcomes.

In designing a safe transport system there is a need for a holistic approach, and current safety policies are therefore focusing more on defining safety criteria, or boundary conditions, rather than identifying risk factors (OECD 2008). The development of risk curves is the first step in creating that holistic understanding of what would constitute a safe system.

Injury Risk Curves

Injury risk curves are another essential part of the Vision Zero approach. As mentioned in other chapters, according to Vision Zero the road transport system should be adapted to the limitations of the road users, by anticipating and allowing for human error. The primary aim is not to totally eliminate the number of crashes but to align the crash severity with the potential to protect from bodily harm. In order to do that, detailed knowledge on the human tolerance to blunt force is needed.

Different injury risk curves have been developed for passenger car occupants, pedestrians (see, e.g., Kullgren 2008); Gabauer and Gabler 2006; Rosen and Sander 2009; Niebuhr et al. 2016) and motorcyclists (Ding et al. 2019). Other studies have also identified age as critical factor affecting the injury outcome for a given crash severity. For instance, with regard to car-pedestrian collisions, Kullgren and Stigson (2010) reported that at 40 km/h the risk of sustaining a MAIS 3+ injury is almost twice as high for elderly 60+, compared to all pedestrians in general Fig. 1.

Injury risk curves can be inherently affected by different types of different measurement errors, especially if based on crash reconstructions. As pointed out by Kullgren and Stigson (2010), impact speeds in crash reconstructions can include measurement errors in the 20% magnitude, which greatly affects the injury risk functions, especially at higher impact speeds. As shown in Fig. 2, the injury risk function would become more flat with increasing measurement error. This issue implies that injury risks are underestimated at higher impact speeds, which has significant practical implications for setting safe speed limits. As illustrated below, setting the threshold for acceptable risk is set at 10% based on data including 25% measurement error would result in a more than twice as high risk based on the original data.

It is important to point out that it is difficult to compensate the influence of measurement errors, or poor data quality in general, by increasing the data size. On the contrary, data sources with greater precision, that is, data based on EDR (Event Data Recorders), should be used whenever possible, even if the number of available cases is limited.

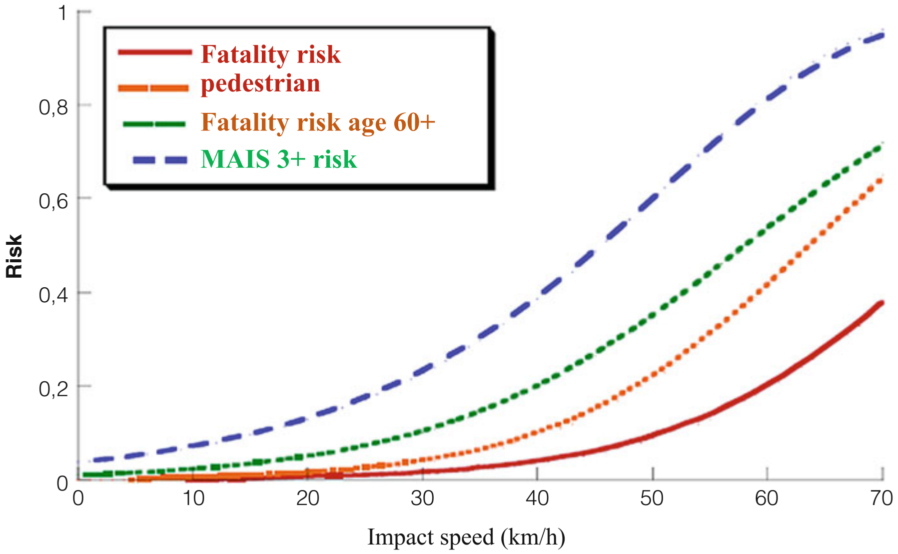


Fig. 1 Injury risk curves for pedestrians hit by cars. (Source: Kullgren and Stigson (2010))

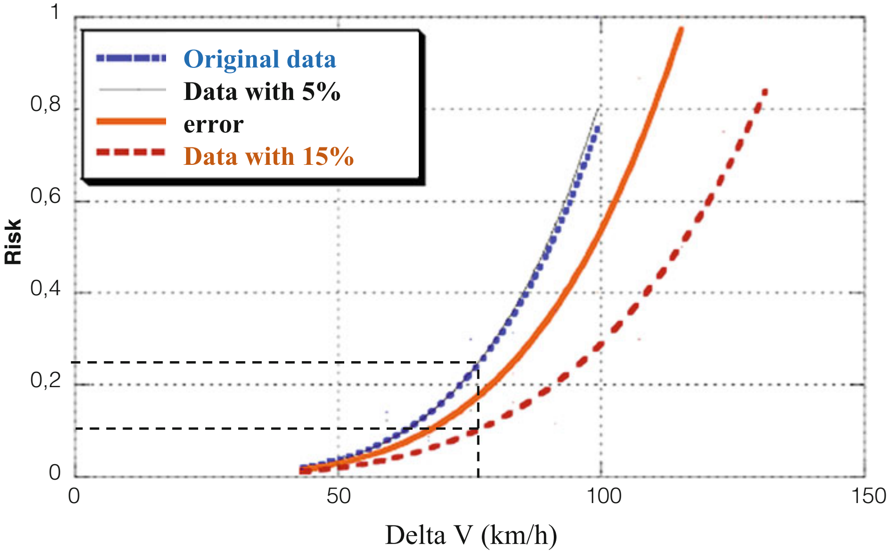


Fig. 2 Estimated effect of measurement errors on injury risk curves. (Source: Kullgren and Stigson (2010))

Model for Safe Traffic

A natural extension of risk curves, which outlines boundary conditions for specific crash configurations and road users, is to define system boundary conditions. System boundary conditions could be described as a combination of system element characteristics such as road infrastructure, vehicles, roads use, and speed such that they provide a safe system. Linnskog (2007) suggested a model as Fig. 3 where the combination of safe roads, safe vehicles, safe road use, and safe speed would produce safe traffic. For the model to be useful in different road environments, a dynamic approach was suggested where if one element failed it would need to be compensated by strengthening another. A typical example would be to adapt the speed limit to the function and safety quality of road infrastructure. Thereby a safe system can be created not only by heavy infrastructure investments but rather by a conscious decision of safe and appropriate speed in combination with infrastructure investment based on a road's strategic movement function. It is also important to note that the model criteria need constant review in relation to vehicle fleet turnover and as more advanced vehicle safety technologies enter the market.

Linnskog (2007) suggested a model for safe traffic for passenger car occupants with criteria being a Euro NCAP 5-star car, an iRAP 4-star road and a road user using seatbelt, being sober and complying with the speed limit. Stigson (2009) validated this model with the use of in-depth analysis of fatalities and serious injuries and found it to valid with a few exceptions, such as collisions with heavy goods vehicles. Also, Stigson (2009) further developed the model by suggesting that some of the road user requirements as seatbelt wearing, speed limit compliance, and unimpaired

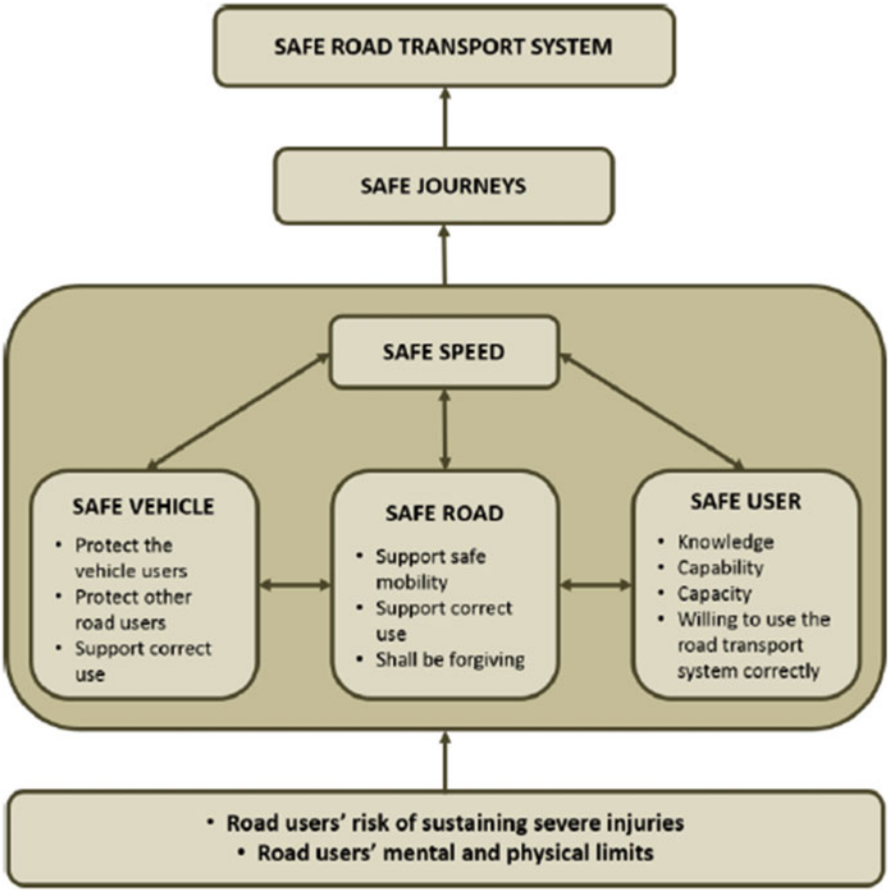
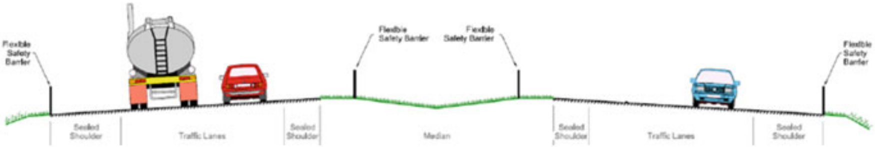


Fig. 3 The model for safe traffic adopted by the Swedish Transport Administration. (Adapted from Linnskog (2007))

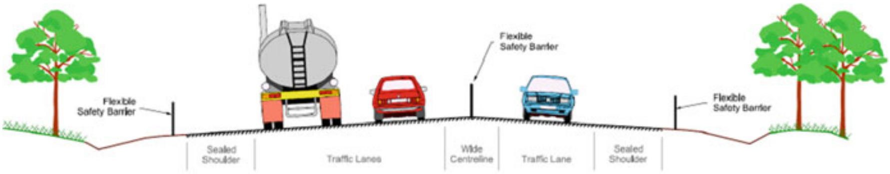
driving should be guaranteed by the implementation of vehicle technology rather than being road user dependent.

In a similar matter, but with a more future focus, a model for safe traffic in 2050 is being developed and validated in Victoria (Australia) with the purpose to understand infrastructure requirements to achieve zero road trauma by 2050 when a new the national long-term target of zero by 2050 was set (Strandroth et al. 2019). Based on the in-depth investigation of fatal crashes, the implementation of road cross-sections as outlined in Fig. 4 is investigated, in combination with a 5-star vehicle model year 2025 with safety technologies as outlined in the Euro NCAP roadmap (Euro NCAP 2017).

Even though this example is limited to passenger cars on midblock sections of high-speed rural roads, it illustrates the value safe system models. These models enable a back-casting approach where a future desired state can be compared with the current system state resulting in a gap-analysis useful for future planning.



Concept of a Safe System cross-section for divided freeways



Concept of a Safe System Cross-section for undivided highways

Concept of a Safe System Cross-section for undivided rural roads

Fig. 4 Concepts of cross-sections for different road types. (Source: Strandroth et al. (2019))

By doing this, one can identify additional programs and innovation needed to achieve zero and understand how to optimize the pathway to zero.

From a Vision Zero perspective it is thereby essential to develop and validate models for safe system for all road users in all situations, as it forms the basis for Vision Zero planning and implementation.

In-Depth Analysis of Crashes and Injuries

In road safety, as for other areas of epidemiology, a commonly used approach is case studies – where in-depth investigations of uncommon events are used to gain deep insight. This is one of the key prerequisites for road safety analysis with Vision Zero. Basically, macro analyses based on mass data need to be complemented with in-depth knowledge on crashes. It is also important to acknowledge that the road transport system is far from static – it is an intrinsically ever-moving entity that needs to be constantly monitored and studied. Therefore, having up-to-date in-depth studies of crashes makes it possible to follow up the current performance of the road transport system, to identify new deficiencies, as well as to test new hypotheses on future countermeasures.

A concrete example on median barriers is presented below. Using police-reported crashes matched with road data, Carlsson (2009) reported an 80% reduction of fatalities on newly built 2+1 roads. Clearly, this is an important result that strongly supports the further implementation of 2+1 roads as soon as possible. However, on the path toward zero it is essential to truly understand the circumstances of the remaining 20% fatalities that were not addressed by mid-barriers. This could be referred to as "getting the magnifying glass and zooming in on the leakage from a treatment," which would be very difficult task to perform using mass data. The more effective a treatment is found to be, the more important it becomes to understand the leakage. This is where detailed knowledge through case studies can support quick action by road authorities by detecting non-conformities and supporting adjustments of existing countermeasures or even the development of new countermeasures to address them. Theoretically, even one single case involving a new non-conformity could be enough to require action on the whole road transport system. Again, it becomes evident that data quantity can never replace quality.

In-depth studies are also often used to find potential benefits, especially for pre-production vehicle technologies. While the analysis of in-depth cases naturally has to deal with challenges regarding subjectivity and reliability, a number of studies have shown that it is possible to minimize this issue by setting logical decision-trees and having redundant analyses. Anti-lock Brakes, Electronic Stability Control, Autonomous Emergency Braking, Lane Keeping Assist, Barrier treatments, and Audio Tactile Line Markings are all examples of vehicle safety systems and road safety treatments which future benefits are assessed using a case-by-case approach (Sternlund 2017; Rizzi et al. 2009; Sferco et al. 2001; Swedish Transport Administration 2012a, Doecke et al. 2016).

Analysis of Future Safety Gaps

When aiming for a society free from serious road traffic injuries, it has been common practice in many countries and organizations to set up time-limited and quantified targets for the reduction of fatalities and injuries (OECD 2008). In setting these targets, the EU and other organizations recognize the importance of monitoring and predicting the development toward the target as well as the efficiency of road safety policies and interventions (EU 2010). Predicting the future status of the road transport system is, however, important not only with respect to target monitoring. According to Tingvall et al. (2010), it also plays an important role in the process of operational planning and in the prioritization of future actions.

Typical questions that arise as organizations, cities, regions, jurisdictions, and countries target zero are: How close to zero will our current strategies take us? What crashes and injuries remains in the future when all the treatments in our current toolbox are implemented and what further innovations are needed to ultimately eliminate road trauma? These are some of the questions that this chapter seeks to answer in order to facilitate Vision Zero planning.

The Challenges with Using of Retrospective Accident Data

The nature of the road transport system in many regions of the world has changed rapidly over the last decade as safety improvements in road infrastructure, vehicle fleet, and speed management have changed the characteristics of the system components. Not only has the condition state of the transport system changed, the characteristics of the crashes have also changed. For instance, Sweden has had a large reduction in car occupant fatalities since the beginning of the twenty-first century; however, the reduction is most evident in head-on crashes in contrary to single vehicle crashes. Strandroth (2015) has shown that this reduction was the result of systematic improvements, such as the installation of median barriers on roads with high traffic volume and/or vehicle improvements like the fitment of ESC and improved crashworthiness. Hence, as the road transport system continues to evolve it is quite reasonable to believe that the crashes of the future will differ a lot from the crashes of today and the past. Especially keeping in mind a future where cars can drive autonomously and the consequences of driver errors may be prevented, however, other challenges connected to automated vehicles may possibly arise (Lie 2014; Eugensson et al. 2013). Micro-mobility may also present the same possibilities and challenges.

Often when benefit assessments are made, retrospective data are used to describe accident scenarios that the technology is assumed to address (eValue 2011; Kuehn et al. 2009; Fach and Ockel 2009). The benefit estimations of a technology that will be introduced on new cars in a couple of years will then be based on accident data that may be several years old. Strandroth (2015) showed that the maximum benefit of a vehicle technology can be delayed for 10 or even 20 years. Hence, there can be a large time distance between maximum benefit and the time from which the accident data was collected and utilized in the benefit assessment. This fact can make retrospective analysis of crash data invalid when trying to predict the future impact of new or existing safety measures.

Naturally, accident data will always be intrinsically retrospective. However, the validity of the crash data need to be controlled by taking into account the evolution of the transport system when estimating benefits of future technologies.

Methods to estimate future benefits of road safety interventions based on the development of a combination of countermeasures can according to the Transportation Research Board be classified as statistical or structural (TRB 2013). TRB recognize statistical methods as an essential engineering tool for “formulating an initial, preliminary understanding of the relationship between variables” (TRB 2013). As a complement to statistical analysis, structural analysis has been proposed as an approach to identify why crashes occur and to explain causal relationships in road safety. A structural model is described by Davis (2004) as a model that “consist of deterministic mechanisms that draw on background knowledge concerning how the driver–vehicle–road system behaves. . .First, the relevant mechanisms for a specific type of crash are identified. Then, they are used to quantify the causal effect of the treatment on each mechanism. Finally, the frequencies of the mechanisms are aggregated for the facility of interest.”

Methods for prediction with a structural approach have been introduced and used in, for example, Sweden and Australia. In Sweden, a model suggested by the Institute of Transport Economics in Norway was used to forecast the number of lives saved by different road safety interventions introduced in 2007 and beyond (Swedish Road Administration 2008). This was done to facilitate the decision on an interim road safety target in Sweden. The effect of the individual interventions was calculated as the exposure multiplied by the effectiveness. The number of lives saved from all interventions was then estimated by the total sum multiplied by a factor of 0.6 to adjust for double counting (Swedish Road Administration 2008).

In South Australia, a model was developed for the South Australian Government by Anderson and Ponte (2013) which aimed to quantify the benefit from a number of safety improvements until 2020. The model took implementation rate and time into account and related every intervention to its relevant target population. In this study, the target population was defined as the group of fatalities prevented by a specific intervention. Other external factors such as traffic growth and changes in the vehicle fleet were also taken into consideration. A model developed by Vulcan and Corben (1998) was numerically implemented by Corben et al. (2009) in Western Australia and used the same approach. The overall benefit from all interventions (I1, I2, . . ., In) in the Australian model was calculated as 1-(1- I1) · (1- I2) · . . . · (1- In). Hence, the interventions were treated as independent.

Correlation, Independence, Overlapping Variables, Non-Linearity, and System Effects

Although the assumption of an independent relationship could sometimes be true and applied in retrospective evaluations, it has been shown in some cases to be invalid and therefore not appropriate to describe the future. Tingvall et al. (2010) identified at least two major challenges that are linked to the dependent relationship between different SPIs and the nonlinearity between an increase of an SPI and the final outcome. Regarding the relationship between SPIs, earlier studies have shown some possible alternatives that are all based on the fact the SPIs do not act alone, but are rather interacting components in a complex system.

In some cases it is clear that SPIs are correlated. This is the case with seat belt use and impaired drivers, since the probability for impaired drivers to be unrestrained in fatal crashes have been found to be larger than for sober drivers (Tingvall et al. 2010). Also, Nilsson (2004) found correlations between alcohol, seat belt use, and speed limit compliance in studies with self-reported data. One other possible interaction between SPIs could occur where a combination of two or more SPIs is conditional, in the sense that the effect of one factor is dependent on, or enhanced by, another factor, for example, system effects.

Strandroth et al. (2011) illustrated an example of system effects by showing that the injury reducing effect of more pedestrian-friendly car fronts depends on the speed limit where the pedestrians are struck by the car. In that study, hospital records were used to calculate the mean risk of impairing or fatal consequences. The results showed a significantly lower mean risk of fatal or impairing injuries for cars with a higher Euro NCAP pedestrian score. Interestingly, the risk difference in 30 km/h speed zones was 42%, while in 50 km/h speed zones the difference was 25%; and in 70 km/h no risk differences could be found (Fig. 5).

Broughton et al. (2000) assumed this relationship when evaluating the past benefit of vehicle safety, interventions against drink-driving and road engineering. But also in an attempt to forecast the benefit of these interventions, the same study based the calculation on the theory of independence. If the SPIs are treated as independent or simply additive without interaction, double counting becomes a risk if the populations addressed are in fact overlapping. However, if system effects are introduced with a combination of SPIs, there is a risk of underestimating the combined effect by just adding them. Elvik (2009) stated that many studies earlier have overestimated the combined effects of SPIs, and suggested a more conservative approach described as the method of dominant common residuals. In that method it is assumed that the introduction of one road safety measure makes another measure entirely ineffective.

Another way of dealing with the combined effects is to simply summarize the effects and then use a multiplying factor lower than 1 in order to compensate for the correlation (Swedish Road Administration 2008). Furthermore, even if a valid and reliable number of casualties could be foreseen, it is still just a number and insufficient to describe qualitatively and to identify safety gaps.

The other challenge to predicting a final outcome from the combination of several improvements is the fact that there is not always a linear relationship between the development of an SPI in traffic and the final outcome. In-depth studies from fatal

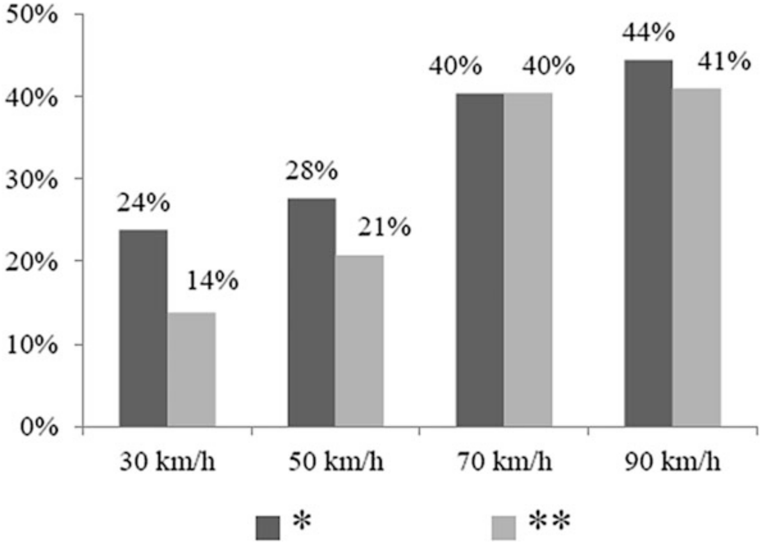


Fig. 5 System effects illustrated by comparison of mean risk for fatal or impairing injuries in one and two star cars Euro NCAP rated in different speed limits. (Source Strandroth et al. (2011))

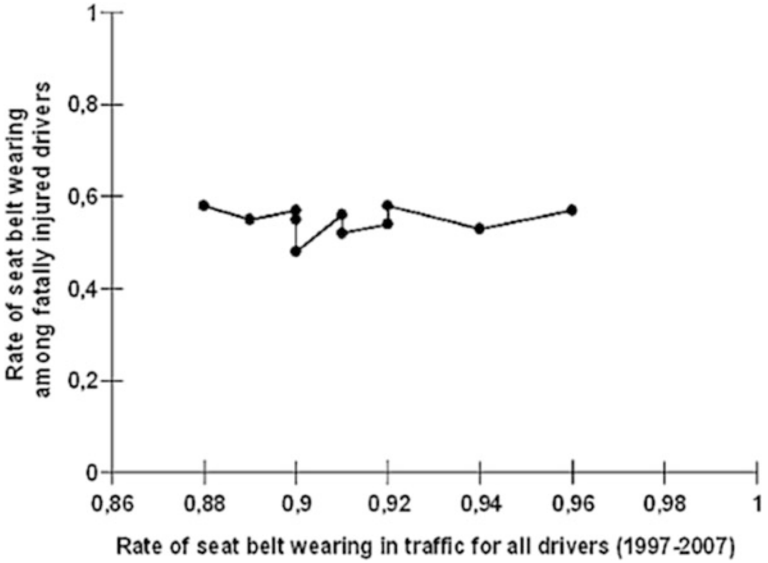


Fig. 6 Rate of seat belt wearing in traffic for all passenger car drivers vs. seat belt wearing for fatally injured drivers, from 1997 to 2007. (Source: Tingvall et al. (2010))

crashes combined with measurement on a whole population indicate that an increase of a safety factor among the whole population might not lead to an improvement in the final outcome. Tingvall et al. (2010) relate this to the fact that the improvement could address another part of the population than the one involved in severe crashes. Figure 6 shows an example where the increase in seat belt rate for all drivers does not increase the seat belt rate in fatal crashes.

Another explanation for the nonlinearity could be the slow turnover of vehicles in a vehicle fleet, and that the distribution of vehicle mileage over vehicle age is not linear with the proportion of fatal and severe crashes. Figure 7 shows that when a cohort of cars has driven 80% of their lifetime mileage, they have only been involved in 50% of their fatal and severe crashes (STA 2012c). Hence, older cars are in general over-represented in severe crashes, and as new safety technologies penetrate the market it could take many years before the technologies reach the target population. Often this nonlinearity is ignored in benefit assessments.

An Analytical Approach in Vision Zero Planning and Target Setting

To overcome issues with nonlinearity, double counting and invalid old crash data, Strandroth et al. (2015) suggested a new approach to understand the future impact of road safety interventions by combining knowledge from system improvements with in-depth crash data. Figure 8 gives a basic overview of the analytical approach in Vision Zero planning. While each step is described separately, please see Strandroth (2015a) for further reading.

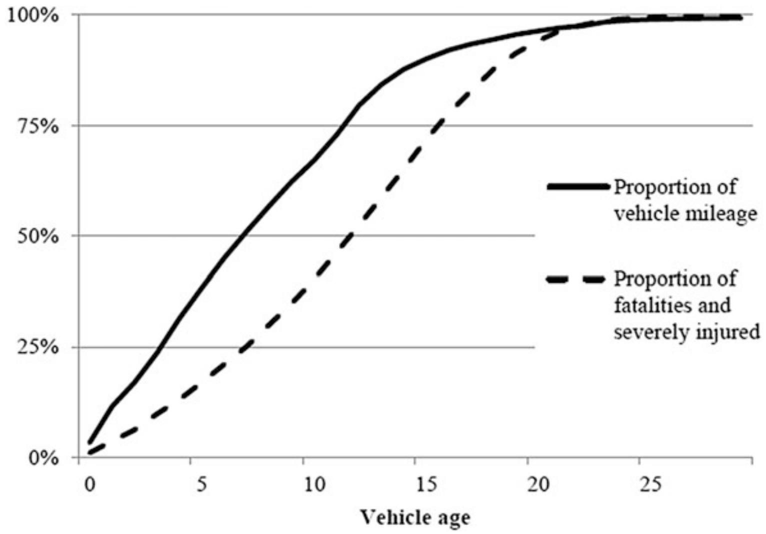


Fig. 7 Accumulated passenger car mileage and involvement in fatal and severe crashes over passenger car age. (Source: STA (2012c))

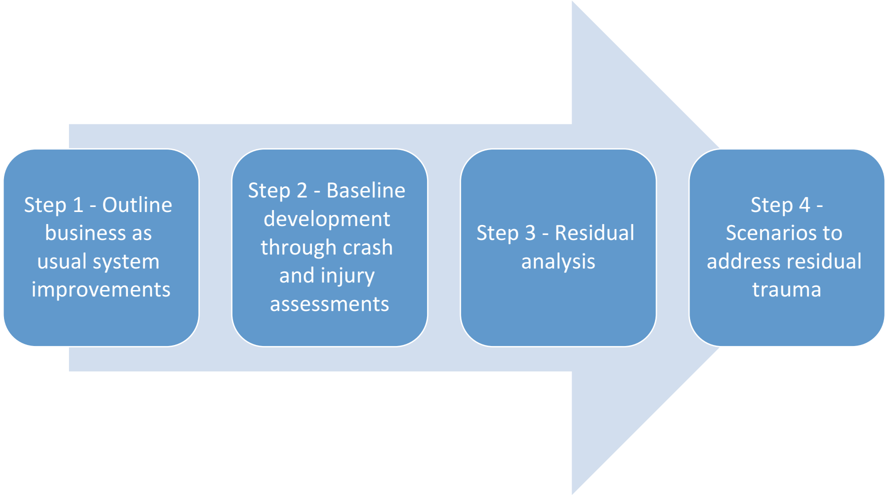


Fig. 8 Basic overview of the analytical approach in Vision Zero planning

Step 1: Outline Business as Usual System Improvements

The first three steps are about developing a baseline business as usual scenario which aims to illustrate a baseline development of fatalities and injuries. In this context, a baseline can be defined as the projection of today's fatalities and current risk levels affected by already planned system improvements. This includes infrastructure treatments in the current delivery pipeline but also vehicle safety improvements due to vehicle fleet turnover. It could also be more general factors such as travel speed changes or changes in general deterrence levels.

To consider the future impact of the baseline safety improvements, they all need associated business rules around implementation timeline, target crash pools, and effectiveness. Business rules are essential to make the modeling repeatable and scientifically sound. They cover in detail which crashes, involving who and in which situations that would be prevented by certain treatments. The business rules also need to capture every inclusion and exclusion criterion in the target crash pools, that is, extreme violations, excessive speeding.

Crash data format and quality would determine the method of modeling. In-depth crash data enables case-by-case analysis of crashes that allows detailed understanding and engagement and deals with double counting when estimating future treatment effectiveness. However, the resource intensity of case-by-case analysis limits the number of crashes that can be modeled to hundreds instead of thousands in contrast to a statistical approach using mass data. In reality, it is rarely the case that in-depth analysis of thousands of crashes is needed to understand the systematic risks in a jurisdiction, why a random sample could be selected for this specific purpose. However, in some cases, such as when analyzing big data, a similar structural model, however with a statistical approach, could be used in the analysis of serious injuries which are vast in numbers. For further reading see Strandroth et al. (2016).

Independent of the crash data format, information on the roads, vehicles, and people involved in the crashes must be linked to unit-records on the same level of detail as the crash data as well as future treatments with their associated business rules and the target years. The greater the quality of this meta-data, the more transparent and repeatable is the method.

Step 2: Baseline Development Through Crash and Injury Assessment

Crash and injury assessment by application of business rules to crash data would be different between mass data and case-by-case data. In a case-by-case analysis, every crash needs to be carefully examined to understand whether the crash outcome would be the same in a future target year given future system improvements. Each fatality is assessed according to the business rules to decide whether it is likely to be prevented or not in a specific year. Firstly, the prevailing crash type associated with each fatality is considered against the target crash pools to identify relevant treatments and vehicle safety systems. Secondly, the effectiveness business rules is applied to see whether the crash circumstances are such that the fatality would be expected to be prevented or not. Finally, implementation time is taken into account to understand in what year the fatality is expected to be prevented (if relevant). If the fatality is considered to be prevented by any of the agreed road safety improvement measures, it can be removed from the residual.

As an example case, let us assume that a passenger car with model year (MY) 2007 was involved in a single vehicle loss-of-control scenario in 2018. The crash occurred on a main national road with median barriers but without roadside barriers. When leaving the lane on the right side of the road, the driver over-corrected, lost control, and rolled over resulting in the driver being killed. The crash would sort into the target crash pool relevant to ESC, roadside ATLM, and road-side barriers. In this case we assume the circumstances do not exclude the crash from the effective envelope of ESC and barriers; however, ATLM where not assumed to be effective. The car was not equipped with ESC which, in this hypothetical example, became standard in this region of the world in 2012. Based on the five-year difference between 2007 and 2012 the crash would be expected to be prevented five years after the original crash in 2018, thus prevented and removed from the residual in 2023. In this way, not only the age of the vehicle fleet is taken into account when projecting the benefit of fleet renewal but more importantly the age of each vehicle involved in fatal crashes. This process is then repeated if the crash belongs to more than one crash pool to understand what else might have prevented the fatality. In this hypothetical case, there are no specific projects planned on this road but since it is a main national road it is expected to be fitted with barriers to 2030. In summary, ESC and the fitment of roadside barriers are expected to prevent the crash in 2023 and 2030, respectively. However, every crash is only removed once from the residual to avoid double counting of treatment benefits. Thus, this particular crash would be removed from the residual only once in 2023.

After the initial application of system improvements, general improvements that are not necessarily associated with individual crash pools can be applied (e.g., travel speed changes, enforcement elasticities). One has to be careful though not to add general factors to the degree that they represent the majority of future benefits as issues with double counting might come to effect. And in some cases, also general improvement could be associated with specific crash pools to avoid double counting. That is the case for example with crashworthiness which is a more general improvement over time while at the same time specific to only car occupant injuries. External factors like risk exposure increase due to population growth or demographic changes could also be included at this stage.

Step 3: Residual Analysis

Following the establishment of a baseline, not only is it possible to estimate the level of future residual trauma but also to investigate the characteristics of this trauma. As previously mentioned, typical questions are: How close to zero will our current strategies take us? What are the characteristics of crashes and injuries remaining in the future when all the treatments in our current toolbox are implemented and what further innovations are needed to ultimately eliminate road trauma? Other questions might be: Are interim targets estimated to be achieved? What road users are favored in the delivery of safety improvements under the “business as usual” scenario? When and where will the majority of trauma reduction benefits from safer and more advanced vehicles be realized?

The investigation of future residuals can then guide the development of future treatments and interventions to close the gap between the baseline and future targets, both near-term and long-term. Of particular interest is to understand why future crashes are estimated to not be prevented. In this context, at least three basic reasons can be mentioned. First, residual due to implementation delays – when the relevant interventions exist but are not implemented in time. Naturally this residual would be diminishing over time. Second, residual being outside the effective envelope – when relevant treatments exist and are expected to be implemented in time, but the circumstances of the crash are such that the injury outcome are not avoided or mitigated sufficiently. Third, there is no relevant intervention – when there is no intervention in the pipeline (or maybe none at all) to address the crash outcome.

Step 4: Scenarios to Address Residual Trauma

As described in Steps 1–3, a logical reduction of future trauma based on the implementation of planned interventions can be used to make informed decisions on ambitious, achievable, and empirically derived interim targets. The natural next step is to recognize potential for additional improvements and trauma reductions by comparing the baseline with scenarios based on the implementation of additional countermeasure. Alternatively, the benefits of a more rapid implementation of treatments could be investigated as the example in Fig. 9 which illustrates the benefit of a more rapid uptake of vehicle safety technology. Normally in road safety

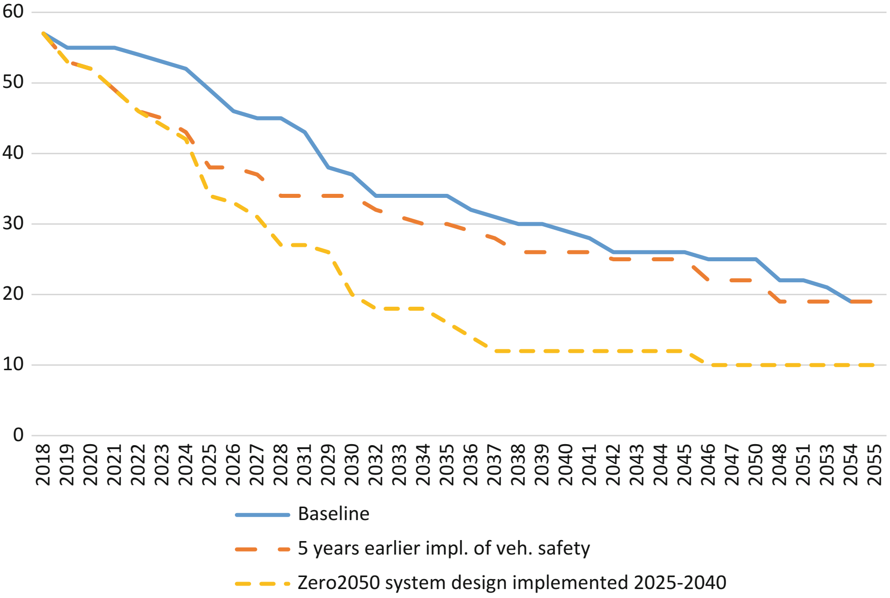


Fig. 9 An example of different scenarios

management and strategy development it is seldom valuable to reflect on the single impact of one intervention. Instead, the combined benefits of several interventions are of interest when interim road safety targets are to be set. The third line in Fig. 9 illustrates the combined effect of accelerated implementation of vehicle safety and increased efforts in infrastructure improvements.

The last but not least important step in this approach in the method would involve using the baseline modeling to develop Safety Performance Indicators and associated targets to enable system transformation monitoring. For further reading please see STA (2012b).

Methodological Considerations

One relevant question is whether prediction models in general should aim for a higher complexity by including as many variables as possible in order to reflect reality in the best possible way. Or, if methods to describe the future should be kept simple to preserve transparency and repeatability. Of course, it could always be argued that the more variables that are included in a model, the closer the model will represent real life. However, if more and more variables are included it could become harder to establish the causal relationship needed to understand the output of the model.

For instance, Broughton et al. (2000) states that even if statistical forecasting can be a powerful tool it has some weaknesses and often the modelers have no theory to guide their choice of model. Therefore, the current practice is to use a few alternative ones and choose the one that fits the existing data best. With no theory to guide the choice of model, functions could be formatted poorly and be problematic such as having correlated independent variables or induce nonexistent correlations (Hauer 2005). The challenge relating to multivariate models is that they are either additive or multiplicative. However, it has been shown in Strandroth (2015a) and in previous research that SPIs are not only additive or multiplicative. When simply added together, double counting becomes an issue, and with a multiplicative approach it is ignored that SPIs can also be conditional (where the effect of one improvement is dependent on another). Hence, when dealing with combined interventions, a deterministic logic approach is preferable as it could be more transparent and able to tackle double counting and conditional improvements, even though it is hard to image any method that would completely eliminate these issues.

Summary and Key Messages

Road safety analysis is an essential element in Vision Zero planning practices as it is used to provide guidance on what has been successful in treating past trauma problems, how to treat current risks in the road transport system and how to design a future safe system. As with all analytics, road safety analysis is reliant on good quality data in order to provide valid and reliable guidance. However, more data is not always the solution and data quantity should never be seen as a substitute of quality. On the contrary, small datasets can be very valuable if analyzed with robust methods. This is especially the case when sample sizes would naturally decrease due to road safety interventions (i.e., close to zero). The closer to zero we get, the more important is the analysis of outliers and nonconformities. And this type of quality management of the road transport system is only possible with in-depth data.

Defining future interventions and strategies in an accurate way requires in-depth knowledge of crashes and injuries, robust methods, and clear hypotheses. In order to design a Safe System, it is essential to understand the effective envelope of system interventions, that is, which crashes and injuries are prevented, what is not prevented and why. From an analytical prospective this requires a clear hypothesis of the cause and effect and not only correlation. And when selecting possible confounders, it is important that they are based on a hypothesis, and not just invented. If included without any hypothesis, they may pick a variation that is not real. In other words, it is important to distinguish between possible correlation and causation.

Another aspect of understanding the benefits of future interventions is that the road system is constantly changing, affected by everyday improvements like the renewal of the vehicle fleet, hence making retrospective data unsuited to describe the problems ahead. Naturally, crash data will always be retrospective in nature. However, the validity of the crash data needs to be ensured by taking into account the evolution of the transport system when estimating benefits of future interventions.

Road safety analysis is also about providing an analytical framework for the vision to become tangible and implemented in the day-to-day operation of road safety stakeholders. Some basic analytical steps for Vision Zero target management are presented in this chapter as follows:

1. Outline a baseline scenario with "business-as-usual" safety improvements
2. Baseline development through crash and injury assessment
3. Analyze the residual to identify future safety gaps
4. Develop scenarios to address residual trauma, set ambitious but achievable trauma targets and define Safety Performance Indicators for system transformation and set their long term and interim targets

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Speed-Limits in Local Streets: Lessons from a 30 km/h Trial in Victoria, Australia

29

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Abstract

Fatal and Severe Injuries (FSI) to vulnerable road users is a major road safety problem internationally. Recent resolutions by the Global Ministerial Conference on Road Safety called for a blanket 30 km/h speed limit in urban areas to address this problem. A project undertaken in Melbourne, Australia, set out to evaluate the effectiveness and benefits of a lower speed limit in a local residential area in the City of Yarra. The intervention comprised replacing 40 km/h speed limit signs in the treated area with 30 km/h signs with an adjacent untreated control area. A before and after study was employed with speed, resident surveys, and estimated safety benefits as measures of its success. Modest reductions in mean speed were observed in the after-phase of the study while benefits were impressive for vehicles travelling at higher speed levels where the risk of severe injury or death is greater. These findings represent an estimated 4% reduction in the risk of severe injury for pedestrians in the event of a collision. Questionnaire responses showed an increased degree of support for the 30 km/h speed limit in local streets in the trial area. The implication of these findings for road safety is discussed, along with the challenges and potential hurdles. Lower speed limits in local streets and municipalities is one important measure to help address vulnerable road users in residential local streets.

Keywords

Road safety · Speed limits · Local streets · Vulnerable road users · Severe Injury

Introduction

Lowering speed limits in local streets addresses two of the five pillars on which the Global Plan for the United Nations (UN) Decade of Action for Road Safety is founded. These are Pillar 1 – building road safety management capacity; and Pillar 4 – safer road user behavior and the issue of speed control (WHO 2005). The UN also note the importance of speed management as a key element in adopting a safe system approach to road safety. Other publications by WHO (2004), Corben et al. (2006), and TAC (2018) identify speed as a key risk factor in road traffic collisions, with pedestrians and cyclists at increased risk of a severe or fatal injury given a road crash.

Vehicle speeds in residential areas has long been associated with the risk of a serious injury and death to Vulnerable Road Users (VRU) specifically pedestrians and cyclists. There is a breadth of literature describing the relationship between the risk of injury and vehicle speed (e.g., Davis 2001; Rosen et al. 2011; Logan et al. 2019). Figure 1 shows an example of this relationship.

The World Health Organization (2018) recently reported that the number of traffic deaths reached a high of 1.35 million in 2016 and that globally, more than half of

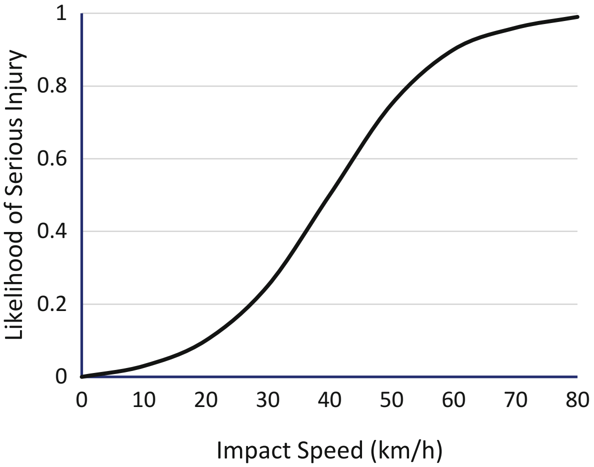

Fig. 1 Severe injury risk curve for pedestrians. (Source: Logan et al. (2019))

these were among pedestrians, cyclists, and motorcyclists (Vulnerable Road Users). They further pointed out that road traffic injuries are the leading cause of death among children and young adults, aged 5–29 years. The Transport Accident Commission of Victoria, the statutory insurer of personal liability for road accidents in this state, further reported that from 2009 to 2018, more than 400 pedestrians lost their lives on Victorian roads of which one third of those were aged 70 years or older, and that most died in the metropolitan area of Melbourne (TAC Victoria 2018).

Speed Limits in Local Urban Streets

A 30 km/h (20 mph) speed limit is commonly adopted in many European, UK, and USA municipalities, given these are predominant residential precincts. ETSC (2015) noted that many European countries such as Austria, Brussels, France, Germany, Italy, Netherlands, Spain, Sweden, and Switzerland have implemented 30 km/h speed zones in many of their regions. In addition, several states in the USA such as New York, Wisconsin, Oregon, and Boston, too, have also implemented 20 mph limits on low volume local streets, work zones, and schools (Small 2019). Finally, Auckland city in New Zealand, also recently announced they had cut speed limits in the CBD to 30 and 40 km/h on other major roads (NZ Herald 2019). These countries have recognized the safety benefits of lower speed limits in urban areas with frequent and planned interactions between VRU and cars.

Global Mandate for 30 km/h Speed Limits

Global Ministerial Conference

In February 2020, the third Global Ministerial Conference on Road Safety was held in Stockholm, Sweden, and one outcome of the conference was the release of a formal statement related to road safety objectives up until 2030 (Trafikverket 2020).

The report from this meeting proposes a vision for the evolution of road safety and recommends a new target of 50% reduction in road deaths and serious injuries by 2030 based on expanded application of the five pillars, adoption of Safe System principles, and integration of road safety among Sustainable Development Goals.

A set of ***nine*** recommendations were proposed from the meeting to realize the vision over the coming decade. One resolution of this declaration (Recommendation 8) was for countries to mandate a maximum road travel speed of 30 km/h in urban areas where there is a mix of vulnerable road users and vehicles. It noted that a speed limit in urban areas commensurate with this maximum travel speed was necessary to prevent serious injuries and deaths to vulnerable people when human errors occur.

A Safe System Approach

The Safe System methodology has become a preferred philosophical approach to achieving greater improvements in road safety around the world. It calls for the adoption of a systemic view of road safety involving safe vehicles, safe human behavior, safe roads and road infrastructure, and importantly, safe speeds, when examining road safety improvements.

It is no longer acceptable to simply blame the driver as the main cause of road crashes, but rather one element in a much wider view of causal factors in road crashes. While crashes will inevitably continue to occur, it is important that the kinetic energy imparted to the car occupants in a crash should be less than what they are able to tolerate resulting in severe injury or death.

Tingvall and Haworth (1999) first listed these values dependent of the type of collision, vehicle design, and full use of the vehicle's restraint system. Mooren et al. (2014) subsequently published these figures dependent on the type of infrastructure and traffic as shown in Table 1.

Many countries including Australia and New Zealand have adopted these values when setting speed limits in urban and rural settings. Unfortunately, the degree to which they are adhered to is variable across various states and territories. An OECD guidance document on the Safe System approach emphasizes the need for very low speed limits – no greater than 30 km/h – where conflicts with pedestrians are possible (OECD 2008).

Table 1 Safe System maximum vehicle speeds. (Source: Mooren et al. (2014))

Type of infrastructure & traffic	Possible traffic speed (km/h)
Locations with possible conflicts between pedestrians and cars	30
Intersections with possible side impacts between cars	50
Roads with possible frontal impacts between cars	70
Roads with no possibility of a side or frontal impact (only impact with the infrastructure)	100+

The Benefits of Lower Speed Zones

Grundy et al. (2009) set out to estimate the benefit of 20 mph (32 km/h) traffic speed zones on traffic collisions, injuries, and fatalities in London, using an observational study of geographically coded police data on road casualties between 1986 and 2006. They examined changes in road casualties, estimating the effect of introducing 20 mph zones on casualties on a range of existing speed zones, based on these crashes.

They reported that the introduction of 20 mph speed limits was associated with a 42% reduction in casualties, when accounting for changes in casualty rates on adjacent roads. They also reported that reductions were greater for young children and the elderly, and for the more serious injury outcomes. They concluded that 20 mph speed zones would be effective measures for reducing serious injuries and death among pedestrians involved in car crashes.

Ingamells and Raffle (2012) and Steeve Davies Gleeve (2014) further claimed that a 20 mph speed limit is the right policy on the grounds of safety, sociability, and ensuring a healthy population. While the focus of this Chapter is on the safety benefits in terms of fewer fatal and severe injuries, they noted other benefits for the residents include street calmness, incentives for more walking and cycling, reduced pollution and noise, improved mobility and independence, and physical and mental wellness.

20s Plenty for Us

The "*20s Plenty for Us*" in the United Kingdom is a non-profit organization formed in the UK early this century by Rod King MBE, Founder and Campaign Director. He noted that the objective of the campaign is for 20 mph (32 km/h) to become the default speed limit on residential and urban streets in the UK. Goodyear (2015) reported that by 2015, there were more than 15 million people in the United Kingdom living in communities where the speed limit is 20 mph (a figure of around 23% of the UK population). Goodyear claimed that this was achieved without the need for any additional physical calming on most streets while allowing for some streets to have a higher limit on particular roads when justified. She stressed, however, that any limit above 20 mph should only be after a considered decision based on local circumstances.

The Nottingham City Council is a member of the *"20's Plenty for Us"* program. In 2012, the Council conducted a survey of its residents in Sherwood (of Robin Hood fame) and found that 63% of respondents supported the introduction of a 20 mph (32 km/h) speed limit on their street and 52% of them would like to see 20 mph speed limits extended to other parts of the City. From a before-and-after trial of lower speed limits on local streets in Sherwood, they found a speed reduction of 1.0 mph (1.6 km/h) average speed in the trial region with a 3.0 mph (4.8 km/h) reduction in the 85th percentile speed limit. They claimed these reductions include reductions in crashes and injuries to VRU, in these streets (Fildes et al. 2017).

Community Acceptance

The Global Road Safety Partnership (Silcock et al. 2008) noted that crash risk for Vulnerable Road Users is a special problem in most countries that warrants special attention. In setting local speed limits, however, they claimed it is important to know what the public is likely to accept first before committing to lower speed limits. They stress the need for community surveys to be undertaken to indicate the level of public support for these lower limits.

More recently, the ETSC (2015) pointed out that opinion polls in several countries have repeatedly shown majority public support for lower speed limits in urban areas. In a response to the EU's Urban Mobility Package last year, they called on the EU to encourage all member states to adopt speed limits of maximum 30 km/h in residential areas and zones where there are large numbers of VRUs.

Speed Limits in Urban Victoria

The current default urban speed limit in Victoria, Australia, is 50 km/h (31.3 mph) although speed limits on major urban arterial roads are typically posted up to 60 km/h (37.5 mph). On heavily congested roads and in school zones, though, limits have also dropped to 40 km/h (25 mph).

Among other Local Government Areas in the state, the City of Yarra, an inner urban Local Government Authority in Melbourne, recently adopted a blanket speed limit on local roads across its municipality of 40 km/h (25 mph) as part of its commitment to the Towards Zero program, widely adopted in Australasia. We understand that while there have been a few examples of the introduction of 30 km/h speed limits in select regions in Australia with a high mix of vulnerable road users and vehicles, none of these have ever been evaluated in terms of their safety benefits (Fig. 2).

Fig. 2 Typical streetscape in Fitzroy municipality in the City of Yarra

The City of Yarra

The City of Yarra is an inner urban metropolitan municipality in Melbourne, Victoria, Australia. It has a population of around 100,000 residents over 2000 ha and includes 12 inner suburbs. It is located on the fringe of the Central Melbourne Business District and is one of the older Melbourne metropolitan municipalities. Its age profile shows it is over-represented in young (<20 years) residents and those aged more than 30 years. It also has twice the proportion of older (65+ years) residents than the rest of Victoria. Given its location adjacent and within comfortable cycling and walking distance to the CBD, it typically has a high number of pedestrians and cyclists, and Council is concerned that 40 km/h is too fast in its residential areas (Fildes et al. 2017).

The 30 km/h Trial

Motivation Behind Trial

The City of Yarra Council is motivated to enhance the safety of vulnerable road users and move toward their vision of zero travel-related deaths and serious injuries within the municipality. The trial was seen as an opportunity to offer a demonstration of the challenges and benefits of lowering speed limits in an urban setting without substantive changes to the road infrastructure, as they relate to speed and community acceptance. It was also seen as an avenue to raise public awareness of the relationship between speed, safety, and local amenity. Public awareness campaigns were not limited to the community within the trial area but communicated throughout the whole municipality.

Key decisions related to the trial were passed through formally constituted Council meetings, and this included identifying an area within the municipality that would be amenable to a trial. A key consideration here was to identify an area without planned modifications to the road or built environment that would meaningfully show the trial outcomes. Moreover, it was also an area that was modest in size with demarcated clear boundaries. It is important to note that the trial area was not identified based on classic road safety selection criteria, such as addressing a poor crash history or speeding concern.

Two adjacent traffic management zones (or local area places) in the suburbs of Fitzroy and Collingwood were identified as candidates, and these were combined as the trial area. Two additional adjacent traffic management zones in the same suburbs were endorsed as a control area, for the purpose of providing exposure measures for observations made in the trial area.

Study Methodology

Study Design

In June 2017, the council approached the Monash University Accident Research Centre (MUARC) to assist in implementing a 30 km/h trial in a selected region of

Fig. 3 Regions selected for the treated and untreated regions in the City of Yarra trial

Fitzroy and Collingwood with an associated untreated adjacent control region. MUARC's role was also to oversee the implementation of the trial and evaluate the outcome from a safety perspective.

The study design aimed to assess differences in travel speed before and after implementation of the 30 km/h speed limit with an adjacent untreated control region still set at 40 km/h. Figure 3 shows the area in the City of Yarra selected for the lower speed limit trial. The trial ran for 12 months from September 2018.

Speed Observations

Speeds were measured from 91 sites located across both the treated and untreated regions covering both collector and one-way streets and cul-de-sacs. Speed data were collected 24/7 across both weekdays and weekends using road tubes installed at specified sites by contracted traffic surveyors.

Attitudes

It was also important to assess residents' attitudes to these changes as a measure of likely acceptability. Two online community surveys were conducted during the before and after phases. Invitations were mailed to a random selection of property addresses in the treatment area ($n = 2000$) and in the non-treatment area ($n = 2000$). The approach was the same for the baseline and the 12-month after samples. The questionnaire comprised 24 questions focused on their demographics, a range of questions related to their attitudes to the trial, and other associated local issues. Respondents were asked to complete an online questionnaire and sampling rates were 484 (24%) at baseline and 548 (27%) on completion of the trial.

Safety

Given the size of the trial, it was not possible to expect enough data on crashes that occurred during the study period. However, it was possible to compute the likely injury benefits in terms of Killed and Severe Injuries (KSI) from the observed speed changes, both before and after the trial. In addition, the speed distributions for those travelling above the speed limits before and after the trial as well as those travelling above the Safe System recommended speed categories.

The Findings

Speed Reductions

Average Speed

The average and 85th percentile speeds observed before and after the 30 km/h trial in the treated and untreated (control) locations are shown in Table 2 below.

The average and 85th percentile speed reductions were modest in both regions (median values were similar to the mean values and trends). The reductions in speeds in the control regions were unexpected, and interpreted as a carry-over effect, given that the control region was immediately adjacent and marketing for the trial did not clearly separate the two regions. Nevertheless, it did have a negative impact for the analysis, discussed further below.

Speed Categories

Importantly though were the speed findings above the speed limit, shown in Table 3. The three values were chosen based on the speed limit and Safe System values for these localities. The average percent speed reductions for the three-selected speed categories shows significant larger speed reductions for the 40 and 50 km/h

Table 2 Mean and 85th percentile speed, before and after the 30 km/h trial

Measures	Before (km/h)	After (km/h)	Reduction (%)
Treated – average speed	27.6	27.3	−1.1
Treated – 85thile speed	36.0	35.0	−2.8
Control – average speed	29.4	28.6	−2.7
Control – 85thile speed	38.0	37.0	−2.6

Table 3 Observations exceeding speed categories, before and after the 30 km/h trial

Measures	Before (%)	After (%)	Reduction (%)
Treated – 30 km/h	36.71	34.42	6.24
Treated – 40 km/h	5.38	3.89	27.73
Treated – 50 km/h	0.41	0.25	38.69
Control – 30 km/h	46.76	42.68	8.72
Control – 40 km/h	7.95	6.43	19.15
Control – 50 km/h	0.63	0.51	18.44

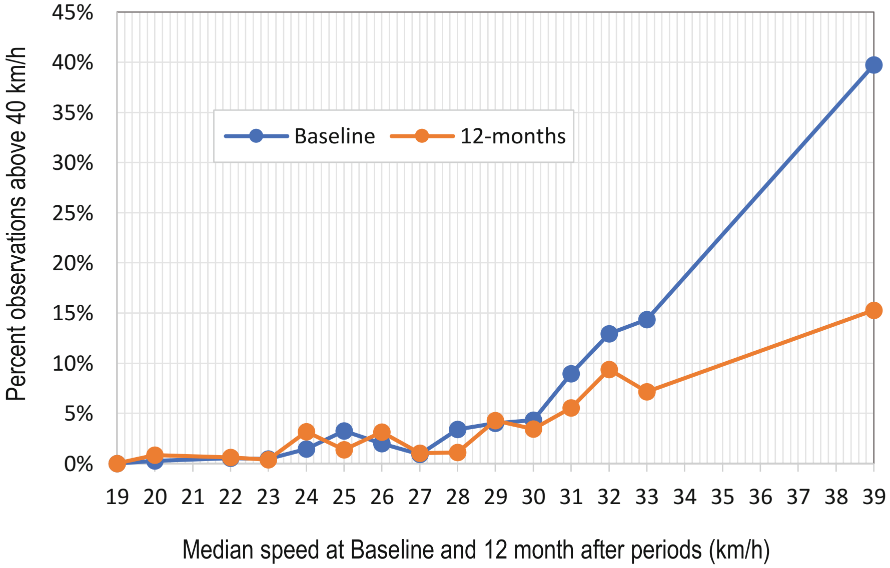

Fig. 4 Percent exceeding 40 km/h by mean speed at baseline

categories at the treated sites and at the controls. These equate to significant reductions in the likelihood of severe injury at the treated sites with the 30 km/h speed limit, compared with the untreated control sites.

Speed Trends: Before and After

The relationship between the median speed at baseline and at 12 months by speed category is a further indicator of speed changes at the various sites and/or traffic conditions where the lower speed limit had its greatest impact. Figure 4 shows the percent of observations at the treated sites exceeding 40 km/h before and after treatment. As the mean speed increased, the percent of observations also increased but noticeably less after the treatment than before. It further confirms that the speed attributed to the lower speed limit had its greater impact on sites with higher initial speeds.

Table 4 Overall treatment effect of the 30 km/h trial in speed reduction benefits

Measure	Odds ratio	CI (95%)		Significance
Exceeding 30 km/h	1.07	–	–	$P > 0.05$
Exceeding 40 km/h	0.89(−11%)	0.87	0.92	$P < 0.001$
Exceeding 50 km/h	0.75(−25%)	0.67	0.84	$P < 0.001$

Treatment Effect

The final speed analysis assessed the overall "treatment effect" of the trial used a modelling approach that adjusted for the difference between the treated and control speed reductions, that is, what was the real effect of the 30 km/h trial (see Table 4). The treatment effect was assessed against the odds of a speed observation exceeding 30, 40, and 50 km/h, in the treatment area, minus the reductions observed at the control sites.

Thus, the real treatment effect of the 30 km/h trial after adjustment was a reduction in the odds of a vehicle speed exceeding 40 km/h by around 11% and exceeding 50 km/h by 25% in the after phase. The treatment was found to not reduce the odds of a speed observation exceeding 30 km/h.

Thus, it can be concluded that the expected overall benefit of the City of Yarra 30 km/h trial in terms of speed reductions was achieved. While there was little difference in average speed before and after the trial, the main benefits were among the higher speeders where greater benefits in terms of fewer severe injuries were likely in a crash.

Community Survey

The community survey key question asked during the trial was whether the respondent would support the introduction of a 30 km/h speed limit on the street in which I live/work/own in the City of Yarra (Lawrence et al. 2017). Their responses to this question are shown in Fig. 5.

Interestingly, the yes responses to that question went from 42.7% before to 50.3% after, that is, an 18% increase in support for the trial and an associated decrease in non-support. While many of the other question responses showed little difference before and after, there was an increase in support of 10% that the reduced speed limit will not impact on travel time, another 4% that it will be safer for children and the elderly, and 3% that lower speed limits will reduce injury severity in a crash.

Safety Benefits

The final analysis was to estimate what the likely percent reduction in severe injuries would be given the speed reductions above. This estimate was based on modelling the association between the speed reductions of the treatment effect, given the severe injury risk curve for pedestrians, shown earlier. The modelling approach is illustrated in Fig. 6 below.

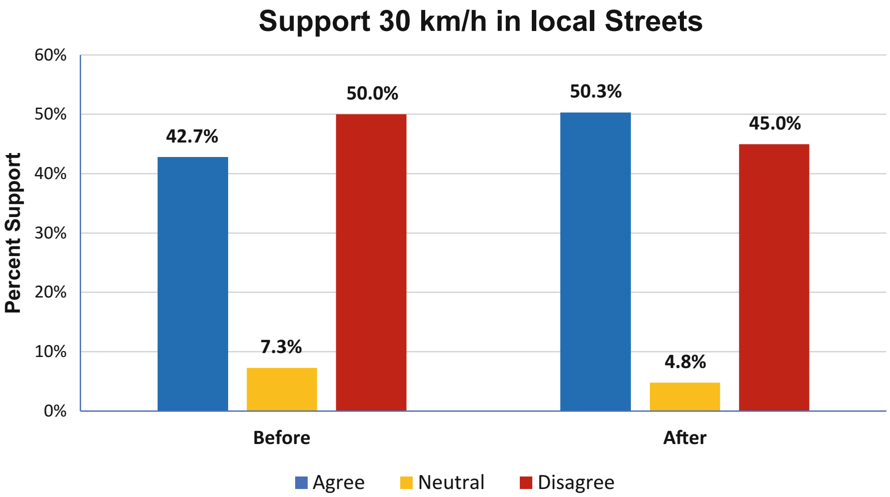

Fig. 5 Residents' support for a 30 km/h speed limit where they lived, worked, or owned

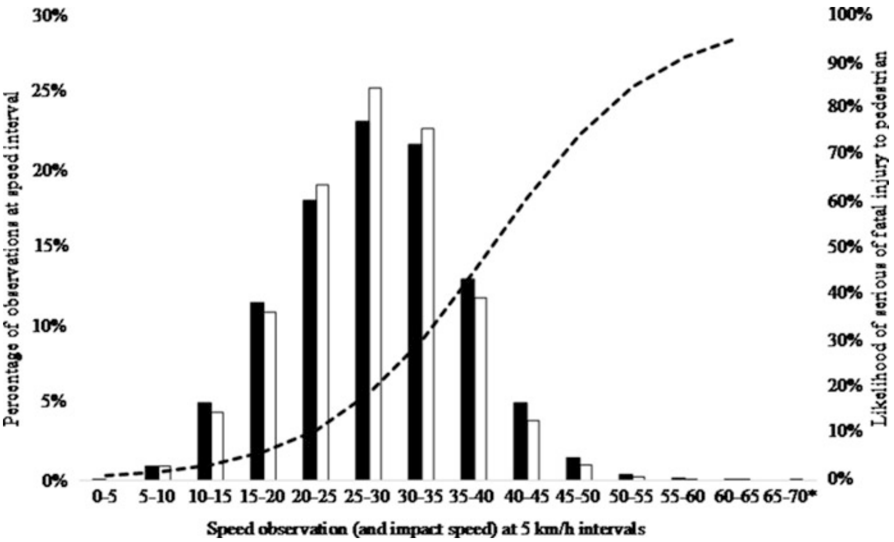

Fig. 6 Crash distributions before and after by the injury risk curve shown earlier in Fig. 1

The potential injury savings from the 30 km/h speed-limit trial over the previous 40 km/h speed-limit, were estimated by identifying the difference in the relative risk of injury, before and after the intervention, using the Davis (2001) risk curve.

The findings showed that the risk of sustaining a serious or fatal injury, given collision involvement, reduced from 24% before, to 23% after treatment. This represents a 4% reduction in the risk of sustaining a severe injury, should a collision occur between a motor-vehicle and a pedestrian. While this might sound like a relatively small improvement, it does represent a sizeable number of vehicles (between 200,000 and 300,000 annually) that will travel at excessive speeds likely to cause severe injuries to vulnerable road users. This analysis does not account for any reductions in the risk of a collision on account of the reduced speed, although this may also occur due to the lower speed limit (WHO 2004).

Crash Reductions

The risk of having or not having a collision given the speed reductions noted above was beyond the scope of this trial. Nevertheless, there are physical relationships between speed and the distance it takes to stop, reported in studies by Anderson et al. (1997) and Corben et al. (2006). Factors that affect stopping distance include initial travel speed, driver reaction time, braking capability of the vehicle, and the coefficient of friction between the tyres and the road surface. Corben et al. (2006) estimated that for a reduced travel speed from 40 to 30 km/h, the stopping distance reduces from 22 to 15 m (a 32% reduction), leading to a potential added saving in injury from total preventing the crash thereby adding additional safety benefits from those noted above (Fig. 7).

Summary of Results

In summary, there were modest reductions in average and 85th percentile speeds in both the trial and control areas, although larger reductions were observed at higher

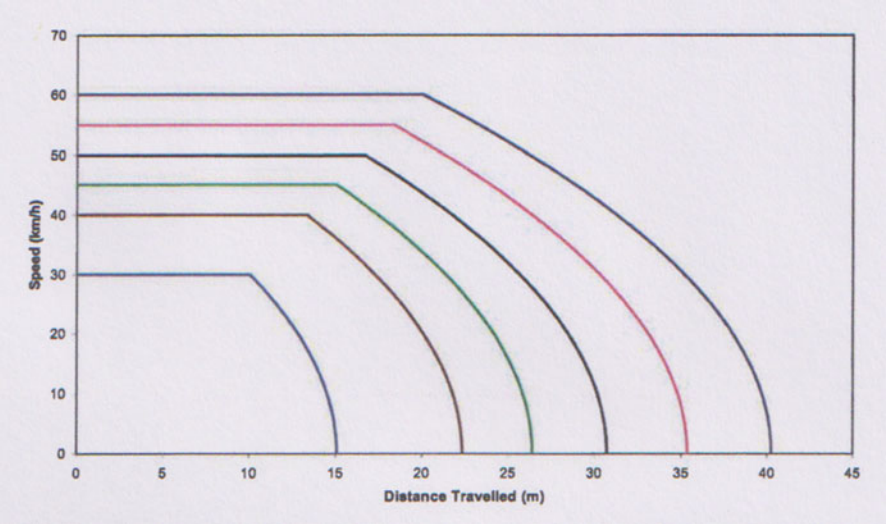

Fig. 7 Stopping distance by travel speed (Corben et al. 2006)

speed levels above 40 and 50 km/h in both regions. After adjusting the trial findings for the unexpected speed differences in the control region, there was still a significantly "treatment effect" attributed to the 30 km/h trial with a 4% reduction in likelihood of a fatal and serious injury. These reductions are likely to led to a reduction in risk of a pedestrian and other VRUs sustaining a fatal or serious injury in a crash.

Residents' positive attitudes to a 30 km/h lower speed limit increased significantly by 17% at the conclusion of the trial with a sizeable reduction in opposition. There was also a 10% increase in the belief that the 30 km/h trial would have little effect on travel time in these local streets. Small increases were observed in the agreement that the 30 km/h speed limit was safer for children and elderly pedestrians and that lower speed limits are likely to reduce injury severity in a crash. No support was observed, however, for reducing the speed limits in the neighboring main feeder streets.

Implications from the Trial

As noted earlier, this was the first evaluated trial of a 30 km/h speed limit in a residential environment in Victoria, Australia. The trial was expected to achieve reductions in area-wide travel speeds and community acceptance, and this was observed after a 12-month introductory period, especially among the higher speeders in the region. A 4% reduction in the risk of a severe or fatal crash injuries to pedestrians and an increase in community acceptance were also anticipated. A 4% increase in safety for vulnerable road users in Victoria is a worthwhile improvement for pedestrians and bicyclists in residential areas and likely to help address their over-involvement in crashes in these regions.

The findings from the trial support previous published benefits on the effectiveness of adopting a lower 30 km/h speed limits in urban areas (Grundy et al. 2009; Fildes et al. 2017a) and in current best practice in many international countries. It is consistent also in line with the recent call from the Global Ministerial Conference on Road Safety for countries to mandate a maximum road travel speed of 30 km/h in urban areas where there is a mix of vulnerable road users (Trafikverket 2020). It also supports the recommendation from adopting a Safe System approach toward speeds in residential areas (Tingvall and Haworth 1999; Mooren et al. 2014).

It must be stressed though, that 30 km/h speed limits in local streets is not a particularly new finding internationally for protecting pedestrians and cyclists in residential areas. As noted earlier, 30 km/h (20 mph) speed limits are relatively common in areas with high volumes of vehicles and vulnerable road users in many countries around the world. The World Health Organization (2018) noted that Vulnerable Road Users (pedestrians, cyclists, and motorcyclists) are disproportionately impacted globally, accounting for half of all road deaths in 2018. Further, the Global Road Safety Partnership (GRSP 2008) pointed out that in some regions, speed limits on local urban streets need to consider a variety of functions in these regions (school zones, shopping precincts and purely residential areas) and that for some of these zones, limits as low as 20 km/h may be appropriate.

Enforcement

There was a deliberate decision taken at the outset of the City of Yarra trial not to compound the findings of the trial with any police enforcement effects. The Victorian police agreed to this request and while they oversaw the conduct of the study, did not perform any speed enforcement in the area. Thus, the findings reported above are purely based on the motorists' behavior. It is anticipated, though that with time, speed enforcement in the area will be needed to maintain the speed benefits observed.

The Nottingham police reported that, the 20 mph speed limit is enforceable in the Nottingham trial where the limit is clearly marked, and that offenders may be prosecuted. They noted that the primary infringement means is by using speed cameras in 20 mph zones. They claim that this technology is more important than the use of speed humps. Afukaar (2003), however, noted that while active enforcement (e.g., speed cameras and police presence) should be the primary "weapon" used against speeding motorists, supplementary engineering treatments such as rumble strips and speed humps are also effective for speed controls in low speed environments.

From an extensive inquiry conducted by the Auditor General of the Victorian Parliament following a review of the "*Arrive Alive*" camera enforcement program (VicParl. 2006), they concluded that the enforcement program had reduced speeding by up to 20% with no evidence that the program was focused on raising revenue. While most of the speeding reductions were focused on speeds above 60 km/h, they also reported there had been significant reductions in pedestrian trauma and severity of serious injuries during the program: measures sensitive to changes in lower travel speeds.

It is important when speed changes are introduced that it is accompanied with on-going speed enforcement, mass media, public education programs and possibly infrastructure improvements. The Transport Accident Commission stress the need for public acceptance, show the risk of detection is real and the use of the latest enforcement technologies (TAC 2020).

Speed Technology

In addition to police enforcement, there are other technologies available and under investigation to help address police enforcement. Intelligent Speed Adaptation devices can be fitted to vehicles that alert the driver to the fact that he/she is travelling above the speed limit, with and without pedal activation. In a study in Belgium by Vlassenroot et al. (2007), they found large differences between drivers using the technology. While there was evidence of some drivers slowing down and driving at the speed limit, others speeds even increases despite activation of the system. Frequent speeders tend to accelerate quickly up to the speed limit causing average speeds to increase.

Fig. 8 Photo of a Geofence bus trial in Sweden. (Source: Tom Stone (2018))

More recently in Sweden, Payne (2020) reported on a new concept for speed control where vehicle speeds are digitized. The technology is known as Geo-fencing and is currently undergoing city bus and truck trials in Sweden and Norway to evaluate its potential to end speeding in these countries. Using GPS or cellular technologies, the system creates a virtual fence around the vehicle that triggers a pre-programmed action, keeping vehicles under 30 km/h as it enters the trial area (Fig. 8). The author notes that geo-fencing "*has the potential to change the way traffic infrastructure is developed and how different vehicles use the roadway.*"

Finally, in future, Connected and Autonomous Vehicles (CAVs) in use are expected to sense the legalized speed limit in the area they travel at by software using either sign-recognition or GPS interaction and then maintain the appropriate speed autonomously, ensuring the vehicle does not exceed beyond the legal speed for the region. These vehicles are still some time away from widespread use but may well be the ultimate solution, taking the choice of what speed to travel at away from the human occupants of the vehicle.

Challenges and Potential Hurdles

Community Acceptance

As noted above, there is considerable evidence showing that lowering a posted speed limit will increase safety and decrease the number of crashes (Afukaar 2003; WHO 2004; VicParl 2006;). Nevertheless, the greatest challenge in introducing a new (lower) speed limit is always gaining community acceptance of any such change.

As pointed out by Mooren et al. (2014) and others (Lahausse et al. 2009; McGuffie and Span 2009; Soole et al. 2013), part of the problem for governments when introducing safe speed limits is the amount of vocal opposition to lowering the limits. Typically, there is always enthusiasm (positive and negative) when new safety measures are introduced, but it is likely to take significant effort over a long period of time to ensure it becomes commonplace in local streets.

When mandatory wearing of seat belts was first introduced in Australia in the 1970s, more than 90% wearing rates were achieved quickly and maintained through ongoing speed enforcement. Ultimately, behavioral change occurred from early and continual enforcement (Robinson 2011) as well as in marketing programs over a constant prolonged period.

Government Support

Government support is also important which sometimes is not always forthcoming for changing speed limits, given the potential political consequences. Svensson et al. (2013), for instance, noted that in most European countries, the process of setting and implementing speed limits is often delegated to local and regional administrators. They examined the perspectives and priorities of administrators and elected officials in setting speed limits and identified two groups with different philosophies, namely, (i) those who support a mobility perspective (e.g., traffic planners for example), and (ii) those who share a traffic safety perspective (e.g., committed to improve traffic safety through lower speed limits). Further, they noted that in general, municipal politicians, officials in the regional development council, and planners share a strong commitment to regional development and economic growth, but often fail to recognize that these goals may be at the expense of a higher rate of road accidents (and injuries).

Societal Lethargy

There is also a degree of lethargy or resistance within the system generally that needs to be overcome when adopting new systems and procedures. Best evidence for adoption of a lower speed limit can be overlooked for reasons of fear or change to the status quo. In an interesting article by Paul Lawrence in the Harvard Business Review Paul Lawrence in the Harvard Business Review as far back as January 1969, he noted that one of the most baffling and recalcitrant problems that business executives face is gaining employee resistance to change. He noted many reasons for this and identified five principle causes for this challenge. These can include the following:

1. Lack of strong leadership and effective collaboration in making the change.
2. Failure to understand that sometimes, resistance may not be technical but social change.

3. Resistance by certain blind spots and attitudes which staff have because of their preoccupation with the technical aspects of new ideas.
4. Management need to take concrete steps to deal constructively with these staff attitudes.
5. Top executives also need to make greater positive efforts and be more effective at meetings of staff where change is being discussed.

He concluded, however, that once people see that the change is of benefit to them, they acquiesce and often champion the change. This would be expected to occur with the introduction of a lower speed limit in local streets once the benefits are realized and accepted.

Added Costs

To reduce speed limits to 30 km/h, there will be some associated costs in signage and possibly a need for some additional road treatments and maintenance to overcome any local hazards. However, the ratio of benefit to cost is likely to be very positive, given the potential benefits in terms of reduced serious injuries and death to Vulnerable Road Users. As noted earlier, severe injuries to this group is on the rise and it is essentially an inner urban problem.

Furthermore, WHO (2004) maintained that reductions in travel speeds, even at lower speeds, can still result in a meaningful reduction in deaths and serious injuries to VRU in the event of a collision with a motor vehicle.

Conclusion

If Vision Zero's new target of a 50% reduction by 2030 is to be achieved, then reducing travel speed to a level within the human biomechanical tolerance needs to be a priority. As noted earlier, the European Commission noted recently that while the number of crashes has become significantly safer for most road users, the same cannot be said for pedestrians, cyclists, and motorcyclists, who are rapidly becoming the most killed and injured group on their roads and especially in urban areas. The TAC (2018) noted that in the last 10 years, more than 400 pedestrians lost their lives on Victorian roads, with one third of the fatalities to people aged 70 years or over. Around three-quarters of these happened in Metropolitan Melbourne. Similar trends have also been reported by Transport for NSW.

There is a burgeoning problem worldwide among Vulnerable Road Users and speeding in urban streets is seen as a major cause of many of these injuries. Lower speed limits in areas where people live offer some promise to help in the push toward Zero. The third Global Ministerial Conference on road safety in Sweden called for countries to *"mandate a maximum road travel speed of 30 km/h in areas where vulnerable road users and vehicles mix in a frequent and planned manner."* This will certainly require some serious attempts to address all road users, and those more vulnerable. Lower speed limits in local streets and municipalities are important measures to help reduce severe injuries to vulnerable road users in residential local streets.

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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

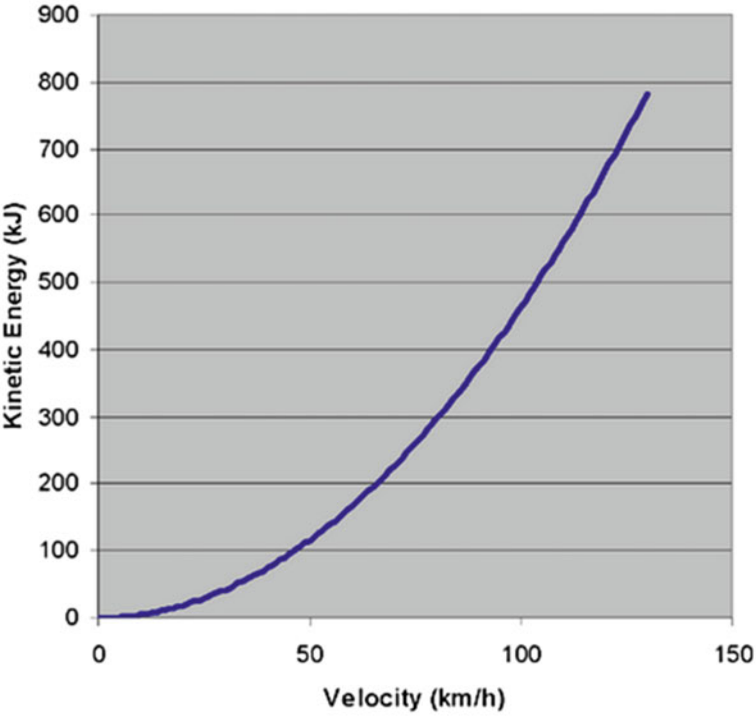

Fig. 2 The relationship between kinetic energy and travel speed

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 ($9.8\ \mathrm{m/s^2}$))
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

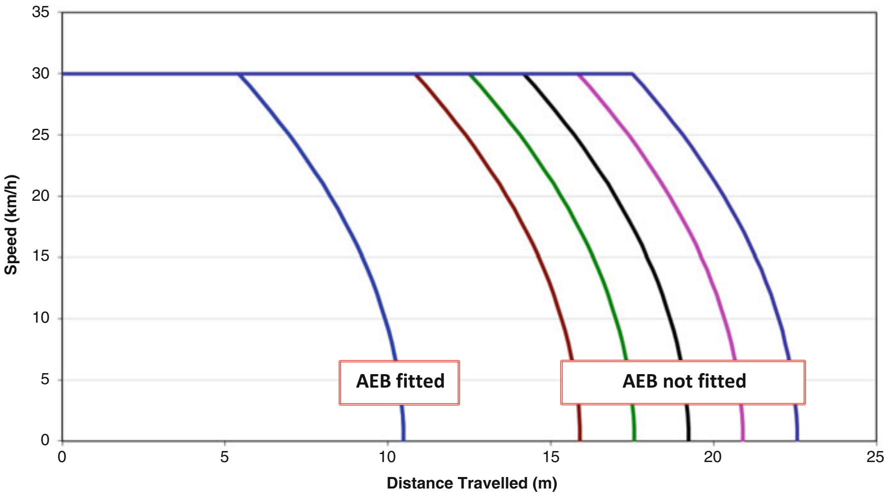

Fig. 3 Stopping distance profiles for an average passenger vehicle, for perception reaction times of 0.65 (AEB fitted), 1.30, 1.50, 1.70, 1.90, and 2.10 s (AEB not fitted). Note: assumed value of coefficient of friction is 0.7

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

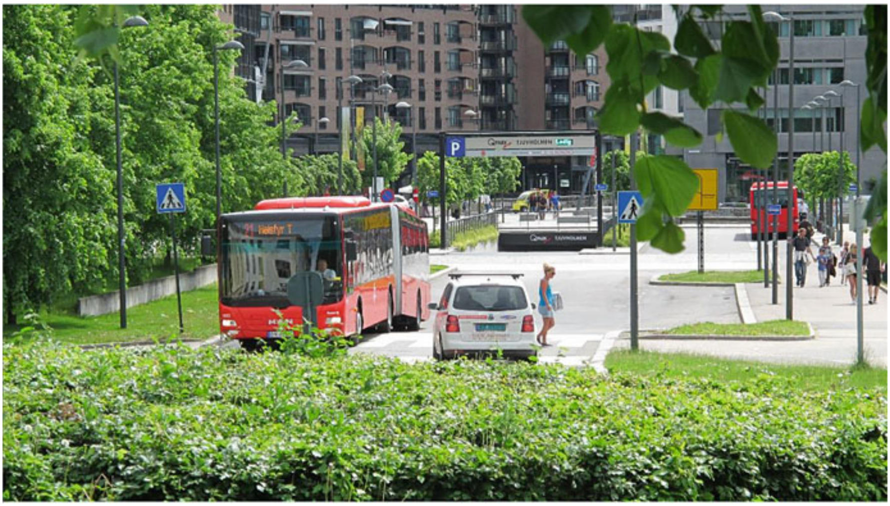

Fig. 11 Pedestrian crossings on speed platforms (Oslo, Norway)

- 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.

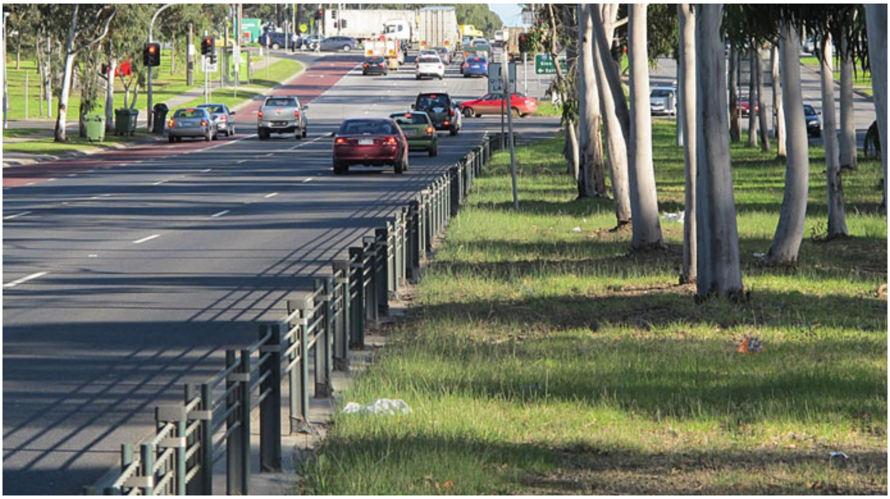

Fig. 16 Continuous flexible barrier systems to manage kinetic energy in lane departure crashes along high-speed, high-movement roads (Melbourne, Australia)

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
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Rural Road Design According to the Safe System Approach

31

Helena Stigson, Anders Kullgren, and Lars-Erik Andersson

Contents

Abstract

This chapter covers design of rural roads according to the model for safe traffic used in the Vision Zero approach. Based on expected levels of the safety of vehicles and road users, the roads and the road side furniture should be designed to avoid fatalities and serious injuries. An introduction is presented covering the safe system approach and how speed limits of roads should be set to reflect the safety standard of the road in relation human injury tolerance and the capacity to

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protect the road users. One section will cover countermeasures to protect vulnerable road users, including speed calming road infrastructure, bicycle and pedestrian paths, bus stops. Another section will cover road infrastructure countermeasures addressing vehicle occupants. It is shown how change of velocity, vehicle mean acceleration, and crash duration are correlated and how they influence occupant injury risk. Design of different types of roads on rural roads is described, such as the two-plus-one lane road design with median barrier, and various ways of separating traffic or preventing run-off road crashes including road barrier design and rumble strips. Safe intersection design is an important part on rural roads that is explained. The last part covers design of the roadside area from a safe system approach.

Keywords

Barrier · Car occupant · Change of velocity · Road design · Road safety · Rural roads · Safe System · Vehicle acceleration · Vulnerable road users

Introduction

The basis for creating a safe road transport system is the human tolerance to impact forces. It is necessary to have knowledge of injury risks for all road users in several impact conditions and for various crash severity parameters. For system providers, it is necessary to know the amount of force/acceleration the road user can be exposed to without an unacceptable risk of serious injuries. For a car occupant, the car and its safety systems are acting as a filter which reduces occupant's loading to acceptable levels. For vulnerable road users, there is no protective filter, or at least not to the same extent, and for those it is important to know the maximum impact velocity that they can be exposed to without risk of fatal or serious injury in case of a crash with a motor vehicle. For car occupants in car crashes, the vehicle acceleration is the most important parameter to control. High changes of velocity in a crash can be handled if the vehicle acceleration is kept below levels likely to cause an injury. The occupant acceleration is controlled by the vehicle and its safety systems together with the road infrastructure and the speed limits. In road traffic, two general ways of controlling the crash severity in collisions between two vehicles or between a vehicle and a vulnerable road user can be identified, either keeping the relative velocity between road users within acceptable levels or separating the road users from each other. In single or multiple collisions, forgiving deformable road side objects and safety barriers can keep the vehicle acceleration below levels likely to cause fatal or serious injuries even at roads with high speed limits. Safety barriers can also be used as mid barriers to avoid head on collisions. The coming sections will further explain how vehicle acceleration can be controlled by speed limits and the design of roads and road side objects.

In most countries, speed limits are chosen to achieve a balance between safety and mobility. Since mobility is a high priority in many countries, road authorities often allow higher speeds than those possible to handle to be a safe road transport system. According

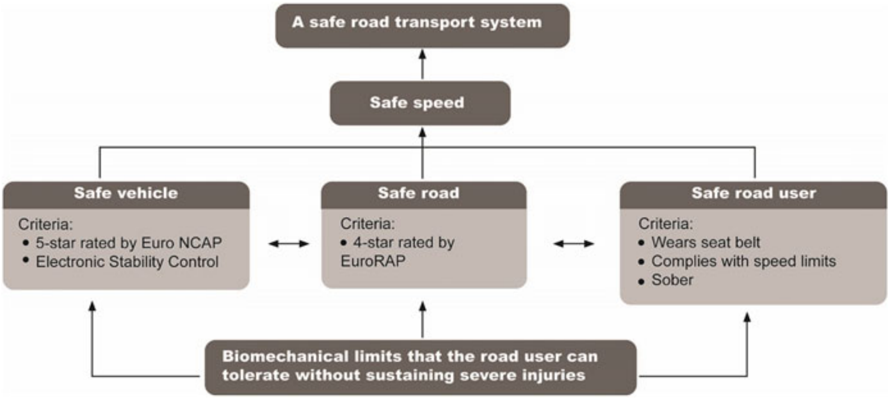

Fig. 1 The model of a safe road transport system with criteria for the vehicle, the road and the road user reflect best practice in the present-day road transport system. (Source: Stigson 2009)

to a safe system approach, the speed limit of the road should be set to reflect the safety standard of the road in relation human injury tolerance and the capacity to protect the road users (Johansson 2008; Stigson 2009; WHO 2008). The speed limit is therefore an explicit design parameter. To address a safe road transport system, the Swedish Transport Administration (STA) has summarized the underlying principles of a Safe System, Fig. 1. The chosen safety performance indicators (SPI) have been shown to have a potential to reduce injury risk and are connected to the road, the vehicle, and the road user and describe how these components together with a safe speed should interact to achieve a safe road transport system (Stigson 2009; Tingvall et al. 2000).

The integrated safety chain described in (Tingvall 2008) illustrates how events from normal driving to a crash can be broken down into phases where every phase can be handled by an action to avoid or mitigate a crash. In a Safe System, the boundary conditions for normal or safe driving in the integrated safety chain are based on the criteria in the Vision Zero model for safe traffic, that is, the conditions that need to be fulfilled to keep the kinetic energy in a crash below levels that could be handled through the chain to avoid serious injuries. Therefore, speed is crucial to either avoid critical irreversible phases in the safety chain or to mitigate an unavoidable situation. Safe driving is defined as compliance with traffic rules: wearing a seat belt, complying with the speed limit, and not driving under influence of alcohol/ drugs. Road infrastructure also has conditions that need to be fulfilled in the model. And the infrastructure could support the driver if deviations from safe driving occur and intervene with infrastructural countermeasures (for example speed humps) to return the driver to safe driving. Johansson (2008) uses the Vision Zero model for safe traffic to describe a maximum travel speed related to the infrastructure, given best practice in vehicle design and 100% restraint use:

- Locations with possible conflicts between vulnerable road users and cars, maximum speed limit 30 km/h

- Intersections with possible side impacts between cars, maximum speed limit 50 km/h
- Roads with possible frontal impacts between cars, maximum speed limit 70 km/h or 50 km/h if the oncoming vehicle is of a considerably different weight
- Roads with no possibility of a side impact or frontal impact, speed limit >70 km/h is allowed

To follow the Vision Zero philosophy, these four points have been defined according to best practices, and the Swedish Transport Administration uses these as design guidelines and to set relevant speed limits in relation to road design (Johansson 2008; Stigson 2009). In the Vision Zero model for safe traffic, these speed limits have been described as safe speed.

Infrastructure Countermeasures to Protect Vulnerable Road Users

To avoid injuries to vulnerable road users, knowledge of correlation between motor vehicle impact velocity and injury risks is necessary to be able to identify a maximum speed limit for motor vehicles in areas with a mix of vulnerable road users and vehicles. Studies have been presented for pedestrian injury risk curves (Kovaceva et al. 2019; Rosén and Sander 2009; Rosén et al. 2011; Stigson and Kullgren 2010). An example is shown in Fig. 2, presenting risk for serious injury (MAIS3+) and fatal injury for older pedestrians above 60 years, who represent the more vulnerable pedestrians. Injury risk curves have also been published for

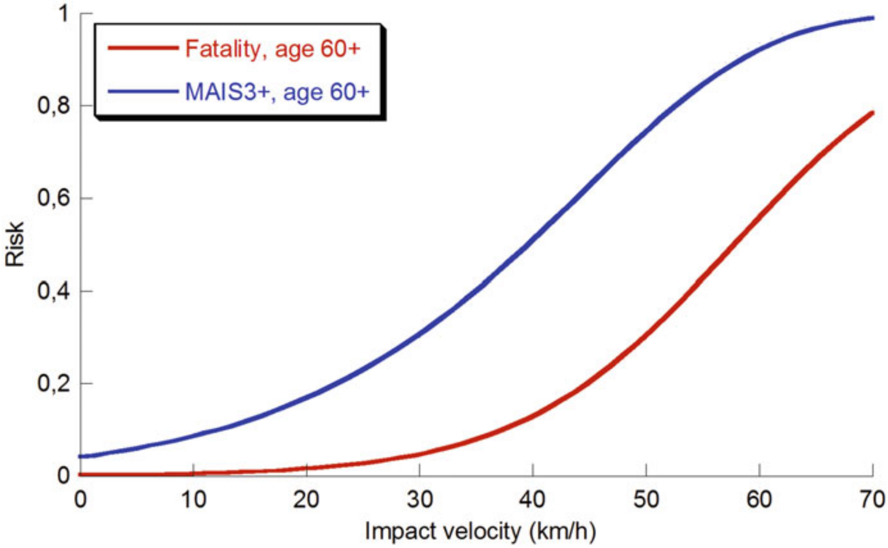

Fig. 2 Risk for fatality and serious injury (MAIS3+) for pedestrians above 60 years age as a function of impact velocity. (Source: Stigson and Kullgren 2010)

motorcycles (Ding et al. 2019). The Vision Zero guidelines recommend a maximum speed limit of 30 km/h when there is a risk for collision with vulnerable road users (Johansson 2008; Kullgren et al. 2017; Kullgren et al. 2019; STA 2019). Keeping the speed below 30 km/h entails the possibility to ensure that the injury risk can be below critical levels, but also the possibility to detect a vulnerable road user and to act to avoid a collision. However, on rural roads with lower proportion of vulnerable road users, stakeholders allow higher speeds even in area with mixed road users. It is possible to include further countermeasures. Studies have shown that a combination of speed calming road infrastructure, bicycle helmets, and more protective car fronts may reduce the risk for permanent medical impairment among bicyclists up to 95% (Ohlin et al. 2014). In addition to passive safety systems, Autonomous Emergency Braking (AEB) with pedestrian and bicyclist detection has been introduced in cars lately and has also been shown to be effective (up to 40% reduction) (Rosen et al. 2010). On rural roads, autonomous emergency braking has a large potential to protect pedestrians and bicyclist (Kullgren et al. 2017; Kullgren et al. 2019).

On rural roads, the relative velocity between the motor vehicle and the vulnerable road users is high. As seen in real-world data, maneuvers in which a driver overtakes a cyclist on a rural road are critical since they occur at high speed, with a short duration and with little time to avoid a crash (Dozza et al. 2016). The most common accident scenario on rural roads is that bicyclists are struck while cycling along the side of the road and are often struck in the rear (Kullgren et al. 2019), while pedestrians are most often the struck while crossing the road (Kullgren et al. 2017). In Sweden, vulnerable road users struck by motor vehicles are most often killed on roads with a speed limit of 70 or 90 km/h. As mentioned above, the Vision Zero guidelines recommend a maximum speed limit of 30 km/h but this is rare in rural areas. However, to avoid collisions and to protect vulnerable road users on rural roads, several concepts could be used. Examples are pedestrian and bicycle paths and crossing points, plane separation (e.g., pedestrian tunnels and footbridges) with the intension to separate the road user categories and/or to achieve safe speeds. For well-frequented passages, pedestrian tunnels and footbridges are the most effective solution. To reduce the risk, center refuges are often implemented in intersections where the number of pedestrians and cyclists is low. However, this should not be regarded as a solution according to the Vision Zero since the travel speed of the motor vehicle is not addressed. Studies have shown that roundabouts reduce the number of injured pedestrians (Gross et al. 2013; Hydén and Varhelyi 2000; Persaud et al. 2001; Retting et al. 2001), but increase the number of car-to-bicycle crashes resulting in more injured cyclists (Daniels et al. 2010; Hydén and Varhelyi 2000). Therefore, it is recommended to use speed calming road infrastructure to lower the travel speed.

Speed Calming Road Infrastructure

To protect vulnerable road users in collisions with motor vehicles, it is important to control the vehicle speed. Accident analysis on rural roads (Kullgren et al. 2017)

Fig. 3 Example of use of a chicane to control vehicle speed. Photo: Helena Stigson

have shown that a speed limit alone is not sufficient to reduce vehicle speed in areas with vulnerable road users. There is a need for supplementary measures that physically prevent from speeding. On rural roads, various solutions have been used aimed to reduce vehicle speeds in areas with common occurrence of vulnerable road users. Speed humps and chicanes can successfully be used to both raise attention and to reduce speeds at intersections or at road sections (Agerholm et al. 2017; Lee et al. 2013; Pucher et al. 2010). An example is shown in Fig. 3. Vertical or lateral shifts in the carriageway and road narrowing to a single lane or to a reduced width have also been used and evaluated showing positive results (Harvey 1992).

Bicycle and Pedestrian Paths

To increase safe cycling and walking on rural roads, there is a need for physical separation in form of separated paths if the speed limit exceeds 60 km/h (CROW 2007). Studies have shown that bicycle paths have a large potential to reduce accidents between vehicles and vulnerable road users (Kullgren et al. 2017; Kullgren et al. 2019). The design of bicycle and pedestrian paths often varies between cities/built-up areas and rural areas. In rural areas it is desirable to have paths separated from the road, an example is shown in Fig. 4, as the expected potential is higher (Kullgren et al. 2019). The separation could also be achieved by a road barrier between the vehicle lane and the bikes lane. In cities bicycle lanes, most often is located at the side of the road due to space requirements.

In rural areas where there is a mix of vulnerable road users and motor vehicles, another road design has been developed and tested to address the safety for vulnerable road users based on road sharing often named two-minus-one rural road, see for example (Herrstedt 2006; Visser van der Meulen and Berg 2018). The two-minus-

Fig. 4 Example of how vulnerable road users could be separated from motor vehicles on rural roads. (Photo: Anders Kullgren)

Fig. 5 Example of Two-minus-one-road from a Swedish pilot study. (Source: Visser van der Meulen and Berg 2018)

one road only has one central driving lane and wide shoulders on both sides, Fig. 5. Cars should only use the wide shoulders in situations with oncoming traffic, otherwise the intention is that all motor vehicle traffic should use the central lane. The solution is used on rural roads where both speed and traffic flow are low and with the purpose to give more space to pedestrians and cyclists. The concept has been used in the Netherlands, Denmark, and Sweden.

Bus Stop Location in Rural Areas

Safety for public transport users during accessing or ending theirs trips is essential since public transport users begin and end their journeys as pedestrians. When choosing the location for a public bus stop, the possibility for pedestrians to access the bus stop should be taken in consideration. It is important to avoid forcing the pedestrians to walk along a road towards a bus stop, or to cross the road to/from the bus stop or to stand at the roadside waiting to hail a bus. It is important to take in account that pedestrians, in case they need to cross the road to reach a bus stop on the other side of the road, will take a shortcut if possible. A safety fence close to the bus stop could be used to prevent pedestrians to cross the road in a noncontrolled way (Kullgren et al. 2017). Access to crossings, tunnels or footbridges should be close to the bus stop. The use of safety fences can also address and prevent suicide.

Infrastructure Countermeasures Addressing Vehicle Occupants

In car crashes, the crash severity level to which a human is exposed to depends on several factors, such as relative velocity between a vehicle and its collision partner, the mass and structure of the vehicle, and its collision partner and the crash situation, including impact angle, overlap, etc. Various crash severity parameters, such as change of velocity and mean and peak acceleration, are influenced in different ways by all the above-mentioned factors. From a mechanical standpoint, the change of velocity of a studied vehicle is primarily influenced by the relative velocity between two vehicles or vehicle and object and the vehicle masses, and only to a small degree influenced by the structure of the involved vehicles and objects, whereas the vehicle acceleration depends on all the above-mentioned factors. Therefore, the influence on vehicle acceleration and change of velocity varies depending on the mass and structure of the collision partner, for example, stiffness. With the help of data from recorded crash pulses (Event Data Recorders (EDRs) or crash pulse recorders), that entail the possibility of measuring acceleration during the crash phase, this can be verified under real-world conditions. Studies based on real-world collisions have shown that especially change of velocity and vehicle acceleration during the crash phase of a car crash influences the risk of being injured. An example of how change of velocity and vehicle mean acceleration are correlated in crashes is shown in Fig. 6. It has also been shown that if the mean acceleration is below a critical level, the duration of the crash is allowed to increase without an increase in injury risk, Fig. 7. Correlation between injury risk in frontal impacts versus crash severity measured in real-world collisions (change of velocity, mean and peak acceleration, and crash pulse duration) has been presented by, for example, Gabauer and Gabler (2008); Kullgren (1998, 1999); Stigson et al. (2012); Ydenius (2002,

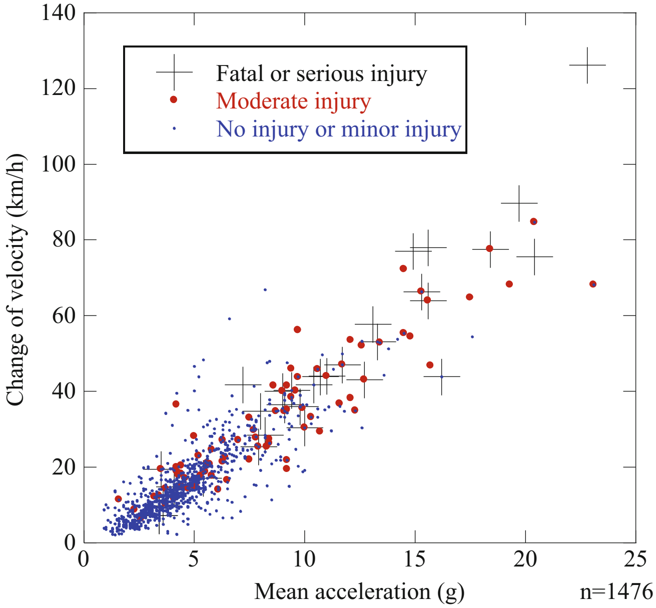

Fig. 6 Correlation between change of velocity and mean acceleration for crashes with occupants of different injury status. (Source: Folksam)

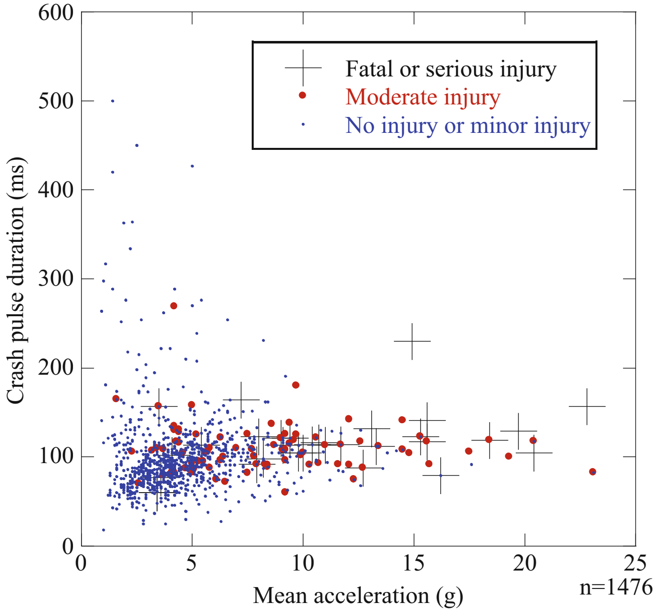

Fig. 7 Correlation between mean acceleration and crash pulse duration for crashes with occupants of different injury status. (Source: Folksam)

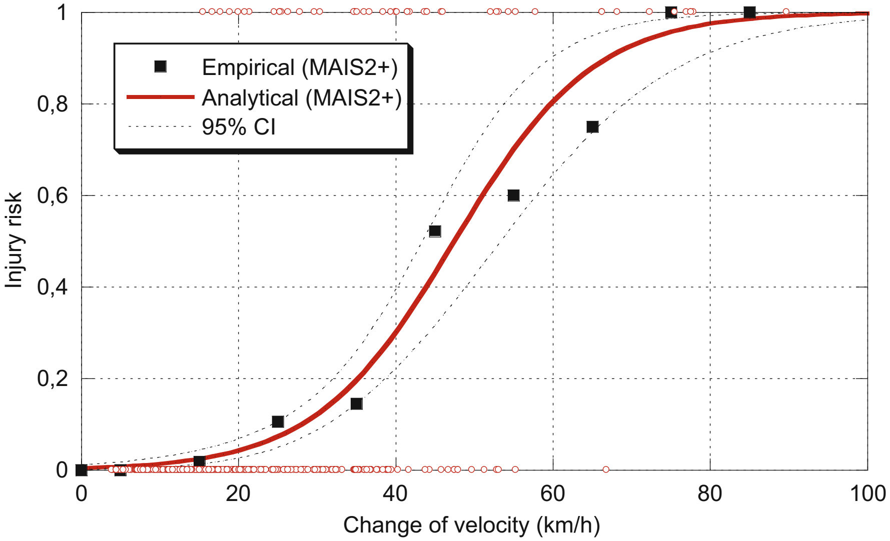

Fig. 8 Risk of a MAIS2+ injury for front seat occupants versus change of velocity in frontal impacts (Stigson et al. 2012)

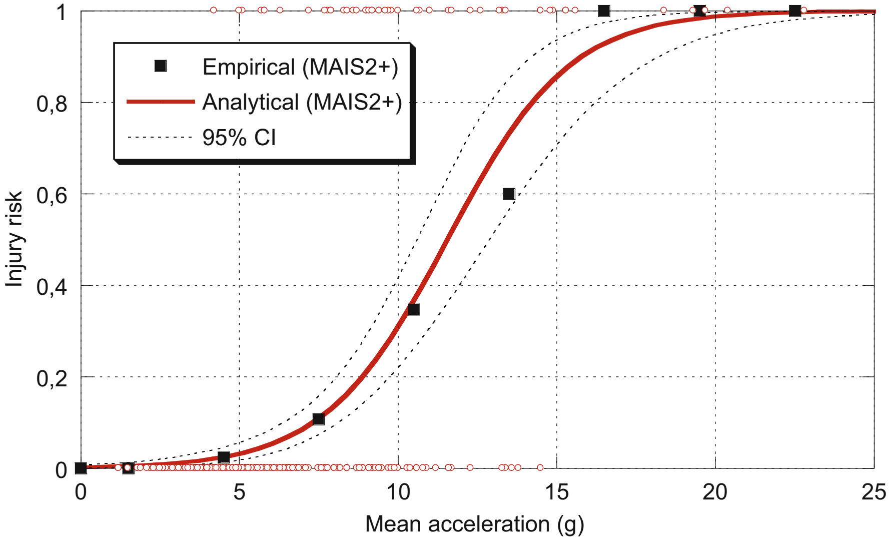

Fig. 9 Risk of a MAIS2+ injury for front seat occupants versus mean acceleration in frontal impacts (Stigson et al. 2012)

2010). Two examples of injury risk functions are shown in Figs. 8 and 9. And for rear-end crashes, injury risk curves have been presented for both mean acceleration and change of velocity (Krafft et al. 2005; Kullgren and Stigson 2011). Furthermore, risk curves based on real life side impact data have been presented (Sunnevång et al. 2009).

The three most common and severe crash types are head-on crashes, run-off-the-road crashes, and crashes at intersections, and therefore, the thresholds of a safe road transport system mentioned above are designed based on the survivable limits of these three crash scenarios.

To fulfill the criteria of a safe road according to a safe system approach (Johansson 2008; Stigson 2009) and to minimize the injury outcome, different infrastructure design could be used. Crash severity could be limited when foreseeable crash scenarios arise, by, for example, removing trees and other objects close to the road or installing a safety barrier between the vehicle and roadside objects such as trees, poles and rocks. Furthermore, two-way single carriageways with traffic in opposite directions could be allowed with a speed limit of up to 70 km/h based on the current vehicle crashworthiness (Johansson 2008; WHO 2008). To prevent interaction of vehicles with other vehicles and objects at higher speeds, the road should have safety barriers to prevent crossing over and guardrails to protect loss of control into objects in the roadside area (trees, poles, rocks, or rollover tripping mechanisms) (Rechnitzer and Grzebieta 1999). To further prevent run-off the-road crashes, the road needs to have a clear safety zone adapted to the speed limit or equipped with a guardrail. The model of a safe road transport system has been used to identify safety gaps and to find nonconformities in crashes (Lie 2012; Stigson and Hill 2009; Stigson et al. 2008; Stigson et al. 2011). The infrastructure and road safety have been identified to have a significant impact on the severity of the outcome (Stigson et al. 2008). Divided roads were the most effective factor avoiding fatal crashes among car occupants. Furthermore, it has been identified (Stigson et al. 2008) that in Sweden collisions with heavy goods vehicles (HGV) account for over half of all crashes that occurred on undivided roads with a speed limit of 70 km/h. This is one of the safety gaps where the biomechanical tolerance of the road users and the design criteria of the road transport system are not compliant and needs to be addressed.

Road Types on Rural Roads

Road type has been found to be the dominating factor for the rate of killed or seriously injured (KSI). By providing a median separation, often in form of safety barriers, the risk of head-on collisions can be dramatically reduced. Divided roads have half the KSI rate compared with single carriageways. Several studies have shown that the risk of injury is lower for divided roads than for single carriageways (Carlsson and Brüde 2005; Elvik and Vaa 2004; Stigson 2009; Tingvall et al. 2010; Wegman 2003). Furthermore, on undivided roads, the average crash severity is higher and the proportion of frontal collisions with oncoming vehicles is higher (Ydenius 2010). A study on real-world crashes has been conducted based on the Vision Zero model for safe road traffic mentioned above (Fig. 1) and also according to the European Road Assessment Programme (Euro RAP), a program that like Euro NCAP for vehicle safety evaluates and provides star ratings for roads, (Stigson

2009). The study shows that the crash severity is significantly lower in crashes occurring on roads with a safety standard fulfilling the Vision Zero criteria compared to crashes occurring on roads with a poor safety rating. Crash severity and injury risk were lower on roads with a good safety rating with a speed limit of 90 km/h to 110 km/h, compared with roads with a poor safety rating, irrespective of speed limit. On the other hand, crash severity was higher on roads with a good safety rating with a speed limit of 70 km/h, than on roads with a poor safety rating with the same speed limit. While it was found that a higher speed limit resulted in higher crash severity on roads with a poor safety rating, the opposite was found on roads with a good safety rating. The main reason for this was that lanes for traffic travelling in opposite directions were more often separated at higher speeds on roads with a good safety rating.

The crash distribution differs depending on road type, although single-vehicle crashes account for the highest proportion regardless of road type (Johansson and Linderholm 2016). On undivided roads, the proportion of fatally injured car occupants is greatest in head-on and single-vehicle crashes. By using divided roads almost all head-on collisions could be eliminated. Furthermore, intersection crashes are rare on these roads while rear-end crashes are more common. The risk of single-vehicle crashes on divided roads is less than half of the risk on undivided roads. This could be explained by higher safety standard of the roadside areas, but the main reason is that the median barrier will prevent all run-of-the-road crashes to the left. Approximately 40% of the single-vehicle crashes on undivided roads are estimated to be run-of-the-road crashes to the left (Johansson and Linderholm 2016).

The Two-plus-One Lane road Design

The 2 + 1-lane road design incorporates two lanes of traffic in one direction and one lane in the opposite direction separated by a median safety barrier, in many cases a wire-rope barrier, Fig. 10. The 2 + 1-lane roads with wire-rope barriers that were introduced by the Swedish Transport Administration in 1998 have been shown to reduce the number of fatally and seriously injured road users on Swedish roads. The 2 + 1-lane roads were a cost-effective way of increasing road traffic safety on Swedish single-carriageway roads with severe injury pattern records. The existing single-carriageway road have been and are still updated to be provided with a median barrier to separate opposing vehicles mostly within the existing road space required for the old single-carriageway. Follow-up studies have shown that the number of fatally injured road users on these segments has been reduced by approximately 79% compared with the situation earlier (Carlsson 2009). Another study (Brüde and Björketun 2006) supports this finding, since 2+1-lane roads with wire-rope barriers were shown to have the lowest KSI rate of all road types. Vadeby (2016) found that the number of fatalities and seriously injured decreased by 50% and that the total number of personal injury crashes decrease by 21%. Based on best practice, some road designs such as 2+1-lane roads have been considered in a more favorable light than others regarding casualty reduction and cost benefits (Johansson 2008). In case

Fig. 10 Example of a design of a 2 + 1 lane road. Photo: The Swedish Transport Administration

of a crash on these roads, the road and the vehicle design can together reduce crash severity and thereby succeed in protecting the road user from sustaining a serious or fatal injury. The 2+1-lane design has been introduced outside Sweden, for example, in Spain, Ireland, and New Zealand. In general, by applying mid- and side barriers on Swedish rural roads, the number of fatalities can be reduced by 85–90% (Johansson 2008).

Barriers Types

Despite improvements in vehicle safety and the vehicle occupants' awareness of benefits associated with safety devices, fatal and serious injuries continue to occur. Crash tests like Euro NCAP are mainly focused on how passive vehicle safety systems protect occupants in vehicle-to-vehicle crashes. For instance, no crash test is included in Euro NCAP to evaluate the capacity of the vehicle to protect the occupant in a frontal single-vehicle crash into a safety barrier. However, road safety features such as barriers are tested to fulfill standards. Ydenius et al. (2001) show that the characteristics of different types of barriers (concrete, semi-rigid W-beam, and flexible wire-rope barriers) vary considerably regarding transferred crash energy and physical behavior. The study shows that wire-rope barriers can reduce the vehicle acceleration below 5 g even at high impact angles (up to 45 degrees). W-beam barriers also generates relatively low vehicle mean acceleration, while concrete barriers will generate high acceleration levels in the vehicle. Based on real-world crashes with recorded vehicle acceleration, rigid barriers in average generated almost 40% higher mean acceleration than other types of guardrails (Stigson et al. 2009). This is also shown in Table 2 in a coming section. However, all barrier types would fulfil main purposes of mid separation or preventing run-off-road crashes.

Barrier Design for Motorcycles

The design of safety barriers has been criticized by, for example, motorcycle organizations, as the commonly used safety barriers mainly have been designed for cars. However, many designs developed to also protect motorcyclist have been presented and are also used in many countries, such as Austria, Belgium, Check republic, France, Germany, Italy Luxemburg, the Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, and Switzerland. Figure 11 shows an example from Spain where a motorcycle protection system (MPS) has been added at the lower part of a standard w-beam barrier with the intention to avoid contacts between a sliding motorcyclist and the poles of the barrier.

Sliding crashes will be reduced in the future, due to the fitment of ABS on motorcycles. However, further development and fitment of improved protection of safety barriers is necessary. Crash tests indicate that MPS are beneficial also in upright collisions (Berg et al. 2005; Folksam 2015). But more focus should be directed towards road barrier design for upright crashes (Rizzi 2016). The top of the barrier will have a role for reducing health loss among motorcyclists (Grzebieta et al. 2013) and (Folksam 2015). Advanced top protections have been tested by, for example, Berg et al. (2005). The basic idea is that the top of the barrier needs to be smooth, soft, and also possible to retrofit on existing barriers (Folksam 2015; Rizzi 2016) (Fig. 12).

Fig. 11 Example of W-beam barrier with an added MPS. Photo: SMC, Sweden

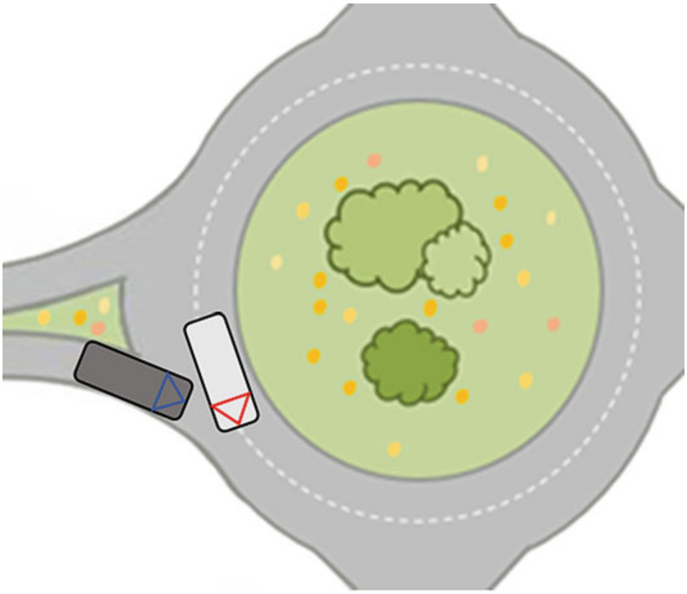

Fig. 12 Impact angle and speed will be changed by replacing a traditional intersection with a roundabout

Rumble Strips

Rumble strips as centerline or road edge lines have been shown to prevent crashes (Persaud et al. 2004; Rajamaki 2010; Sayed et al. 2010; Sternlund 2019). The strips will give a rumbling sound when driving over and thereby alert the driver to act. A large variation in crash reduction associated with drifting has been shown. The studies referred to above show reductions between 10% and 54% depending on the road type, speed limit, type of crash, and injury severity studied. In general, a reduction of 25%–30% of head-on crashes and single-vehicle run-off road to the left was shown. A reduction of 40% (19–56%, 95% CI) has been shown for cars fitted with Electronic Stability Control (Sternlund 2019), which appears to be a bit higher than cars without.

Intersections

To reduce crashes, specifically side impacts, resulting in severe injuries in intersections, a roundabout or a plane separated intersection can be introduced to avoid interference with opposing traffic and with left- and right-turning vehicles. Based on the Vision Zero model or Euro RAP mentioned in the introduction, a high safety rating intersection would be an intersection with a speed limit of maximum 50 km/h (Stigson 2009). According to the Euro RAP rating, roundabouts could allow speeds above 50 km/h since the design reduces the speed to acceptable levels while maintaining the traffic flow. How a safe speed can be achieved in roundabouts is further described below. At high traffic flow and with speed limits, above 50 km/h a grade separation is required. In car-to-car side impacts with modern side airbag-equipped cars, the occupants could be protected from severe or fatal injuries up to an impact speed of 60 km/h (Sunnevång 2016). Therefore, other countermeasures are needed to avoid side impacts at higher impact speeds. In the future, speed could probably be controlled with AEB intersection systems (Sander 2018) or with smart infrastructure communication with the vehicle or with vehicle-to-vehicle communication. The speed in an intersection could also be controlled by chicanes to reduce the speed before entering the intersection.

Intersections with traffic lights should not be regarded as a traffic safety solution in line with Vision Zero, but rather as a solution that supports mobility. Traffic lights will not prevent or correct driver errors at an early stage, and therefore, the crash severity will be higher in case a crash occurs. Road design solutions such as roundabouts have been shown to dramatically reduce the number of crashes resulting in injuries (by up to 80%) at intersections compared with traditional intersection designs (Brüde and Vadeby 2006; Gross et al. 2013; Persaud et al. 2001). Compared to a traditional intersection, a roundabout has less conflict points, which is illustrated in Fig. 13. The advantage of a roundabout is that a roundabout specifically addresses crossing path and left turn scenarios by reducing travel speed and possible impact angle, Figs. 12 and 14. Studies have shown that by replacing intersections with roundabouts, speed, number of conflict points, and number of side impact crashes were reduced and thereby also the number of the injuries to both car occupants and pedestrians (Gross et al. 2013; Hydén and Varhelyi 2000; Persaud et al. 2001; Retting et al. 2001). However, the number of car-to-bicycle crashes has been shown to increase in roundabouts as compared to intersections, resulting in more injuries to cyclists (Daniels et al. 2010; Hydén and Varhelyi 2000). Furthermore, the crash type distribution will be affected when replacing a traditional intersection with a roundabout. Studies have shown that the proportion of rear-end and side-swipe crashes will increase (Mandavilli et al. 2009; Polders et al. 2015). The ultimate solution to minimize potential conflict points at intersections is grade

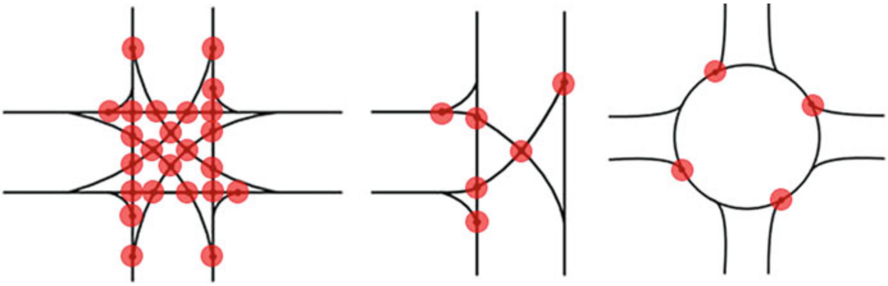

Fig. 13 Potential conflict points of major conflict of intersections, left: four-leg crossing 24 conflict points, middle: T-junction 6 points, right: roundabout 4 points

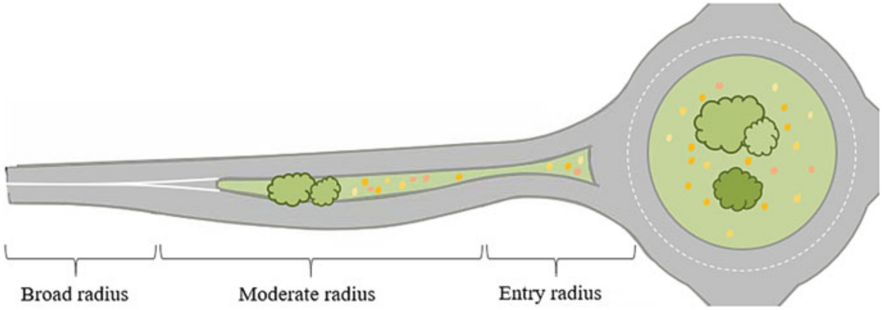

Fig. 14 An example of chicanes at roundabout approach aimed to reduce entrance speed

separation, but this solution is also associated with high costs and is primarily applied on roads with high traffic flow.

Several aspects need to be considered when designing a roundabout. Lateral displacement when entering a roundabout must be designed to achieve the desired speed reduction particularly on rural roads. One example is the use of chicanes on road sections entering roundabouts aimed to reduce the entrance speed, Fig. 14.

Roadside Area

To prevent that a run-off the-road crash results in sever or fatal injuries, the road needs to have a safe clear zone adapted to the speed limit or equipped with a safety barrier. To secure protection for crashes with barriers with all vehicle types, the barrier should be designed and tested for each of them. Based on the Vision Zero model mentioned in the introduction and the criteria set up by Euro RAP, the road should have physical barriers or a safety zone wider than four meters on roads with a speed limit of 70 km/h or higher to protect a car occupant in a loss of control into objects in the roadside area (trees, poles, rocks, or rollover tripping mechanisms). The safety zone that the vehicle needs to stop safely when leaving the roadway or that helps to reduce the crash energy to an acceptable level so that it will not result in a fatal or serious injury differ depending on road type, speed limit, the topography, and factors like curvature as well as traffic flow, Table 1. In addition to this, the size of the safety zone also depends on the bank height, if it is straight or inner/outer curve and radius on any curve (Fig. 15).

A safety zone should not have fixed objects or other hazards. Fixed objects lower than 0.1 m above ground level could be tolerated. Trees exceeding 0.1 m in diameter are considered as fixed objects (Johansson and Linderholm 2016). Examples of hazards are precipices (vertical fall with height ≥ 0.5 m or side slope $> 1{:}3$) and deep water (exceeding 0.5 m at medium water levels). If the requirements regarding safety zone could not be achieved, the road should be equipped with a guardrail. Road side objects needed within the safety zone should be designed and placed in such a way that critical vehicle acceleration levels are not exceeded during a run-off-road crash.

Table 1 Safety zones used in Sweden for various types of roads (STA 2020)

Speed limit (km/h)	Road type	New/redesign	Traffic flow (vehicles per day)	Safety zone (m)
120	F/H			≥ 12
110	F/H			≥ 11
	DR	New	> 8000	≥ 11
	DR		≤ 8000	≥ 10
	DR	Redesigned		≥ 10
100	DR		> 4000	≥ 10
	DR		≤ 4000	≥ 9
	DR	Redesigned		≥ 9
	2-lane	New	≤ 1500	≥ 9
	2-lane	Redesigned		≥ 9
80	2-lane	New	> 8000	≥ 8
	2-lane	New	4000–8000	≥ 7
	2-lane	Redesigned	2000–4000	≥ 7
	2-lane	Redesigned	1000–2000	≥ 6
	2-lane	Redesigned	≤ 1000	≥ 5

Note: F/H: Freeway/Highway (divided), DR: Divided arterial Road with centerline barrier, 2-lane: undivided two-way two-lane arterial road

For example, poles should be deformable or having a base that allow the pole to detach from the base in a controlled way in case of a crash. Figure 16 shows an example of a pole with a deformable element in the base aimed to lower vehicle acceleration in the event of a crash.

Collisions with rigid roadside objects account for a large part of fatal crashes around the globe, in some countries more than 40% (Delaney et al. 2003; DfT, 2005; ETSC 1998; IIHS 2005; RISER 2005). Many studies from different countries have found that trees account for most rigid roadside objects leading to fatalities (Delaney et al. 2003; Evans 1991; IIHS 2005; La Torre 2012). In vehicle collisions with narrow objects, such as poles and trees, the load is often concentrated to only a small part of the car. Therefore, only a minor part of the energy absorption structure is involved (Durisek et al. 2005; Durisek et al. 2004). To lower the vehicle acceleration in a crash, deformable objects should be used, which has been clearly demonstrated in crash tests (Kloeden et al. 1999; Steffan et al. 1998). The resulting vehicle acceleration in a crash should always be kept below critical levels likely to cause an injury. An analysis based on real-world data with crashes into various road side object shows that the least harmful crash type was single-vehicle crashes into deformable guardrails, in which no crash was found with a mean vehicle acceleration higher than 9 g, Fig. 15 and Table 2, (Stigson 2009). A mean vehicle acceleration below 9 g correlates with a less than 25% risk of sustaining moderate or more severe injuries (Stigson et al. 2012). In single-vehicle crashes, the average mean vehicle acceleration was 45% higher in collisions with rigid roadside objects than in collisions with deformable objects. Based on results like this, a design guideline could be identified regarding maximum mean vehicle acceleration to be accepted in frontal impacts. The results presented by Stigson (2009) suggest 9 g as a maximum level.

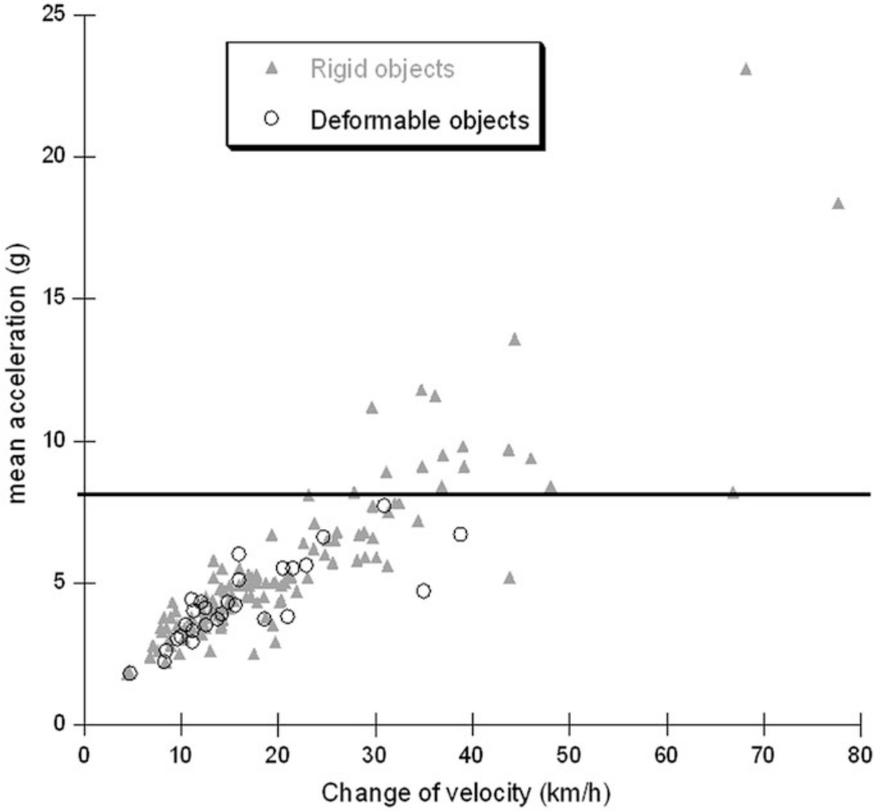

Fig. 15 Distributions of vehicle mean acceleration in crashes with rigid and deformable objects, from (Stigson 2009)

Fig. 16 Lightning column with a deformable element in the base aimed to lower vehicle acceleration in a crash. (Photo: Helena Stigson)

Table 2 Frontal single-vehicle crashes with different collisions partners, from (Stigson 2009)

Type of crash object	Change of velocity Δ V (km/h)	Mean acc. (g)	Duration (ms)	n
Rigid object	21.3	5.8	102.7	74
Trees	22.1	6.1	101.2	23
Rock face cutting	25.1	6.0	117.5	6
Rocks/boulder	20.7	5.2	107.6	12
Culvert	17.9	4.8	106.2	4
Rigid barrier	21.3	5.7	105.9	9
Bridge pier	19.3	6.7	80.0	1
House wall	16.6	5.8	77.9	6
Embankment	22.5	6.0	106.5	13
Deformable object	15.0	4.0	106.1	51
Deformable pole	15.1	4.0	107.4	30
Deformable guardrail	15.0	4.1	104.3	21
Other	12.9	4.0	92.1	33
Total	17.1	4.8	101.5	158

The section above describes the performance of deformable object in crashes mainly with passenger cars. Most deformable object are far too stiff to be able to lower the occupant loadings when struck by, for example, motorcycles and mopeds.

Cross-References

► Road Safety Analysis

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Speed and Technology: Different Modus of Operandi

32

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Abstract

Within Vision Zero as a strategy, it is imbedded the fact that injuries occur when the mechanical energy reaches individuals at rates that entail forces in excess of their thresholds for injury. Therefore, according to Vision Zero, there are three main strategies to eliminate fatalities and severe injuries due to road crashes: protect people from exposure of harmful energy, reduce the risk of events with harmful energy, and protect people from harmful energy in the event of a collision. Controlling speed is therefore of the task of utmost importance in a strategy such as Vision Zero.

A traffic enforcement camera, or "speed camera," system has the possibility to control speed in a road system, and it has the possibility to affect its road users both at a macro and a micro perspective. In a micro perspective, it primarily concerns how effective the cameras are locally at the road sections where the enforcement is focused on, while at a macro perspective it is more focused on how the camera enforcement system and strategies, possibly together with the overall enforcement strategy, affects attitudes and norms related to driving with excessive speed. Experience worldwide has proven the effectiveness of automated speed cameras in reducing speed and, in turn, crashes and injuries.

In this chapter, firstly the rationale behind speed limits, speed management, and speed compliance strategies will be explored and analyzed, in particular from a Vision Zero perspective. Secondly, various different approaches to speed camera systems in Europe, in Sweden, Norway, the Netherlands, and France, will be analyzed and further explored. Finally, based on similarities and differences in approaches in these countries, in the last section some aspects concerning the setting of speed limits, speed management strategies that underpin the choice of camera technology, and modus of operandi, safety effects of and attitudes toward cameras, will be explored and discussed.

Keywords

Vision Zero · Public policy · Speed limits · Speeding · Traffic safety cameras · Speed cameras · Traffic enforcement cameras

Introduction

Speed limits and speed monitoring and enforcement are a rather sensitive topic in most countries. To a significant extent, this is due to what people perceive is the primary goal with the road safety work, namely, the reduction of accidents, or to reduce crashes as many people prefer to express it. In this traditional approach, most of the attention is focused on people's behavior due to the fact that in-depth studies have shown that 90% of all accidents are due to human factors (Evans 2004). In this traditional context, speed becomes one risk factor, among others, used to explain the occurrence of an accident, and many times other factors such as distraction, fatigue, alcohol, and drugs seem to be more obvious and significant.

In October 1997, the Riksdag (the Swedish Parliament) adopted Vision Zero as a new long-term goal and strategy for road safety in Sweden (Swedish Parliament 1997; Belin et al. 2011). Imbedded in Vision Zero as a strategy is the fact, which was revealed by William Haddon already in the 1960s, that injuries occur when the mechanical energy reaches people at rates that involve forces in excess of their injury thresholds (Haddon 1968, 1980). Therefore, according to Vision Zero, there are three main strategies to eliminate fatalities and severe injuries due to road crashes: protect people from exposure of harmful energy, reduce the risk of events with harmful energy, and protect people from harmful energy in the event of a collision. To control the speed is therefore of the utmost important task in a strategy like Vision Zero.

Speed as one important risk factor is a valid logic in the context of a more traditional approach, but if the problem that one tries to solve is not accidents per se but rather the outcome in terms of fatalities and serious injuries, the speed instead becomes the core of the entire road safety work. People do not suffer from injuries due to distraction, fatigue, alcohol, and other factors. To put it bluntly, as long as one's speed is low, they will survive a crash even if they are driving impaired due to operating under the influence. Speed limits and speed monitoring and enforcement therefore play an important role both traditionally and from a Vision Zero perspective, however, from rather different angles.

Change of speed and its relation to accidents and the severity of injury is one of the most researched topics in the field of road safety. According to Elvik (2009), change of speed and road safety could be described in terms of different power functions, where the power function is greater for higher levels of severity. For example, a reduction of average speed by 10% will reduce fatalities by approximately 40%, serious injuries by 30%, and accidents with minor injuries by 10%.

There are several ways to control the speed in the road transport system – for example, speed limits and a variety of speed-reducing devices. The State of Victoria in Australia is an innovator for road safety practices on a global scale. For example, Victoria was the first jurisdiction in the world to introduce the compulsory use of seat belts, back in 1970, and random breath testing (RBT) in 1976 (Trinca et al. 1988). True to their tradition, in 1989 the State of Victoria started to implement a large-scale automatic speed camera program (Bourne and Cooke 1993). This was the first time in the world that extensive use had been made of this technology (Sagberg 2000). After this, quite a number of jurisdictions around the world have followed.

In this chapter, firstly the rationale behind speed limits, speed management, and speed compliance strategies will be explored and analyzed, particularly from a Vision Zero perspective. Secondly, the different approaches to speed camera systems in Europe, namely, in Sweden, Norway, the Netherlands, and France, will be analyzed and further explored. And then finally, based on similarities and differences in approaches in these various countries, in the last section some aspects concerning the setting of speed limits, speed management strategies that underpin the choice of camera technology, and modus of operandi, safety effects of and attitudes toward cameras, will be explored and discussed.

Setting Speed Limits

The speed limit constitutes the legal objectives for the monitoring and enforcement, similar to the blood alcohol limits establishes legal objectives for how much alcohol a road user is allowed to have in their blood while driving. This is something people mostly accept and take for granted; however motives and criteria that underpin a speed limit system are paramount for its legitimacy and thereby also important for public control and sanctions.

In a Swedish context, it is obvious that motives that underpin a speed limit system have evolved and change over time. In 1907, the Swedish Government launched the first road traffic regulation for automobiles. The regulation stipulated, among other things, that motor vehicles were not allowed to drive faster than 15 km/h in urban areas and 25 km/h in rural areas. During the period 1910–1930, the maximum speed limit was increased to 35 km/h in urban areas and 45 km/h in rural areas (Swedish Parliament 1906). The use of the automobile was heavily regulated primarily because it was seen as an unwelcome element in a transport system which mainly consisted of horse transports. In the 1930s, an opinion was raised against these static speed limits. The advocators argued that the vehicles and the roads had a higher standard and therefore were designed to allow a much higher speed. It was better, according to the advocators, to put the entire responsibility on the individual to adjust their speed according to the situation. Therefore, a new speed regime with free speed, both in urban and rural areas, and with a significant proportion of self-responsibility was introduced in 1936 (Swedish Parliament 1936).

After World War II when the number of cars rapidly increased and along with this, the number of fatalities increased dramatically, the epidemic situation forced the Swedish Government to take a variety of different steps to improve the road safety situation. The experts were not sure that the freedom for the driver to choose their own speed was such a good idea. Besides, it was difficult for the police to enforce inappropriate choice of speed, and the police needed clearer guidelines regarding which speed to allow. The elected officials responded to that request, and the first step was to re-regulate the speed in urban areas. In 1955 a new default speed that stipulated 50 km/h in urban areas (this speed limit is still in place) was introduced (Swedish Government 1955). During the years 1960–1967, temporary speed limits for the rural roads were introduced – especially during holidays. The speed limits were 80, 90, or 100 km/h. In 1968, a trial with general differentiated speed limits was introduced and the idea was to allow higher speed on roads with higher standards. In 1971 a default 70 km/h speed limit for rural roads was introduced. The debate about having speed limits or not vanished from the agenda and was replaced by a discussion of which criteria the speed limits should be based on (e.g., on what roads should the responsible traffic authorities allow 90 km/h or 110 km/h).

One of the most important criteria when the speed limits first were discussed was the drivers' acceptance. The advice was that the speed should be around 85th percentile which means the speed 85% of the vehicles not are exceeding (see Fig. 1, the evolution of speed limit system).

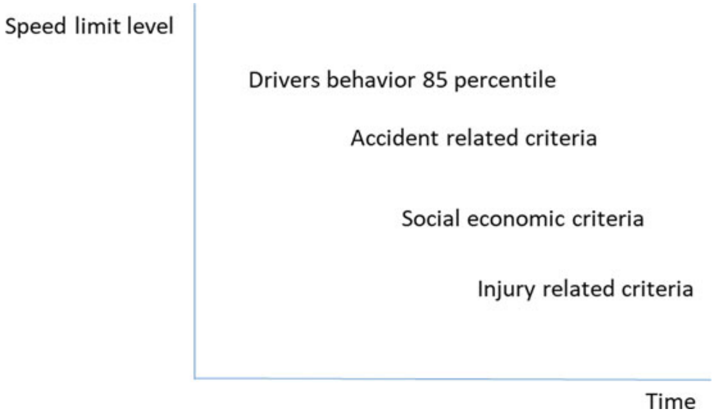

Fig. 1 Evolution of important speed limit criteria in Sweden

Soon it became obvious that alignment routing, passing sight distance, and accident rate needed to be considered before a speed was decided, and these accident-related criteria have dominated since the 1970s (Swedish Government 1978). In the 1980s, the experts advocated that speed limits should be established from a cost-benefit perspective (Carlsson 1976). The idea was that one could calculate an optimal speed limit for different road environments. This method has never been implemented in reality, though.

According to Vision Zero, road users' tolerance against external violence should be the basic design parameter for the speed. Based on this design parameter, it has been suggested that the risk for different crash types should set the maximum speed. For example, in the situation where there are risks for crashes with cars and unprotected road users, the speed limit should not be higher than 30 km/h and for risks for head-on collisions (i.e., cars to cars) at a speed not higher than 70 km/h (https://www.roadsafety.piarc.org/en/road-safety-management-safe-system-approach/safe-system- elements).

A speed management system in order to achieve safe speed in the long run is summarized in Fig. 2. First, one needs some long-term principals which appear in Table 1. However this might be difficult to achieve in the short term; therefore jurisdictions have to allow a higher speed than what is appropriate from a Vision Zero perspective. These should however only be short-term considerations. Irrespective of if the speed limit is established based on long-term safety principals or short-term practical considerations, the governmental authorities need also to ensure that the traffic complies with the speed limits, which is the last step.

Influencing Road Users' Speed Behavior

Kinetic energy is one of these risks in our society that people do not feel and therefore do not have a natural perception of, in comparison with the risks of such things as snakes, spiders, heights, etc. pose. Therefore the speed that people choose is largely dependent

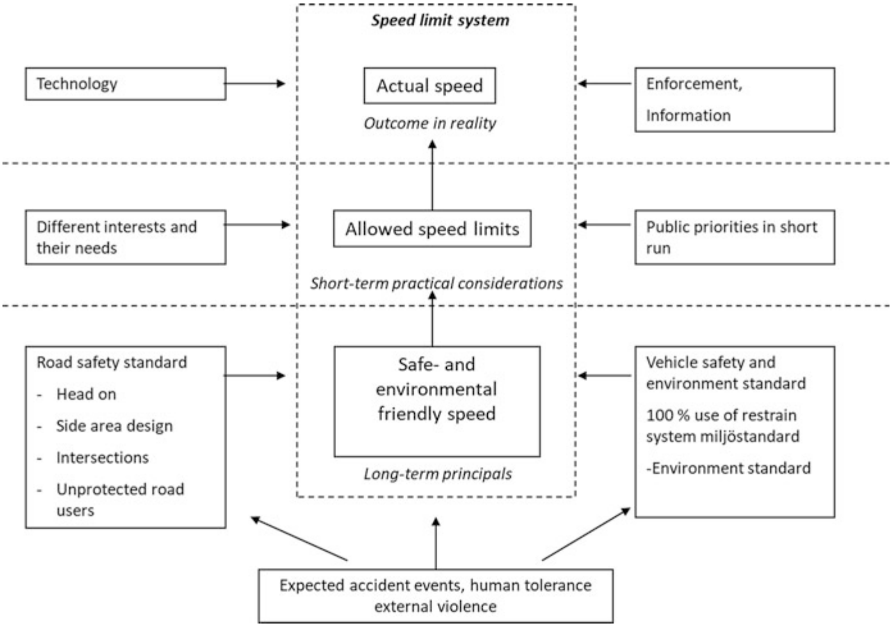

Fig. 2 Speed management system in order to achieve safe speed according to Vision Zero and environment

upon stimuli from the environment such as the road environment, weather, surrounding traffic, and posted speed limits, among other factors. To know intellectually about the risk will also be important. Control interventions such as manual and automated enforcement have significant impact on people's compliance with the speed limits. Risk for sanctions in terms of fees and losing the driving licenses are also important. A couple of important questions are therefore important to discuss; who should be the target group for the enforcement and how are the interventions supposed to work?

Firstly, if the speed limit is set according to the 85%, already a large majority of the traffic will comply with the speed limit. Therefore, enforcement is aimed to influence 15% of the road users. As early as in the 1950s, the expression "people drive as they live" was coined (1953 Års Trafiksäkerhetsutredning 1954). Therefore, these 15% was blameworthy, and the enforcement should focus on this risk group, especially those who are driving too fast. What underpins this high-risk strategy are of course that these groups are, individually, more risky from a road safety perspective. Even though the criteria for setting the speed limits have changed, the most popular enforcement strategy is still to focus on the high-risk groups. However with such approach, one might end up in what researchers refer to as the "public health paradox," (Rose 1981) namely, a more general effect on road safety is obtained if instead of focusing on a small population of speeders, efforts are made to influence the larger normal population who are only speeding little too much. The individual strategy has its advantages (Rose 2001), and it very probably fits well in with how

Table 1 Speed limit system in Sweden, Norway, the Netherlands, and France. Extracted from ETSC (2019)

	Sweden	Norway	Netherlands	France
Proportion (in %) of observed speeds of cars and vans higher than the speed limit on 50 km/h urban roads and mean observed driving speed on these roads in free flow traffic.	46.5 km/h mean speed; 65% below the speed limits	49 km/h mean speed; 54% below speed limits	N/A	49.4 km/h mean speed; 54% below speed limits
Proportion (in %) of observed speeds of cars and vans higher than the speed limit on rural non-motorway roads and mean observed driving speed on these roads in free flow traffic.	Speed limit 70 (2016) 68.3 km/h mean speed; 45% below the speed limits	Speed limit 70 69 km/h mean speed; 57% below the speed limits	N/A	
	Speed limit 80 (2016) 81.9 km/h mean speed; 42% below the speed limits	Speed limit 80 77.4 km/h mean speed; 58% below the speed limits		
	Speed limit 90 (2016) 88.9 km/h mean speed, 52% below the speed limits			Speed limit 90 (2016) 81.6 km/h mean speed; 69% below the speed limits
				Speed limit 110 (2016) 105.2 km/h mean speed; 81% below the speed limits
Proportion (in %) of observed speeds of cars and vans higher than the speed limit on motorways and mean observed driving speed on these roads in free flow traffic		Speed limit 100 (2017) 100.1 km/h mean speed; 47% below the speed limits	Speed limit 100 (2011) 98.6 km/h mean speed; 53% below the speed limits	
	Speed limit 110 (2016) 111.6 km/h mean speed; 40% below the speed limits	Speed limit 110 (2017) 102.3 km/h mean speed; 66% below the speed limits		Speed limit 110 (2016) 103.3 km/h mean speed; 70% below the speed limits

(continued)

Table 1 (continued)

	Sweden	Norway	Netherlands	France
			Speed limit 120 (2011) 113.8 km/h mean speed; 65% below the speed limits	
				Speed limit 130 (2016) 121.8 km/h mean speed; 72% below the speed limits

Unlike Victoria, Australia, the studied countries camera programs are primarily based on fixed cameras, and the number of cameras per million inhabitants varies between 41 (Norway) and 135 (Sweden) cameras. Speeding tickets per 1,000 inhabitants varies between 8 (Sweden) and 391 (the Netherlands)

the police interpret the law and prioritize their operations, namely, to catch offenders. However from a general road safety perspective, they would see more benefit if they influence a large proportion of the normal population.

Secondly, which also to some extent reflect the choice between the high-risk strategy or the population strategy, what is the appropriate mechanism for influence. According to Kahneman (2011), human behavior is based on two different systems, namely, system 1 and system 2. System 1 is fast and automatic, emotional, and unconscious. System 2 is slow, calculating, and conscious. Our enforcement strategies are, mostly implicitly, based on an idea about what system actually influences the road users' behavior. If one believes that the road users are rational and are carrying out conscious calculations about the costs and benefits of speeding, one refers speeding to an action originating from system 2. However if one thinks that speeding is an automatic and unconscious behavior, they believe it stems from system 1. Later in this chapter, speed camera systems in Victoria in Australia and Sweden will be discussed, and it appears that Australia based their system more on system 2 and Sweden on system 1 theory on road user behavior.

Manual Enforcement or Technology

Especially if the goal with the enforcement strategy is to catch those who deliberately violate the law and traffic rules, and therefore put themselves and others in danger, covert manned enforcement seems to be an appropriate strategy. Manual enforcement might also be an option within a more population-focused strategy however in this case based on an overt strategy. However according to some researchers, it is difficult for a police organization to maintain a high-profile manned enforcement over a long period of time (Bjornskau and Elvik 1992). This adaption

Fig. 3 Adaptation process police enforcement

process can be seen in Fig. 3. However technology creates new options. Regardless of strategy, automated enforcement can be put in use 24/7/365 and therefore deal with some of the negative effects and costs of manual enforcement.

Different Modus of Operandi

Many jurisdictions around the world have defined speed and speeding as important factors to control in order to focus on improving the road safety situation or even in the long run achieving a safe system. Many jurisdictions are also using an automated speed camera system to achieve these goals. However there are differences in the design of these systems and the way these systems are set up and operate. In other words, different ideas and strategies underpin these systems. In a study (Belin et al. 2010), speed camera system in Sweden and Victoria, Australia, was explored and compared. First, at least in early 1990, the lack of road safety was seen as caused by unappropriated behavior, and speeding was one of the most important. According to this study, the approach adopted in Victoria was based on the concept that the drivers are rational and they strive for driving as fast as possible and they are doing deliberate calculations of the cost and the benefits and therefore are choosing a speed where these are in balance. Based on an earlier section, it seems that the Australian system is grounded in the theory that speed behavior is emanating from system 2. Second, the Australian seems to have expanded their high-risk group "police model" with the focus on offenders to a large population. Regardless of who and where, speeding is a blameworthy behavior and needs to be detected and punished. Therefore the aim was to catch a large proportion of the drivers that exceed the speed limit, so that they experience the consequences, specific deterrence, and avoid re-offending and in turn tell others that they have been caught and suffered punishment, resulting in a general deterrence. The overall aim appears to be to establish a social norm that speeding is a serious offense along with supporting the introduction of large-scale camera surveillance. This was supported by broad informational campaigns with the aim to upset and outrage the viewers. Victoria was a forerunner in the beginning of 1990 when they took this new technology from demonstration phase to implementation of a large-scale speed camera system. However Sweden, Norway, the Netherlands, and France followed and gradually implemented their own large-scale speed camera system. In this section, these systems will be described and explored. Based on available data, focus will be on the systems operation in 2015.

Method and Data

A literature review was done in the literature databases Scopus and TRID, primarily focusing on studies from 2008 to 2019. Scopus is the world's largest bibliographic database, focusing on scientific articles in all subjects. TRID is an integrated database that combines the records from TRB's Transportation Research Information Services (TRIS) Database and the OECD's Joint Transport Research Centre's International Transport Research Documentation (ITRD) Database. TRID provides access to more than 1.25 million records of transportation research worldwide. In addition to the searches in the databases, a request about gray literature was made from personal contacts.

In addition to the literature review, data from a study about speed enforcement in Europe done by ETSC (European Transport Safety Council) was used, ETSC (2016, 2019). ETSC is an independent nonprofit organization based in Brussels dedicated to reducing the numbers of deaths and injuries in transport in Europe. The report shows that methods on the levels of speed enforcement differ greatly between EU member states.

To compare attitudes in different countries, data from ESRA (E-Survey of Road Users' Attitudes) is used. ESRA is a joint international initiative of research centers and road safety institutes across the world, and in its first stage (ESRA1 2015), the project has surveyed road users in 38 countries on 5 continents, and in ESRA2 (2018–2019), 48 countries participated. ESRA data is collected through online panel surveys, using a representative sample of the national adult populations in each participating country (at least $N = 1{,}000$ per country). It is a jointly developed questionnaire, which is translated into national language versions. The themes covered include self-declared behavior, attitudes and opinions on unsafe traffic behavior, enforcement experiences, and support for policy measures. The survey addresses different road safety topics (e.g., driving under the influence of alcohol, drugs, and medicines, speeding, distraction) and targets car occupants, motorcycle and moped drivers, cyclists, and pedestrians. The aim of ESRA is to collect comparable data on the road safety situation and culture indicated by the road users' past and habitual behaviors, attitudes, beliefs, perceived norms, and values. The ESRA data is used as a basis for a large set of road safety indicators. These indicators provide scientific evidence for policymaking at national and international levels (see http://www.esranet.eu).

Four countries in Europe (Sweden, Norway, the Netherlands, and France) with different modus operandi and different levels of enforcement were selected and investigated in more detail, regarding modus operandi, level of speed enforcement, attitudes, and traffic safety effects.

Speed Camera System in Sweden, Norway, the Netherlands, and France

In a couple of reports from the European Transport Safety Council (ETSC) (ETSC 2016, 2019), data has been assembled concerning a variety of countries' speed control methods systems and speed camera system and their characteristics. Based on this, some interesting findings are summarized in Tables 1 and 2.

Table 2 Speed camera program and its characteristics in Sweden, Norway, the Netherlands, and France in 2015. Extracted from ETSC (2016)

	Sweden	Norway	Netherlands	France
Inhabitants	9, 7 million	5, 1 million	16, 9 million	66, 4 million
Total number of cameras (in operation)	1315	341	852	3953
Fixed cameras	1300	317	642	2180 886 (empty boxes)
Proportion of fixed cameras	99%	93%	75%	78%
Time over distance cameras	0	24	24	100
Owner responsibility	No	No	Yes	Yes
Speeding tickets from camera	78,423	90,524	6,609,418	12,728,539
Cameras per million inhabitants	135	41	50	60
Tickets per 1000 inhabitants	8	17,5	391	192

The speed limit, the mean speed, and the compliance of speed limits differ between the studied countries. All countries have 50 km/h, but it seems that Sweden has lower mean speed and higher compliance of the urban speeds compared to Norway and France. When it comes to rural roads, however, Sweden seems to have, compared with Norway and France, a lower compliance with the speed limits. The same pattern can be found when it comes to compliance with speed limits on motorways.

Even though all four countries studied based their camera operation on a system of fixed cameras, there are differences in the manner in which the owners of a vehicle are regulated, the number of traffic tickets, and number of cameras, and this might reflect strategic differences in the modus of operandi between these countries.

Firstly, both in Sweden and in Norway, in order for the government to assert liability for a speeding violation, the driver must be identified by a photograph. In the Netherlands and France, at least for the less severe speeding violations, it is sufficient to identify the car via the number plate and send a ticket to the owner of the car. If the owner hasn't driven the car, he or she will need to file a report as to who the actual driver was. Owner or driver liability could be a sensitive legal issue (SOU2005: 86), and, at least from a Swedish point of view, the government has not seen any possibilities to put any type of liability on the registered owner of the car for speeding violations. According to Swedish legal experts, owner liability conflicts with Swedish legal tradition. Driver versus owner responsibility could therefore has a large impact on how a camera system can operate from an administrative point of view and that might, at least partially, explain the number of traffic tickets that are issued. Secondly, there are large differences between Sweden and the rest of the countries in terms of the number of cameras per million inhabitants and how many traffic tickets are issued per 1,000 inhabitants. Sweden has about 2.5 more cameras per inhabitants however at the same time 50% less tickets issued per 1,000 inhabitants than in Norway. The Netherlands has similar number of cameras as Norway and France; however 49 times more tickets per 1,000 inhabitants are

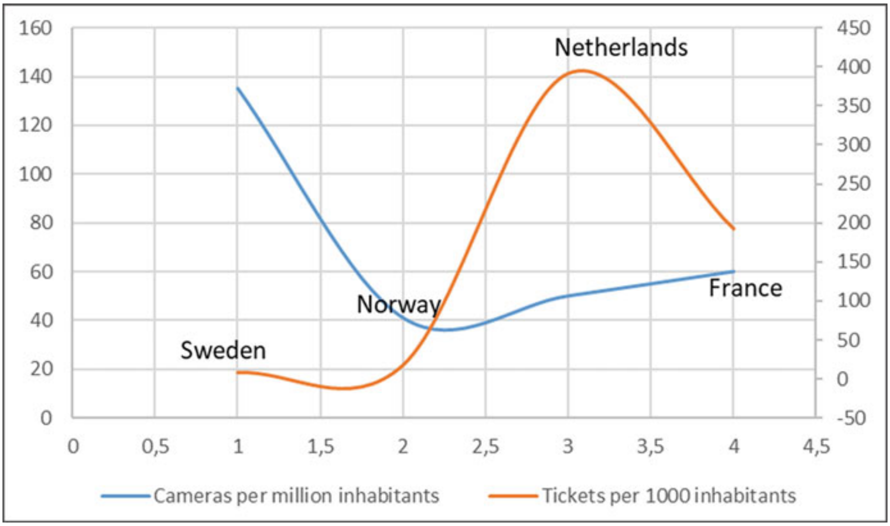

Fig. 4 Cameras and speeding tickets per inhabitants in Sweden, Norway, the Netherlands, and France. (Data from Table 2)

issued in the Netherlands than Sweden. The number of cameras and tickets per inhabitants is summarized in Fig. 4. Apparently, Sweden is at one extreme and the Netherlands is at the other.

Attitudes to Speeding and Enforcement

The different enforcement strategies in the four countries might lead to differences regarding attitudes and self-reported behavior in relation to speeding. Based on data from ESRA (2015), some comparisons of Sweden, Norway, the Netherlands, and France are made. As shown in Fig. 4, the number of speeding tickets per 1,000 inhabitants differs between the countries and especially between Sweden and the Netherlands. In ESRA, questions about perceived risk versus actual risk (self-reported) are investigated. Car drivers were asked to indicate their perceived likelihood of being checked by the police for speeding and how many times they have had to pay a fine for speeding during the last 12 months (Fig. 5). In Sweden it is only 2% that report that they have had to pay a fine at least one and in Norway 4%, while in the Netherlands it is about 15% and 11% in France. The pattern is the same for perceived risk with low values for Sweden and Norway, and higher for the Netherlands and France. In France, about 55% of the car drivers think it is a big chance of getting caught by the police, in the Netherlands 35%, while in Sweden and Norway it is only almost 20%.

Self-declared excessive speed behavior in Sweden, Norway, the Netherlands, and France is shown in Fig. 6. Answers from 1 (never) to 5 (almost) always, the figure reports 4–5 (often). Sweden and Norway show somewhat higher levels of self-

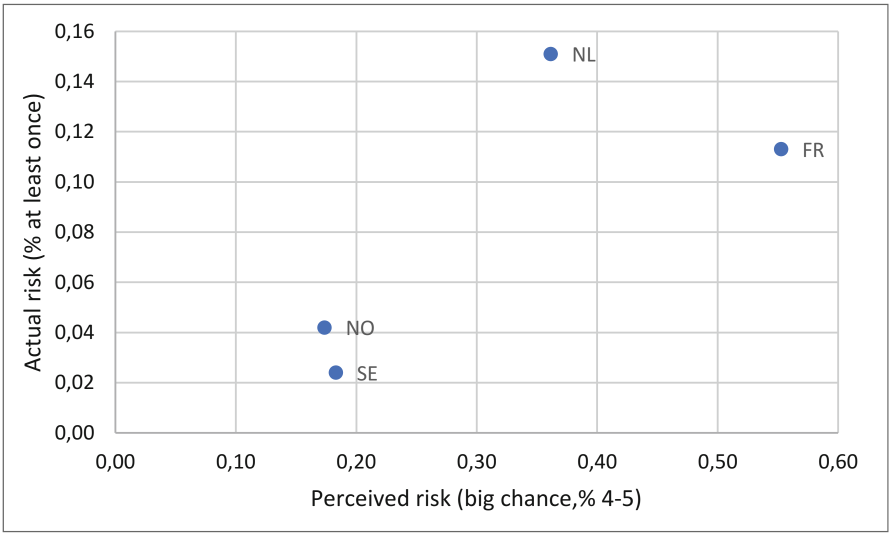

Fig. 5 Perceived versus actual risk. Perceived risk: On a typical journey, how likely is it that you (as a CAR DRIVER) will be checked by the police for respecting the speed limits (including checks by police car with a camera and/or flash cameras)? (1 = very small chance to 5 = very big chance). Actual risk: In the past 12 months, how many times have you had to pay a fine for violating the speed limits? (% of at least once). ESRA (2015)

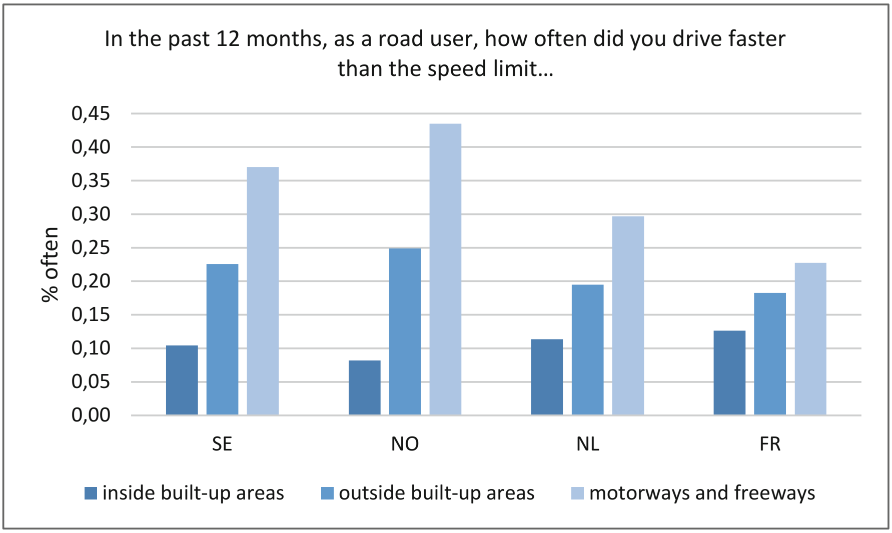

Fig. 6 Self-declared speeding behavior. ESRA (2015)

declared speeding behavior outside built-up areas and on motorways. Inside built-up areas, the trend is opposite with slightly lower reported levels of speeding for Sweden and Norway than for the Netherlands and France.

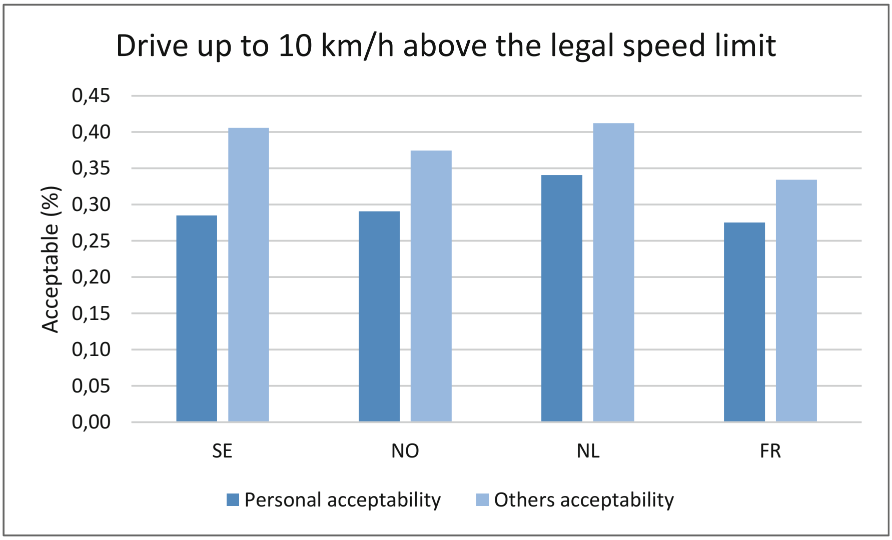

Fig. 7 Personal versus other's acceptability of speeding: "How acceptable … is it for a CAR DRIVER to… ?".% of road users who indicate driving faster than the speed limit as acceptable (% 4–5). ESRA (2015)

In Fig. 7, personal versus other's acceptability of low-level speeding, up to 10 km/h above the legal speed limit, is shown. Answers are on a scale from 1 to 5, where 1 is "unacceptable" and 5 is "acceptable," and the figure shows % answering 4 and 5. It is a rather similar pattern among the countries, with around 30% answering that they personally think it is acceptable to drive up to 10 km/h above the legal limit, while they think that others found it more acceptable (35–40%). The Netherlands has slightly higher values than France, Sweden, and Norway.

In Fig. 8, personal acceptability of unsafe traffic behavior in relation to higher levels of speeding in different situations is shown. Answers are on a scale from 1 to 5, where 1 is "unacceptable" and 5 is "acceptable," and the figure shows% answering 4 and 5. In general, it is more acceptable to exceed the speed limit by as much as 20 km/h on motorways/freeways and not acceptable in urban areas, school zones, and residential streets. On motorways/freeways, Sweden has the highest acceptability for high-level speeding, but on residential streets, France has the highest. In urban areas and school zones, none of the countries found it acceptable.

Traffic Safety Effects of Speed Cameras

Experience worldwide has proven the effectiveness of automatic speed cameras in reducing speed and, in turn, crashes and injuries. Section control, sometimes referred to as "average speed control" or "distance control: trajectory" (using the

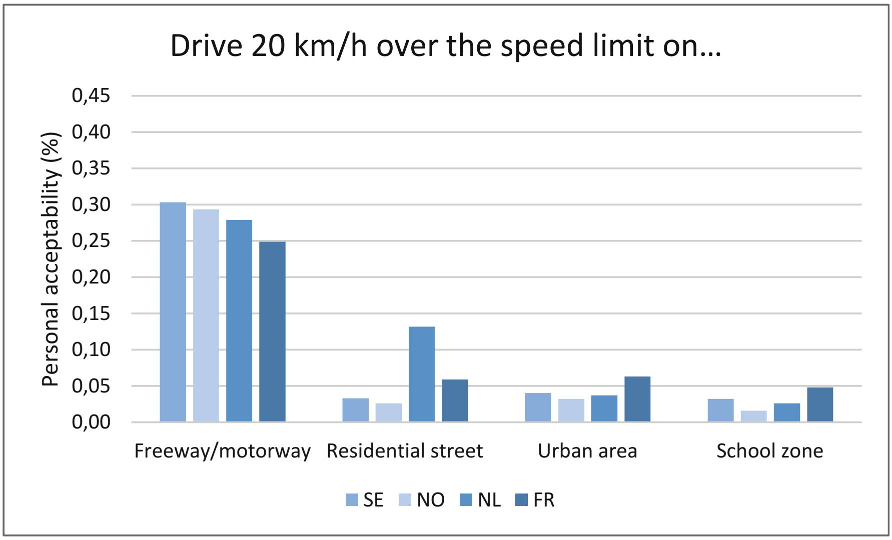

Fig. 8 Personal acceptability of speeding: "How acceptable do you, personally, feel it is for a CAR DRIVER to. . . ?"% of road users who indicate driving faster than the speed limit as acceptable (% 4–5). ESRA (2015)

measurement of the average speed over a section of road), is a relatively new measure, which seems to be very effective not only in reducing speed but also in contributing to more homogenized traffic flow (ITF 2018).

Comparison Between Section Control and Spot Speed Cameras

In Høye et al. (2019), effects of spot speed cameras and section control are studied. For fixed speed cameras, the mean speeds are reduced by 6%–15% within 500 m from the speed camera. For section control, studies in Norway (Ragnøy 2011) showed that section control reduced the mean speed over the section enforced by 11%, similar as the effects at the fixed camera sites. In a literature review by Soole et al. (2013), it was shown that section control reduced mean speeds between 8% and 28%. One advantage with section control compared to spot speed cameras is that mean speeds decrease over a longer part of the road section.

Looking at traffic safety effects, Høye et al. estimate in a meta-analysis that the number of injury crashes were reduced by 19% (−24, −14) and the number of fatalities by 51% (−72, −12) for spot speed cameras. The closer to the cameras, the larger effects on injury crashes. For section control, the injury crashes were reduced by 27% (−36; −16) and the number of fatalities and seriously injured by 54% (−63; −42).

For spot speed cameras, Høye et al. (2019) estimated that with larger distance from the camera, the effects on mean speed tend to be smaller. Looking at effects on mean speed in the near vicinity of the speed camera (< 250 m), the mean speed decreased by 11%; within 500–750 m after the speed camera, the mean speed decreased by 5%; and between 1,000 and 1,250 m after the camera by about 3%. For longer distances, the effects were smaller, and around 2,000 m after the camera, the mean speed decreased by only 1.4%. The number of personal injury crashes decreased by 18% in the near vicinity of the speed camera (<250 m); by 12%, within 500–750 m after; and by 7% at 1,000 and 1,250 m after the camera.

Change of Speed Distribution

Soole et al. (2013) concluded that section control is effective in reducing mean speed, P85, and speed variations between vehicles, and in many studies referred to in Soole et al. (2013), the decrease in P85 was greater than the decrease in mean speed. Similar changes are seen for spot speed cameras in the immediate vicinity surrounding the cameras (Vadeby and Forsman 2017), which suggests a change in the shape of the speed distribution. Overall, P85 decreases more than the average speed, and the proportion of serious offenses decreases more than total offenses. Figures 9 and 10 show the speed distribution before and after new speed cameras are installed on rural roads with a speed limit of 90 km/h (spot speed cameras at camera sites and between camera sites). Before the cameras were introduced (red line), about 60% of all cars complied with the speed limit at the camera sites and about 50% between camera sites. After the cameras were introduced, 90% of the cars complied with the speed limit at camera sites and 60% between sites. Comparing the change in the speed distributions, this was more pronounced at camera sites (Fig. 9). For high speeds, there was a larger displacement to the left after the cameras were introduced.

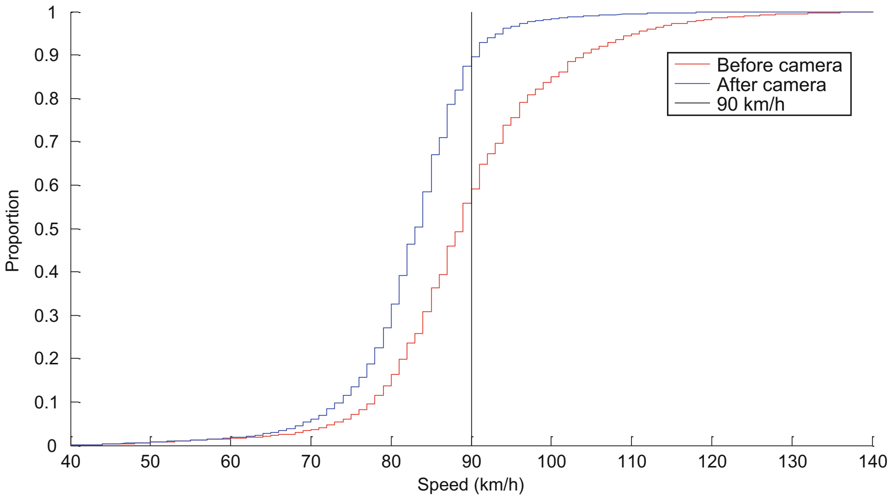

Fig. 9 Effect on driving speed at camera sites of new speed cameras on roads with a speed limit of 90 km/h. Speed distribution for all cars before and after new cameras

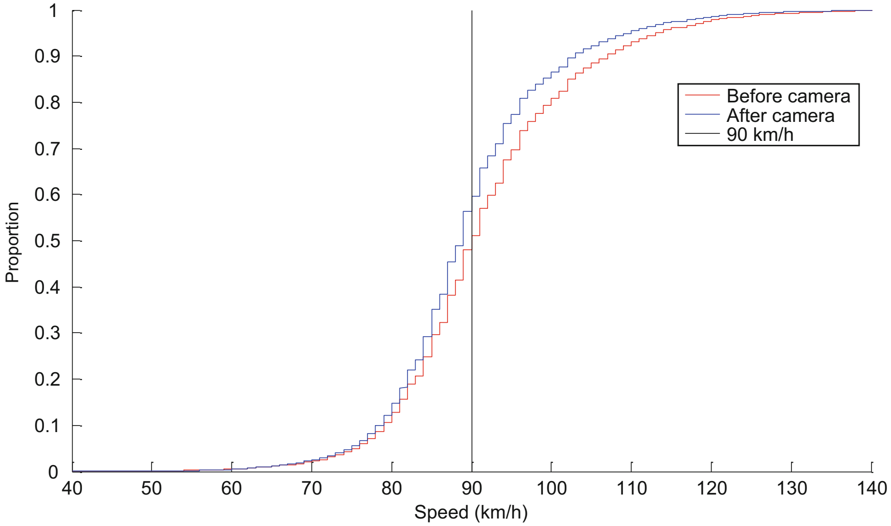

Fig. 10 Effect on driving speed between camera sites of new speed cameras on roads with a speed limit of 90 km/h. Speed distribution for all cars before and after new cameras

Experience from the Netherlands, Sweden, Norway, and France

Sweden

In Sweden, spot speed cameras are used, but the cameras are located along road sections and placed in succession with the aim to lower the speed along the entire road section.

Evaluations of the Swedish speed cameras (STA 2009; Larsson and Brüde 2010) have shown that they decrease mean speed by 4.3% (−3.6 km/h) taken over all camera road sections and speed limits. The reduction at camera sites varies between 7% and 12% depending on speed limit. Between cameras, the reduction was smaller, maximum 5%. It was also shown that the speed cameras reduced the 85th percentile (P85) more than the mean speed, by 5.9% (−5.5 km/h). Similar patterns, with larger decreases for higher speeds, have been found in terms of speed compliance, meaning that those who drive the fastest are most influenced by speed cameras. The proportion of drivers who exceed the speed limit decreased by approximately 34%. As regards traffic safety, Larsson and Brüde (2010) showed that the number of fatalities was reduced by 30% and the number of people killed or seriously injured (KSI) by 25%.

Norway

In Norway, both section control and spot speed cameras are used. Cameras are located on roads with a high injury crash record, and since 2009 there is a criterion on speed (mean speed above the speed limit) and for crash costs (at least 30% above average crash costs on similar roads in Norway). It is possible to install speed cameras at sites that meet one of the criteria.

In Høye (2014b, 2015), the safety effects of spot speed cameras were investigated for speed cameras installed between the years 2000 and 2010. The study showed that on road sections between 100 m upstream and 1,000 m downstream of the cameras, the number of injury crashes decreased by 22%. For longer road sections (3.1 km), the effects were smaller. Ragnøy (2002) evaluated the effects on speeds and concluded that depending on the speed limit and mean speed in the before situation, as well as the distance to the camera, the effect of speed cameras on mean speed varies from −1.4 km/h to −7.1 km/h.

For section control (14 road sections of whom 8 were in tunnels), Høye (2014a) showed that the number of injury crashes decreased between 12% and 22%. An earlier evaluation of Ragnøy (2011) showed that mean speed decreased by 11% at the enforced road section, similar effects as at the near vicinity of the spot speed cameras.

The Netherlands

In the Netherlands, speed cameras are used to register speeding offenses, and the vehicle owners are identified based on vehicle registration number. There are mostly spot speed cameras, both fixed and mobile; however at some motorways, section control has been introduced. The guidelines for where the cameras should be placed states that they should be located at roads with a relatively high number of crashes, where there is a plausible connection between crashes and speed and where there is a relatively high percentage of speeders.

The effects of mobile speed cameras were studied by Goldenbeld and Van Schagen (2005). Their study showed that mean speed decreased with 4 km/h from 82.6 to 78.6 km/h and the percentage of speed offenders decreased from 27.4% to 15.6% on the roads with mobile speed enforcement. The number of personal injury crashes involving motorized traffic decreased by 21%. Effects of regression to the mean were not considered in the analysis, and it is therefore likely that the real effect is somewhat smaller.

France

Automated speed cameras were introduced in France in 2003, following a decision by President Chirac in 2002 to make road safety one of the three major national priorities during his mandate. Fixed and mobile speed cameras were implemented progressively, and between 2003 and 2009, about 1,700 fixed speed cameras were implemented, supplemented by more than 900 mobile cameras. All fixed cameras had a sign identifying its presence approx. 1 km ahead of the camera. In the beginning, it was a central decision to decide exactly where the cameras were to be placed, and they were installed at points in the network with the most traffic. Later on the locations were decided upon at the local level taking the characteristics of the infrastructure and levels of crash risk into account. Between 2002 and 2005, the mean speeds fell by 8.9 km/h on secondary roads and by 7.7 km/h on two- or three-lane highways (two-way roads). Fatalities decreased by 25–35% in rural areas, 38% on urban motorways, and 14% on urban roads (ITF 2018). Viallon and Lamon (2013) showed that the French speed camera program reduced the proportion of fatal crashes attributable to high-level speeding (>20 km/h over the limit) from 25% to 6% over the period 2001–2010 and increased the proportion attributable to low-level speeding from 7% to 13%.

Discussion

In this chapter, speed limits, speed management, and different methods to influence speed behavior has been analyzed and explored. Vision Zero as a policy framework has guided this analysis. The second part of the chapter covers an analysis of Sweden, Norway, the Netherlands, and France speed camera program, or safety camera system which at least Sweden prefer to name it. This analysis also includes a discussion around related traffic safety effects, self-reported behavior, and attitudes.

First, to analyze speed compliance, the speed limits and what criteria that underpins the choice of specific speed limits need to be discussed. In a Swedish historical context, it is obvious that the speed setting rationale has evolved over the years. In practice therefore, there is a mix of speed limits based on different criteria and speed setting regime. It is also obvious that, over the years, every regime drives down the speed limits. The 85-percentile regime implemented in the 1960s has higher speed claims than speed limits set according to Vision Zero. From a safety point of view, this could see as a paradox because at the same time both the infrastructure and the cars have become safer. One explanation could be that safety as a value, within a transport policy framework, has been strengthened over the years and that speed limits are seen as an integrated part of the road transport system rather than only an instrument to limit some road user choice to drive at very high speeds. However from a strict compliance perspective, lower speed limits might increase the proportion of drivers who violate the speed limit (Vadeby and Forsman 2014). Although it is difficult to draw any firm conclusions, it seems that the speed limit sign itself is the most important factor influencing the drivers' choice of speed regardless of the design of the environment and the vehicle. Even if one is on a motorway in a car that can do more than 200 km/h and the speed sign shows 80 km/h, many drivers will comply with the speed sign to a large extent. Without the speed sign, one could expect rather higher speed. Setting the speed limits according to people's actual behavior in order to increase compliance seems therefore rather awkward. Vision Zero is a policy innovation which differs from a traditional approach to road safety in several respects. These differences are also evident when it comes to setting the speed. Traditionally, the speed limit system is seen as an instrument to lower the risk and make the road transport system safer. Based on a

Vision Zero approach, the speed limit system and its different speed limits are seen as a labeling of the safety thresholds. If you as a driver keep within the speed limits, as it is posted and below, then you can expect, if an accident occurs, that you will survive and without any serious injuries. This is radical change in the mind-set when it comes to speed and speed limits, and these ideas are more in line with the society dealing with toxicological substance, for example. These substances are accepted if they are kept below the threshold for serious impact on humans. Although a system like this is complicated and there are lots of trade-offs when it comes to details, this type of system could be easier to communicate to the public. In this context, speed and speed limits are a safety regulation factor. Safe (and environmentally friendly) roads and vehicles enable to facilitate higher speeds regardless of the driver's behavior.

Second, irrespective of what criteria that underpins speed limits, the drivers' speed compliance is an important issue including drivers speed choice and motives. One important dimension is the target group for different interventions, namely, risk groups or population-based strategies. Most countries are most likely carrying out both these strategies; however historically, especially in the more advanced countries, it seems that strategies aiming to increase compliance with speed limits are being advanced with a more population-based strategy. Another important dimension is if drivers' choice of speed is a result of a deliberate calculation of the cost and benefits (the "economic man," an idealized person who acts rationally, with perfect knowledge and who seeks to maximize personal utility) of speeding, or if the choice is more a result of unconscious habits and social norms. In public policy in general and in road safety in particular, the theory about the economic man does have a dominant position. However, due to new research, especially relating to nudging, new perspective has emerged, and the Swedish safety camera system is probably a good example of nudging in practice.

Third, there is a strong ongoing discussion about digitalization automation and new technology in our society. Although these trends could result in completely new products and service, many times it is most cases rather replacements of existing products and services. Speed enforcement is such public service that has gone through a large change from manual enforcement to camera surveillance. Productivity and efficiency are important drivers for this to happen. Finally, speed limit system, speed management, theory about human behavior, use of new technology, and public policies such as Vision Zero are all factors that influence how different jurisdictions manage their speed camera program and its characteristics. In this chapter, we have shown that even though Sweden, Norway, the Netherlands, and France all are countries in Europe, the way that they operate their camera program has both similarities and differences. It seems that all these countries have invested primarily in fixed camera systems. However the systems scale and how they operate are different. It is difficult to evaluate and compare these systems from a safety point view, at least from a macro perspective.

A speed camera system has the possibility to affect the society and its road users both at a macro and at a micro perspective. In a micro perspective, it is primarily about how effective the cameras are locally at the enforced road sections, while at a macro perspective it is more about how the camera enforcement system, possibly together with the overall enforcement strategy, affects attitudes and norms related to speeding. Experience worldwide has proven the effectiveness of automatic speed cameras in reducing speed and, in turn, crashes and injuries. In this chapter where Sweden, Norway, the Netherlands, and France are compared, it is shown that there are large discrepancies in the camera enforcement strategies of the four countries. Looking at the number of cameras, Sweden has 135 cameras per million inhabitants while the other three countries have between 40 and 60 cameras per million inhabitants. If instead the number of speeding tickets is compared, Sweden has only 8 tickets per 1,000 inhabitants, while Norway has 18, France 192, and the Netherlands 391. One interesting question is how these differences affect both the actual outcome of the system in terms of speeds, crashes, and injuries and, however, also the norms and attitudes in the society. In all four countries, evaluations of the camera system are performed; however the evaluation methods are different and the results therefore not exactly comparable. Looking at mean speed, in Sweden the mean speed decreased by about 4% looking at an entire enforced road section, however, with larger effects near the cameras. The Netherlands showed decreases of about 4 km/h as an effect of mobile speed cameras; however the evaluation does not clarify at what distances from the cameras. In France, a general mean speed decrease of about 8 km/h between 2002 and 2005 was seen, attributed primarily to the effects of speed cameras (ITF 2018). In Norway, it was shown that section control decreased average speeds by 11% over the entire enforced road section (Ragnøy 2011), similar effects as in the near vicinity of spot speed cameras. Looking at the reduction of injury crashes, Sweden shows a decrease of severe crashes by 25% and of fatalities by 30%, Norway and the Netherlands a reduction of all injury crashes by about 20%, and France reductions of fatalities by approximately 30% in rural areas. If the differences between injury level in the investigations are considered as estimated by the power model (Elvik 2013; Elvik et al. 2019), it is not possible to show any major differences between these four countries in a micro perspective.

The enforcement strategies and in particular the number of cameras and speeding tickets issued also affect the attitudes and norms of the road users. Results from ESRA show that when car drivers were asked to indicate their perceived likelihood of being checked by the police for speeding, car drivers in Sweden and Norway report much lower perceived risk than the Netherlands and France. In France, about 55% of the car drivers think it is a big chance of getting caught by the police and in the Netherlands about 35%, while in Sweden and Norway it is only about 20%. The pattern is very similar to the number of issued tickets per 1,000 inhabitants. When looking at how many times car drivers that report they have had to pay a fine for speeding during the last 12 months, it is a similar relationship where only 2% in Sweden report they have had to pay a fine at least one and in Norway 4%, while in France 11% and the Netherlands about 15%.

The ESRA survey also investigates self-reported behavior in relation to speeding. In all four countries, it is a similar pattern, where about 30% answering that they personally think it is acceptable to drive up to 10 km/h above the legal limit. The

Netherlands has slightly higher values than France, Sweden, and Norway. Looking at more severe speeding in different situations, it is shown that in general, it is more acceptable to exceed the speed limit by as much as 20 km/h on freeways and motorways and not acceptable in urban areas, school zones, and residential streets. This pattern is the same among the four countries, even though the reported level differs somewhat. On motorways/freeways, Sweden has the highest acceptability for high-level speeding, but on residential streets, France has the highest. In urban areas and school zones, none of the countries found it acceptable to exceed the speed limit by 20 km/h.

In conclusion, the different enforcement strategies regarding the number of cameras and speeding tickets issued has the possibility to affect the society and its road users both at a macro and micro level. Locally, in a micro perspective on the enforced roads, the effects of speed cameras are rather similar among countries, and differences can probably be explained by the type of camera (spot speed or section control), distances between cameras, and local conditions. In a macro perspective, the perceived risk and self-reported risk of getting caught in a speed check is correlated with the number of issued speeding tickets. Though the perceived likelihood of being checked by the police differs between the studied countries, self-reported speeding behavior is rather similar. Therefore, an important aspect that needs to be analyzed and discussed is how to optimize a speed camera system from a road safety point of view. There are two problems that might occur. First, even though a speed camera program delivers lower speed locally, a low amount of fines might hinder the possibility of also affecting a general speed compliance culture. Second, if the system issues many fines, after a while the drivers might regard these fines as simply an extra charge which they are forced to pay – but it will have little or no effect on their speed behavior. A speed cameras system could become primarily a revenue-raising system rather than a road safety instrument. A hypothesis could be that Sweden might not operate their system optimal from a safety point of view and need to increase the number of fines issued. On the other hand, it may be that from a safety point of view in the Netherlands, too many fines are issued. The public perception about raising revenue does matter, considering that it can hinder the implementation of statutes and programs, and it generally has an impact on people's general attitudes.

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Driver Distraction: Mechanisms, Evidence, Prevention, and Mitigation

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Abstract

In this chapter, the reader is introduced to the topic of driver distraction: its definition and mechanisms; its impact on driving performance and safety; approaches to preventing it; evidence-based injury prevention and mitigation countermeasures; and new frames of reference for conceptualizing distraction as traditional driving functions and tasks become increasingly automated. Some strategies that might be considered by societal stakeholders in setting a coordinated agenda for the management of distracted driving going into the future are also presented. Until all vehicles can safely drive themselves, in all conditions, all of the time, it is unlikely that, for driver distraction, Vision Zero will be achieved. In the meantime, however, there is much that can be done to slow its spread and mitigate it effects.

Keywords

Driver distraction · Distracted driving · Road safety · Theory · Impact · Countermeasures · Mitigation · Vision zero

Introduction

Driving is a complex activity that requires, often simultaneously, the performance of one or more driving functions: route finding, route following, velocity control, collision avoidance, rule compliance, and vehicle monitoring (e.g., of fuel status) (Brown 1986). Despite the complexity of this activity, it is common to see drivers engage simultaneously in a range of other, non-driving, activities that have potential to distract them and compromise the performance of these driving functions.

Driver distraction is one of several mechanisms of *driver inattention* (Regan et al. 2011; Engström et al. 2013) and there is converging evidence that it is a road safety problem (e.g., Beanland et al. 2013; Oviedo-Trespalacios et al. 2016; Dingus et al. 2016). This chapter provides the reader with a general understanding of driver distraction and how to manage it as a road safety issue. We commence by defining what is meant by "driver distraction" and distinguishing it from other forms of driver inattention.

Driver Distraction: Definition, Mechanisms, and Impacts on Driving Performance

Defining "Driver Distraction"

Distraction has been defined inconsistently in the literature (Regan et al. 2011). This is problematic as, in the absence of a commonly accepted definition that can be operationalized and used to code crash and incident data, the role of distraction as a contributing factor in crashes and incidents will be ambiguous (Beanland et al. 2013) – and may lead to quite different estimates of its contribution to crashes and incidents (Gordon 2009). Inconsistencies in definition also make the comparison of research findings across studies difficult, or impossible (Lee et al. 2009).

Driver distraction and driver inattention are related constructs. Like driver distraction, there has been inconsistency in the literature around the definition of driver inattention, and some diversity in thinking about the relationship between the two constructs (Regan et al. 2011). To this end, Regan et al. (2011) attempted to elucidate the relationship between driver distraction and inattention, in the form of a taxonomy of driver attention. The taxonomy was derived from a review of previous classifications of attentional failures identified as having contributed to crashes in in-depth crash studies (e.g., Treat 1980; Hoel et al. 2010; Van Elslande and Fouquet 2007; Wallén Warner et al. 2008). Regan et al. (2011) defined driver inattention as "insufficient or no attention to activities critical for safe driving" (p. 1780) and proposed that driver inattention is induced by five attentional mechanisms (identified in Table 1 below), one of which they labelled "Driver Diverted Attention," which is synonymous with driver distraction. (See Regan et al. (2011) for a more detailed

Table 1 Mechanisms of driver inattention (Source: Regan et al. 2011)

Mechanism of inattention	Definition
Driver restricted attention	"Insufficient or no attention to activities critical for safe driving brought about by something that physically prevents (due to biological factors) the driver from detecting (and hence from attending to) information critical for safe driving" (p. 1775); e.g., due to drowsiness or fatigue – driver dozes off momentarily, with eyes closed, and almost hits a pedestrian crossing the street ahead
Driver neglected attention	"Insufficient or no attention to activities critical for safe driving brought about by the driver neglecting to attend to activities critical for safe driving" (p. 1775); e.g., due to faulty expectations; driver neglects to scan to the left for approaching trains at a railway level crossing because s/he does not expect trains to be there (because they are rarely or never seen)
Driver mis-prioritized attention	"Insufficient or no attention to activities critical for safe driving brought about by the driver focussing attention on one aspect of driving to the exclusion of another, which is more critical for safe driving" (p. 1775); e.g., driver looks over their shoulder for too long while merging and fails to see a lead vehicle in front braking rapidly
Driver cursory attention	"Insufficient or no attention to activities critical for safe driving brought about by the driver giving cursory or hurried attention to activities critical for safe driving." (p. 1776); e.g., a driver on the entry ramp to a freeway who is in a hurry does not complete a full head check when merging and ends up colliding with a merging car
Driver diverted attention	"The diversion of attention away from activities critical for safe driving toward a competing activity, which may result in insufficient or no attention to activities critical for safe driving" (synonymous with driver distraction; p. 1776); e.g., a driver reading a text message on a mobile phone while driving; a driver daydreaming or engaged in internal thought that is driving- or non-driving related

description of their taxonomy and Engström et al. (2013) for a description of a very similar taxonomy of driver inattention derived from a first principles review of human attentional theory.)

Regan et al. (2011) defined driver diverted attention (i.e., driver distraction) as "the diversion of attention away from activities critical for safe driving toward a competing activity, which may result in insufficient or no attention to activities critical for safe driving" (p. 1776). This definition was modelled on an earlier definition formulated by Lee et al. (2009, p. 34) that was subsequently endorsed by an international group of experts convened by the International Organization for Standardization (ISO): "Driver distraction is the diversion of attention away from activities critical for safe driving toward a competing activity."

Both of these definitions are widely cited in the international literature and are considered suitable by the authors for framing and interpreting the material reported in this chapter. Both definitions carry with them some assumptions (Regan and Hallett 2011):

- Competing activities can be driving-related (e.g., a flashing low fuel warning light) or non-driving related.
- Driver engagement in competing activities can occur involuntarily or be driver-initiated.
- Competing activities can derive from inside the vehicle or outside of the vehicle.
- Competing activities may derive from unknown sources of distraction internal to the mind, such as when daydreaming.
- Driver engagement in competing activities may interfere with the performance of activities critical for safe driving that can be seen (e.g., a lane excursion) or unseen (e.g., a freeway exit missed).

Engström et al. (2013) characterize "activities critical for safe driving" as ". . .those activities required for the control of safety margins" (p. 17). These include (p. 17) "activities at all levels that are required to maintain acceptable safety margins, such as maintaining headway, keeping in the lane, visually scanning an intersection for oncoming vehicles, deciding whether to yield and interpreting safety-related traffic signs, but excludes those driving-related activities that are not directly related to safety margin control, such as navigation, route finding and eco-driving."

While performance of a competing activity may divert attention away from any of the driving functions identified by Brown (1986), it is the impact of this diversion on activities critical for safe driving that has been of most interest to the road safety community – and is the reason why the two distraction definitions described above have been framed in the way they have.

Factors That Trigger Driver Distraction

An episode of driver distraction may be triggered through various mechanisms that have been found to relate to a driver's state, driver needs, properties of the source of the distraction, internal (to the mind) stimuli that trigger distraction, and a driver's personality characteristics. These mechanisms can, in turn, be classified broadly as either top-down (voluntary; endogenous) or bottom-up (involuntary; exogenous) mechanisms (e.g., Trick and Enns 2009; Lee et al. 2020).

Various driver *states* may trigger a diversion of attention, including boredom, sleepiness, or fatigue (e.g., Atchley and Chan 2011), social angst (e.g., fear of missing out; Atchley and Warden 2012), and emotionality (e.g., affective state; Chan and Singhal 2013). Driver *needs* may also trigger a diversion of attention and include the need to communicate with others (Oviedo-Trespalacios et al. 2020a), to be informed (Engelberg et al. 2015), to be entertained (George et al. 2018; Steinberger et al. 2016), and to satisfy basic biological drives like hunger (Irwin et al. 2015). For example, a biological feeling of hunger may trigger a whole chain of internal thoughts about what a driver would like to eat, where they might find what they want to eat, etc., all of which will distract them. These triggering factors that stem from driver states and needs can be characterized as top-down factors (Trick and Enns 2009).

The physical properties of a source of distraction may themselves become distraction triggering factors from a bottom-up perspective. For example, things that are moving, unusual, attractive, unexpected, threatening, salient, or conspicuous are most likely to entice a diversion of attention away from activities critical for safe driving (Regan et al. 2011). Similarly, internal thoughts or internal stimuli from deep within the mind can trigger distraction in a bottom-up manner (as when daydreaming, mind-wandering, or engaged in task-unrelated thoughts; e.g., Smallwood and Schooler 2006). Finally, personality factors, such as a driver's willingness to engage in distracting activities (Lerner and Boyd 2005) and whether they are particularly vulnerable to attentional capture (distraction prone; Peña-Suarez et al. 2016), may also act as distraction triggers.

There are, in short, many factors that can trigger driver distraction: that is, trigger a diversion of attention away from activities critical for safe driving toward a competing activity.

Competing Activities and Sources of Distraction

A competing activity can be conceptualized as an action performed by a driver on a source of distraction that competes for attention required for the performance of activities critical for safe driving (Regan et al. 2009); for example, as in dialling (the action) a phone number using a mobile phone (the source of distraction). The source of distraction and the actions performed on it by the driver, together, define a competing activity (Regan et al. 2009).

Regan et al. (2009) reviewed seven research studies (five crash studies and two observational studies) in which driver distraction was cited as a contributing factor. They identified around 60 different sources of distraction that gave rise to competing activities in these studies and distilled them into the following broad categories (Regan and Hallett 2011):

- Objects (e.g., mobile phone, advertising billboard, apple).
- Events (e.g., crash scene, lightning).
- Passengers (e.g., child, adult).
- Other road users (e.g., cyclists, pedestrians, other vehicles).
- Animals (e.g., dog).
- Internal stimuli (e.g., that trigger thoughts or the urge to cough or sneeze).

These sources of distraction will be distracting only if drivers interact with them. Regan et al. (2009) identified 53 separate, although not necessarily mutually exclusive (e.g., answering, drinking, listening) actions, that were performed on the various sources of distraction revealed by their analysis.

A consistent finding in the literature is that around 30% of distraction-related crashes derive from driver engagement with distraction sources *outside* the vehicle. These include animals, architecture, advertising signage, construction zones/equipment, crash scenes, incidents (e.g., road rage), insects, landmarks, road signs, road users, scenery, other vehicles, and weather (e.g., lightning) (Gordon 2009).

A failure to differentiate between a source of distraction and the actions performed on it by a driver can lead to imprecision in the classification of distraction sources. Regan et al. (2009), for example, noted a tendency in some of the studies they reviewed to confound the reporting of events, objects, and actions as sources of distraction. The following, for example, were reported as sources of driver distraction in some of the studies they reviewed (e.g., Gordon 2005): “automobile mechanical problem,” “trying to find destination/location,” “driver dazzled by sunstrike,” “checking for traffic,” and “police/emergency vehicles”.

There is also some confusion in the literature about whether driver states (e.g., fatigue) are themselves sources of distraction. The following, for example, were reported as distraction sources in one of the studies reviewed by Regan et al. (2009; Glaze and Ellis 2003): “driver fatigue/asleep” and “alcohol and fatigue/sleep.” Driver states, such as being fatigued or intoxicated by alcohol, are not in themselves sources of distraction. Rather, they are biological states that can give rise to inattention in the absence of a competing activity (Regan et al. 2011). In the taxonomy of inattention proposed by Regan et al. (2011) (see Table 1), this mechanism of inattention is referred to as driver restricted attention.

Types of Distraction and Triggered Responses

Types of Distraction

A source of distraction has certain “modal properties” (Hallett et al. 2011) which, along with its other physical properties, the state of the driver, drivers’ needs and their personality characteristics, may also trigger a diversion of attention away from activities critical for safe driving.

It is the modal properties of a source of distraction that have been invoked in the literature to define “types” of distraction. An advertising sign, for example, may induce “visual distraction” if a driver looks at it and “internal distraction” (see below) if s/he thinks about the message(s) it conveys (Regan and Hallett 2011). Types of distraction have been characterized in the literature in two ways. Regan (2010) and Regan and Hallett et al. (2011) differentiate as follows between six types of distraction based on the sensory modality through which the diversion of attention toward a competing activity is initiated:

- Diversion of attention towards things that we see (“visual distraction”).
- Diversion of attention towards things that we hear (“auditory distraction”).
- Diversion of attention towards things that we smell (“olfactory distraction”).
- Diversion of attention towards things that we taste (“gustatory distraction”; e.g., the taste of a rotten piece of apple).
- Diversion of attention towards things that we feel (tactile distraction; e.g., the feel of a hairy spider crawling on one’s leg).
- Diversion of attention towards things that we think about (internal or “cognitive” distraction).

It is more common in the literature, however, for “types” of distraction to be differentiated according to the *impact* that a competing activity has on activities critical for safe driving (e.g., WHO 2011):

- “Visual distraction” – taking one’s eyes off the road
- “Cognitive distraction” – taking one’s mind off the road
- “Auditory distraction” – taking one’s ears off the road
- “Biomechanical distraction” – taking one’s hand(s) off the steering wheel.

There are, however, problems with this latter way of conceptualizing “types of distraction”: (1) it results in an artificially restricted range of distraction types which have potential to interfere with activities critical for safe driving (i.e., it excludes consideration of tactile, olfactory and gustatory distraction); (2) taking one’s ears off the road is really a by-product of taking one’s mind off the road (e.g., as when failing to hear the sound of an approaching motorcycle when engrossed in a mobile phone conversation), rather than a type of distraction per se; and (3) “biomechanical distraction” is actually a form of bimanual, or structural, interference (Kahneman 1973; McLeod 1977) induced by distraction, not a type of distraction per se.

Triggered Responses

The repertoire of driver actions (e.g., answering, listening, writing) that may be performed on all the sources of distraction known to exist is potentially huge. However, the behavioral effects triggered by these driver actions, that may lead to interference (see below) with activities critical for safe driving, appear finite in number. Hallett et al. (2011) have referred to these behavioral effects as “triggered responses” and have characterized them (for distracted drivers) as follows:

- *Eyes off the road* – driver takes eyes off activities critical for safe driving.
- *Mind off the road* – driver takes mind off activities critical for safe driving.

- *Ears off the road* – driver takes ears off activities critical for safe driving (as a result of having one's mind off the road).
- *Hands or feet off controls* – driver takes hands and/or feet off activities critical for safe driving.

Conceptualized this way, a given type of distraction (e.g., visual distraction; as defined by Regan and Hallett 2011) may give rise to one or more of these triggered responses, often simultaneously. For example, visual distraction, such as that deriving from the diversion of attention toward an advertising billboard, may take both a driver's eyes off the road (as when looking at the billboard) and their mind off the road (when thinking about its contents), and while thinking about its contents, their ears off the road (if they become oblivious to auditory information around them critical for safe driving).

Interference

Triggered responses created by a driver performing an action, or actions, on a source of distraction will likely interrupt or interfere in some way with the performance of activities critical for safe driving.

Driving is a complex, multitask activity (Regan and Strayer 2014; Lee et al. 2009) and different types of attention are required for the performance of activities critical for safe driving, depending on the moment-to-moment requirements of driving. These may include focussed attention, selective attention, divided attention, sustained attention, and switched attention (Wickens and McCarley 2008). Driving, and specifically activities critical for safe driving, also require for their performance the execution of a range of psychological processes that span all stages of the human information processing chain (Michon 1985): detection, perception, short- and long-term memory, decision-making, and responding. Driving typically involves, at any one time, the concurrent execution of multiple tasks, each involving one or more of these types of attention and human information processes. When attention is diverted toward a competing activity, the triggered responses that it generates may interfere with the performance of any or all of these processes during the time that attention is diverted, and may even continue to interfere with activities critical for safe driving for some time after attention returns back to driving (e.g., Strayer and Fisher 2016).

Generally, the degree of interference generated by a competing activity will be a function of three factors (Wickens 2002, 2005):

- The joint demand of the activities critical for safe driving and the competing activity being performed.
- The degree to which both activities compete for access to common human information processing resources (stages of processing [perceptual-cognitive versus action or early versus late processing], processing codes [verbal versus spatial], perceptual modality [auditory versus vocal], and visual channel [focal versus ambient]).

- The manner in which the driver's attention is distributed between both activities in order to meet their joint demands, whether it is divided between both activities or is focussed primarily on the competing activity.

The research community is still at an early stage, however, in operationalizing the specific mechanisms of interference brought about by distraction, which are discussed further in this chapter in the section "Evidence Implicating Distraction as a Traffic Safety Problem." While few of these mechanisms have been operationalized, the impacts that they have on driving performance are better researched and understood. They are discussed in the section "Moderating Factors and Self-Regulation."

Moderating Factors and Self-Regulation

The impact that the performance of a competing activity has on activities critical for safe driving is not constant. The same competing activity (e.g., talking on a mobile phone) may have different effects on activities critical for safe driving depending on factors such as the characteristics of the driver, the demands of driving, the demands of the competing activity, and the ability of the driver to self-regulate their behavior in the face of, or in anticipation of, distraction (Young et al. 2009). Young et al. have labelled these factors "moderating factors" and distinguish between four such factors.

- *Driver characteristics*: There are characteristics of the driver which may influence the impact of distraction on activities critical for safe driving – by moderating a driver's willingness to engage in distracting activities, their ability to divide attention between multiple tasks, and their ability to self-regulate their driving in order to maintain suitable safety margins when distracted (Young et al. 2009, p. 340). These characteristics include driver age, gender, driving experience, driver state (e.g., drowsy, drunk, angry), familiarity with and amount of practice with the competing task, and personality (e.g., the propensity to take risks and succumb to peer pressure) (Huth and Brusque 2014; Oviedo-Trespalacios et al. 2020b).
- *Driving task demand*: The characteristics of the primary driving task itself may influence, in at least two ways, the impact that a competing activity has on activities critical for safe driving: (a) by increasing or decreasing the driver's mental workload and, hence, reducing or increasing the amount of cognitive resources available for performance of competing activities and (b) by modifying the probability that the driver will have to react rapidly to an unexpected critical event that can give rise to a collision (Young et al. 2009). These characteristics include traffic conditions, weather conditions, road conditions/design, the number and type of vehicle occupants, the ergonomic quality of vehicle cockpit design, and vehicle speed (Li et al. 2020a; Onate-Vega et al. 2020; Oviedo-Trespalacios et al. 2017a, 2020b).

- *Secondary task demand*: The demands of the competing activity will also influence the degree to which it interferes with activities critical for safe driving, and hence distracts the driver. Secondary (competing) task characteristics that influence secondary task demand include (a) how similar the task is to driving sub-tasks (e.g., whether it requires visual and/or manual control actions similar to those required for performing activities critical for safe driving), (b) its complexity, (c) whether or not it can be ignored, (d) how predictable it is, (e) how easily it can be adjusted, (f) how easy it is for the task to be interrupted and resumed, and (g) how long it takes to perform the task (Young et al. 2009; Regan et al. 2011; Oviedo-Trespalacios et al. 2020b).
- *Self-regulation:* Self-regulation, in the distraction context, refers to the ability of a driver to self-regulate their behavior in the face of, or in anticipation of, a competing activity in order to compensate for its potentially adverse effects (Young et al. 2009). Young et al. (2009) suggest that self-regulation can occur at the strategic, tactical, and operational levels of driving control (Michon 1985) – in order to regulate their exposure to competing activities (strategic control), to regulate the timing of their engagement in the competing activity (tactical control), and to control mental resource investment in it (operational control). Examples of self-regulation at each of these levels include turning off a mobile phone before a trip (exposure; strategic control), interrupting speech with a passenger when driving through an intersection (timing of engagement; tactical control), and increasing inter-vehicle headway when engaged in a mobile phone conversation (resource investment; operational control) (Saifuzzaman et al. 2015; Oviedo-Trespalacios et al. 2019a; Li et al. 2019; Chen et al. 2020; Bastos et al. 2020).

Impact on Driving Performance

When a driver diverts attention away from activities critical for safe driving toward a competing activity, this may interfere, through the mechanisms discussed, with the performance of driving activities.

Various driving performance deficits are known to arise when drivers are distracted, for a wide range of competing activities – ones that involve interaction with technologies (e.g., mobile phones, iPods, DVD players, navigation systems, e-mail systems, radios, and CD players) and ones involving performance of everyday activities (e.g., eating, drinking, smoking, reading, writing, reaching for objects, grooming, and conversing with passengers). These performance deficits have been discovered in laboratory studies, driving simulators, and in instrumented vehicles driven along test tracks.

The various driving performance deficits reported vary primarily according to the triggered responses induced by the different types of distraction (i.e., eyes off road, ears off road, mind off road, or hands and/or feet off vehicle controls).

Competing activities that primarily take drivers' *eyes* off the road have been found to effect specific aspects of driving performance: the selection of information (e.g., failing to detect relevant information from the roadway; spatially concentrated gaze on the forward road center when eyes are returned to the forward roadway); information processing (e.g., longer reaction times to roadway warnings and braking lead vehicles; change blindness that disrupts the detection of changes in the road scene); and vehicle control (e.g., degraded lane keeping performance; reduced speed; increased following distance). For reviews, see Bayley et al. (2009), Horberry and Edquist (2009), and Bruyas (2013). Generally, delays in event detection are greater for competing activities that are visually distracting than for those that are cognitively distracting (that take one's mind off the road) (Victor et al. 2009).

Competing activities that primarily take a driver's *mind* off the road have also been found to affect specific aspects of driving performance: the selection of information (e.g., spatially concentrated gaze on the forward road center; less attention to peripheral hazards; less checking of rear-view mirrors, speedometer); information processing (e.g., inattention blindness, resulting in the "looked but failed to see" phenomenon; memory loss, resulting in an inability to remember some things that have been seen during a drive); and vehicle control (more hard braking; looking less at traffic lights and missing red lights; more navigation errors; reduced variability in lane keeping performance resulting from gaze concentration; no appreciable impact on following distances; acceptance of shorter gaps when turning across oncoming traffic; small decreases in speed; fewer lane changes; more conflicts with vulnerable road users; more traffic rule violations [speeding; red light running; crossing solid lines]; reduced ability to cope with wind gusts; errors [e.g., stopping at green lights and taking off before lights are green]; reduced scanning of intersection areas to the right; and reduced situation awareness [being less able to identify, locate, and respond to hazardous vehicles and to avoid accidents]). For reviews, see Bayley et al. (2009), Horberry and Edquist (2009), and Bruyas (2013).

The authors are unaware of any experimental research that has isolated the impact on activities critical for safe driving of taking one's hands and/or feet off vehicle controls when distracted (e.g., when steering with one hand while talking on a handheld phone; when steering the vehicle with both knees, as is sometimes seen in video footage from so-called naturalistic driving studies).

Regan et al. (2011; see also Ranney 2008 and Regan 2010) have noted some difficulties in making sense of specific data deriving from studies of the impact of distraction on driving performance. First, it is difficult to rank competing activities in terms of how more or less distracting they are because of differences across studies in methods, measures, and competing tasks employed. Secondly, it is difficult to judge whether a deficit in driving performance within a study brought about by distraction is acceptable, because there is currently no agreement within the international research community on what is an acceptable level of performance degradation for any given competing activity. Finally, the magnitude, and indeed presence, of any performance decrement will be a function of the various moderating factors discussed previously, especially the amount of freedom drivers have to interact in their own way and time with the competing task. Constraining participants to interact with competing tasks in experimental settings in a manner that they would not in the real world may produce performance deficits that simply do not materialize in the real world.

Perhaps one of the greatest difficulties in interpreting driving performance deficits, as pointed out by Regan et al. (2011; see also Wijayaratna et al. 2019), is in knowing to what extent a given reduction in driving performance (e.g., a 20% increase in lateral lane excursions) translates into increased crash risk. Algorithms that link the two remain to be developed and validated.

This section has focussed on the impact of distraction on driver and driving performance. In the following section, we review what is known about the contribution of driver distraction to crashes and crash risk.

Evidence Implicating Distraction as a Traffic Safety Problem

In this section, we examine the impact of distracted driving on traffic safety. We focus here on two types of studies:

- Crash studies that gather information on the frequency and role of distraction involvement in crashes.
- Crash risk studies that aim to provide information about the increased driving risk posed by driver involvement in a distraction-related activity over and above that of the normal risk posed by driving.

Crash Studies

Crash studies use police crash data, medical crash data (from hospital archives), and safety survey data as their main sources of data (Kweon 2011).

In a review of studies using police records from the United States and New Zealand, driver distraction contributed to 10–12% of crashes, and approximately 20% of these crashes involved driver interaction with technology such as mobile phones (Gordon 2009). The Australian National Crash In-depth Study (ANCIS) revealed that 15.9% of crashes were distraction related (Beanland et al. 2013), most commonly involving in-vehicle distraction (13.9%) such as talking with passengers or using the mobile phone. In the USA, a more recent study using the Fatal Accident Reporting System (FARS) database found that 7.7% (13,707 out of 178,677) of all fatal crashes involved distraction (Qin et al. 2019). In a study from Norway, including data from the Norwegian Public Roads Administration (NPRA), it was reported that mobile phones are involved in 2–4% of all fatal crashes, while other in-vehicle distractions excluding mobile phones (i.e., GPS, laptop or tablet computer, video camera, backing camera, passengers, etc.) contributed to 8% of all fatal crashes (Sundfør et al. 2019).

Eby and Kostyniuk (2003) found that rear-end crashes and single-vehicle-run-off-the-road crashes are the two most common types of crash associated with driver distraction. Concerning rear-end crashes, it was estimated that distraction accounts for

21% of all rear-end crashes when the lead vehicle was moving and 24% of all rear-end crashes when the lead vehicle was stopped. Regarding single-vehicle-run-off-the-road crashes, it is estimated that distraction might be the cause of 12–14% of these events.

These studies confirm that distraction is a contributing factor to road crashes. The findings derived from them, however, have some limitations and, as such, must be interpreted with some caution.

Generally, police and hospital crash reports are prone to underreporting of non-fatal cases and a lack of behavioral detail preceding the crash. The lack of behavioral detail around driver distraction could result in an overestimation or underestimation of the problem. In addition, it also limits our capacity to understand the impact of specific behaviors or interactions on crash counts. For example, a common reporting issue in the USA is that a large proportion of crashes reported to involve distraction do not have a specific competing activity listed; rather they specify "distraction/inattention details unknown" (NHTSA 2016). This means that we are often unable to understand the role that technology plays in crash causation in comparison to non-technology distraction or external distractions. Therefore, it is reasonable to argue that crash data should not be the only source of information used for informing evidence-led initiatives for managing distracted driving. More research and innovative data collection and analysis tools are needed to understand the full impact of distracted driving in road crashes.

An emerging alternative to overcome these limitations is the use of naturalistic driving studies, where vehicles are instrumented with video and other sensors to measure driver behavior and performance over extended periods of time. An example of this is the US Second Strategic Highway Research Program Naturalistic Driving Study (SHRP 2 NDS; Dingus et al. 2016), which is the largest naturalistic study ever conducted. The SHRP 2 NDS, also mentioned later on in this chapter, recorded a total of 905 injury and property damage crashes. Dingus et al. (2016) found that observable distractions were associated with 68.3% of all crashes. Given that naturalistic driving studies show the causal link between distraction and crash outcomes (i.e., injury and property damage), at least for observable distraction, it is not surprising that distraction was found to be a greater contributing factor to road crashes in the SHRP 2 NDS than in official records (i.e., police and medical crash data).

Crash Risk Studies

Analyzing crash risk requires additional, supplementary, data on distraction exposure (Kweon 2011); that is, the amount of time spent performing different distraction-related activities while driving. This type of information is typically not collected by police or recorded in hospital archives. Usually, it is collected through safety surveys and in on-road observational studies. It is beyond the scope of this chapter to review in detail all of the literature pertaining to the impact of driver distraction on driver safety. Other resources exist for this purpose (e.g., Cunningham et al. 2017a; Dingus et al. 2016). Rather, we present here an overview of key developments in the understanding of the impact of distracted driving on crash risk.

On-road studies, on which we focus here, comprise naturalistic and quasi-naturalistic approaches that allow for the observation of driver behavior in uncontrolled, or controlled, environments, respectively. In these studies, drivers are observed in their natural driving environment, for weeks or even years, using instrumented vehicles, usually owned by drivers themselves, equipped with video, accelerometers, and other sensors and recording devices (Regan et al. 2013). With new technological developments in in-vehicle driver monitoring, the outcomes of so-called “naturalistic driving studies” (Klauer et al. 2011), which are conducted in uncontrolled environments, are being increasingly reported in the road safety literature. These studies utilize epidemiological methods to sample and analyze the data recorded and provide insightful indications of changes in exposure and risk associated with driver engagement in distracting activities.

Impact of Distraction on Crash Risk

The largest and most comprehensive naturalistic driving study ever undertaken, the US Second Strategic Highway Research Program Naturalistic Driving Study (SHRP 2 NDS; Dingus et al. 2016), involved a comprehensive analysis of the impact of driver distraction on crash risk. Data were collected for 3 years from 3,500 volunteer vehicle drivers, aged between 16 and 98 years. With regards to general distraction (i.e., diverting attention to a secondary task), results from the SHRP 2 NDS demonstrate that, overall, observable distractions increased the odds of having an injury or property damage crash by a factor of 2.0 (odds ratio). An odds ratio (OR) value of 1.0 is considered equivalent to driving while not distracted. Hence, an OR of 2.0 represents a two times increase in crash risk relative to “normal” driving, suggesting that engaging in distracting activities, generally, is a risky activity.

The SHRP 2 study also revealed that, in comparison to other risky behaviors, distraction is one of the most prevalent. Specifically, as can be seen in Table 2, distraction was present during 51.93% of driving time, while other risky behaviors were less prevalent: drug/alcohol impaired driving (0.08%), drowsiness/fatigue (1.57%), speeding (over limit and too fast for conditions; 2.77%), and following a vehicle ahead too closely (0.70%). However, distracted driving risks are relatively lower than some risks generated by other behaviors. Additionally, some distracting activities have been found to be riskier than others. The following section focusses on the risks of some key distracting behaviors reported in the scientific literature, including mobile phone use while driving, and the use of in-vehicle information systems.

Table 2 Crash risk and prevalence of distraction relative to other risky driving behaviors

Behavior	Odds ratio (95% CI)	Baseline prevalence
Observable distraction	2.0 (1.8–2.4)	51.93%
Drug/alcohol impairment	35.9 (17.0–75.8)	0.08%
Drowsiness/fatigue	3.4 (2.3–5.1)	1.57%
Speeding (over limit and too fast for conditions)	12.8 (10.1–16.2)	2.77%
Following too closely	13.5 (4.4–41.4)	0.07%

Adapted from Dingus et al. (2016)

Impact of Mobile Phones Use While Driving on Crash Risk

Naturalistic studies have provided crash risk estimates for driver engagement in a wide range of secondary activities. In addition to the SHRP 2 NDS, another comprehensive naturalistic study was conducted by Fitch et al. (2013), which aimed to understand handheld and hands-free phone use while driving and its impact on crash risk among 204 drivers during a period of 4 weeks in the USA. In the case of mobile phone use while driving, Fitch et al. (2013) found handheld mobile phone use, overall, to increase the odds of having a crash by a factor of 1.4, while Dingus et al. (2016) reported SHRP 2 NDS data confirming that interaction with a handheld mobile phone, overall, increased the odds of having an injury or property damage crash by a factor of 3.6. These findings, however, can be further considered in terms of the different ways in which drivers use their mobile phones.

The following table illustrates the odds of crash risk associated with driver engagement in specific visual-manual mobile phone tasks while driving. As shown in Table 3, the odds of having a crash increases by 73% for drivers engaged in mobile phone tasks that involve visual-manual interactions (i.e., odds ratio of 1.7). Overall, when considering all of the visual-manual interactions with a handheld mobile phone that have been analyzed while driving as shown in Table 3, “dialling a number on a handheld mobile phone” carries the highest risk (i.e., odds ratio of 12.2).

Crash risk data for handheld mobile phone conversations and hands-free mobile phone conversations are presented in Table 4. Dingus et al. (2016) reported that handheld mobile phone conversations increase crash risk by more than two times (OR: 2.2; CI:1.6–3.1). In a more recent study, Dingus et al. (2019) found that talking/listening on a hands-free mobile phone did not increase crash risk (did not have an increased OR).

Recently, Young (2017) recalculated the odds ratio of handheld mobile phone conversations using the SHRP 2 NDS data after controlling for selection and confounding bias and reported that this resulted in an odds ratio of 0.9. This value is not significantly different from 1, implying that there is no change in risk. It is important to note that this result is similar to findings reported in previous naturalistic studies (Fitch et al. 2013). Table 4 also illustrates the odds of crash risk associated with driver engagement in hands-free mobile phone conversations while driving. As can be seen in Table 3, there is no significant change in crash risk for hands-free conversations, with odds ratios of 0.7 for mobile phone portable

Table 3 Crash risk associated with visual-manual tasks

Study	Observed distraction	Odds ratio (95% CI)
Fitch et al. (2013)	Mobile phone visual-manual task (i.e., text messaging/browsing, locate/answer, dial, push to begin/end use, and end handheld phone use)	1.7 (1.1–2.7)[a]
Dingus et al. (2016)	Mobile phone handheld browse	2.7 (1.5–5.1)[a]
	Mobile phone handheld dial (a number)	12.2 (5.6–26.4)[a]
	Mobile phone handheld text	6.1 (4.5–8.2)[a]

[a] Indicates a difference at the 0.05 level of significance

Table 4 Crash risk associated with manual-cognitive tasks (handheld or hands-free device)

Study	Observed distraction	Odds ratio (95% CI)
Fitch et al. (2013)	Mobile phone handheld talk	0.8 (0.4–1.4)
Dingus et al. (2016)	Mobile phone handheld talk	2.2 (1.6–3.1)[a]
Young (2017)	Mobile phone handheld talk	0.9 (CI 0.3–2.3) or 0.9 (CI 0.5–1.7)
Fitch et al. (2013)	Mobile phone portable hands-free talk	0.7 (0.36–1.5)
	Mobile phone integrated hands-free talk	0.7 (0.3–1.7)

[a] Indicates a difference at the 0.05 level of significance

hands-free talk and 0.7 for mobile phone integrated hands-free talk (Fitch et al. 2013). Again, neither value is significantly different from 1, further implying that there is no change in risk. Thus, it would seem that handheld mobile phone conversations and hands-free mobile phone conversations are not generally associated with any significant increase in crash risk.

An important warning, however, is necessary here: conversing (speaking or listening) using a handheld or hands-free mobile phone does not occur in isolation in real driving, as implied in the odds ratios reported above. To perform these actions, drivers are often required to first locate the device, reach for the device, dial, or answer the handheld device. These task sub-components of handheld mobile phone conversations could entail highly intensive visual, cognitive, and manual interactions (e.g., dialling or battery/duration monitoring) which could increase crash risk (Oviedo-Trespalacios et al. 2016). For example, in the Dingus et al. (2016) study, reaching for a handheld mobile phone was an extremely risky interaction, specifically increasing the odds of crashing by 4.8 times. This result is concerning given that limited public education has been provided with regards to the increased risk associated with this kind of mobile phone interaction (Oviedo-Trespalacios et al. 2017b).

Impact of In-Vehicle Information Systems (IVIS) on Crash Risk

As the capabilities of in-vehicle information systems (IVIS) have continued to expand over the years, questions have arisen as to whether or not the use of such systems for entertainment (i.e., infotainment) creates risks on the road.

With regards to crash risk, Dingus et al. (2016) found that driver interaction with IVIS increased the odds of having a crash by 4.6 times among drivers in the USA. The same study found this behavior to pose a higher crash risk in comparison to other risky driving behaviors such as fatigued driving (odds ratio = 3.4) and overall handheld mobile phone use (odds ratio = 3.6). A recent meta-analysis conducted by Ziakopoulos et al. (2019), however, found operation of an IVIS to cause only a small percentage of safety-critical incidents, specifically only 1.66% of total crashes. It is important to note, however, that the results from this study were based on a small number of older articles published from 1996 to 2012, when the range of IVIS technologies and functions was more limited. As the capabilities of IVIS continue to increase, more current, up-to-date, research is required to determine the risks associated with use of these systems.

Impact of Interactions with Passengers on Crash Risk

Dingus et al. (2016) also analyzed crash risk associated with active driver interactions with passengers. Crash risk was calculated using data collected from video segments where drivers interacted with adult/teen passengers 6 s prior to a crash. Information related to talking on a handheld mobile phone while driving, discussed above, was gathered in a similar fashion. The results were as follows:

- Drivers interacted with passengers more frequently (14.5% of the total driving time) in comparison to talking on a handheld mobile phone (3.2% of the total driving time).
- However, talking on a handheld mobile phone while driving increased crash risk by 2.2, while interaction with passengers was associated with only a 1.4 increase in crash risk.

Another meta-analysis conducted by Theofilatos et al. (2018) also calculated crash risks associated with passenger interactions. The analysis included a total of seven studies, and the results were as follows:

- 3.55% of crashes were caused by passenger interactions regardless of age.
- 3.85% of crashes were caused by passenger interactions when teen and child passengers were excluded from the analysis.

Recently, Maasalo et al. (2019) examined fatal crash data to determine the crash characteristics and crash risks of drivers with child passengers. The authors found that:

- Female drivers are involved in twice as many fatal crashes with child passengers in comparison to male drivers.
- Drivers with child passengers have a higher tendency to engage in distractions while driving and pose risks particularly around intersections.
- Drivers with child passengers have fewer risk-taking behavior-related fatal crashes (e.g., through speeding) in comparison to drivers with no child passengers.
- Adult passengers lower drivers' fatal crash risk by helping drivers with child-related tasks.

Collectively, the evidence suggests that primarily cognitive secondary tasks – that take a driver's mind off the road – are not associated with increased crash risk (increased odds ratios) relative to *all* driving but are associated with a small but significantly increased odds ratio relative to model driving (i.e., when drivers are alert, attentive, and sober; OR = 1.25, 95% CI [1.01, 1.54]). (Dingus et al. 2019). The effect on crash risk of driver engagement in primarily cognitive secondary tasks is reliably less severe than engagement in tasks that take the driver's eyes and/or hands away from the driving task (Dingus et al. 2019).

Impact of External Distractions on Crash Risk

As noted earlier, in the section "Competing Activities and Sources of Distraction," there are many sources of distraction external to the vehicle that have potential to distract drivers. Apart from advertising signs, very little is known about the impact of these on crash risk. Generally, it is known from the work of Dingus et al. (2016) that an extended eye glance duration to an external object increases the odds of having an injury or property damage crash by a factor of 7.1 (OR). Driver interaction with both in-vehicle and external sources of distraction may, therefore, increase crash risk.

Roadside advertising signs are designed deliberately to attract and maintain driver attention to information that is irrelevant to driving. In their meta-analysis of existing studies investigating digital roadside advertising signs (i.e., moving images and/or film clips), Sisiopiku et al. (2015) found an increased crash risk associated with driver interaction with digital roadside advertising signs. However, the effect was only observed on sections of road with intersections. Experimental research, on the other hand, suggests that crash risk increases by approximately 25–29% in the presence of digital roadside advertising signs (Oviedo-Trespalacios et al. 2019b). Fixed object, side swipe, and rear-end crashes have been found to be the most common types of crashes in the presence of roadside advertising signs (Islam 2015; Sisiopiku et al. 2015).

Impact of Other Distractions on Crash Risk

Some other distractions have also been shown to increase the odds of crashing (Dingus et al. 2016):

- Reading and writing (including with tablets) – by 9.9 times.
- Reaching for objects inside the vehicle (excluding mobile phones) – by 9.1 times.
- Drinking (non-alcohol) and eating – by 1.8 times.
- Personal hygiene activities – by 1.4 times.

Generally, as noted above, distracting activities that carry the greatest crash risk are those that involve both visual-manual interactions and occupy a greater proportion of a driver's time. Particularly troublesome, in this respect, is the use of handheld mobile phones which, in the Dingus et al. (2016) study, increased crash risk overall by 3.6 times and engaged them for 6.4% of their driving time.

Prevention of Distracted Driving

The road system is complex and, from a distraction perspective, many stakeholders are ultimately responsible for preventing and managing distraction (Department of Transport and Main Roads 2020b): drivers, regulatory and enforcement agencies, infrastructure planners, the insurance industry, the mobile connectivity industry, road users and their associations, the automotive industry, technology providers, the telecommunications industry, employers, and the research community.

Traditionally, the onus of responsibility for safe driving has been on the driver. This approach implies that drivers are solely responsible for road safety and thus are to blame for a crash by not following a particular road rule (Newnam and Goode 2015). Generally, this "victim blaming" approach has, to date, been the status quo of distraction prevention. However, safety professionals and academics concur that this approach is unsuitable to deal with distracted driving (or any other risky behavior; Tingvall and Haworth 1999; Tingvall et al. 2009; Young and Salmon 2015).

Drivers tend to be, and will continue to be, distracted due to a number of factors that are often difficult to control. A good example of this is the use of mobile phones, which are a key part of today's professional and social contexts. Some experts have conceded that ending or reducing phone use is becoming unrealistic (Panova and Carbonell 2018). In addition, there are reports showing that more individuals are establishing maladaptive relationships with their mobile phone, such as "fear of missing out" (FOMO), that could be linked with mobile phone distraction (Elhai et al. 2018; Nguyen-Phuoc et al. 2020). FOMO is a psychological construct that is defined as the persistent desire to stay connected with others' rewarding experiences and has been linked to both negative affectivity (e.g., stress, depression, anxiety) and increased severity of problematic smartphone use (Wolniewicz et al. 2018). Recent research has shown that problematic mobile phone use, which resembles addiction, is linked with mobile phone use while driving (Oviedo-Trespalacios et al. 2019c). Therefore, if drivers are not able to self-regulate their mobile phone use, it is very unlikely that legal requirements alone will prevent mobile phone use while driving. Several researchers concur that the high prevalence of distracted driving is linked to a heavy focus of legislation on the role of the driver, while ignoring the responsibility of the wider road transport system (Young and Salmon 2015; Parnell et al. 2017; Oviedo-Trespalacios et al. 2019c).

To address these limitations, different philosophies have evolved that recognize that distracted driving is a serious problem with unacceptable consequences (i.e., injuries, economic loss, disruption of the transport system, etc.) that drivers cannot always prevent themselves. Some good examples of alternate philosophies include the Swedish Vision Zero and the chains of responsibility, which are linked to the limitations and capabilities of road users (Tingvall et al. 2009). The common aim of the abovementioned philosophies is to reduce or eliminate the consequences of a road crash. This means that a road transport system assumes variability in human performance and creates safety margins to protect road users from the inevitability of such variability; for example, in the case of vehicles drifting out of their lane, the use of lane departure warnings or roadway tactile edge lining that can alert the driver to potential danger.

The integrated safety chain of responsibility (ISCR) is an approach that has been proposed by Tingvall et al. (2009) in the case of distracted driving (see Fig. 1). The ISCR approach uses the sequence from "normal" driving to a potential crash, broken down in stages of progression towards a crash. These stages are used to identify possible interventions along the chain, such as technology in both the vehicle and infrastructure as well as broader interventions involving police enforcement or community education.

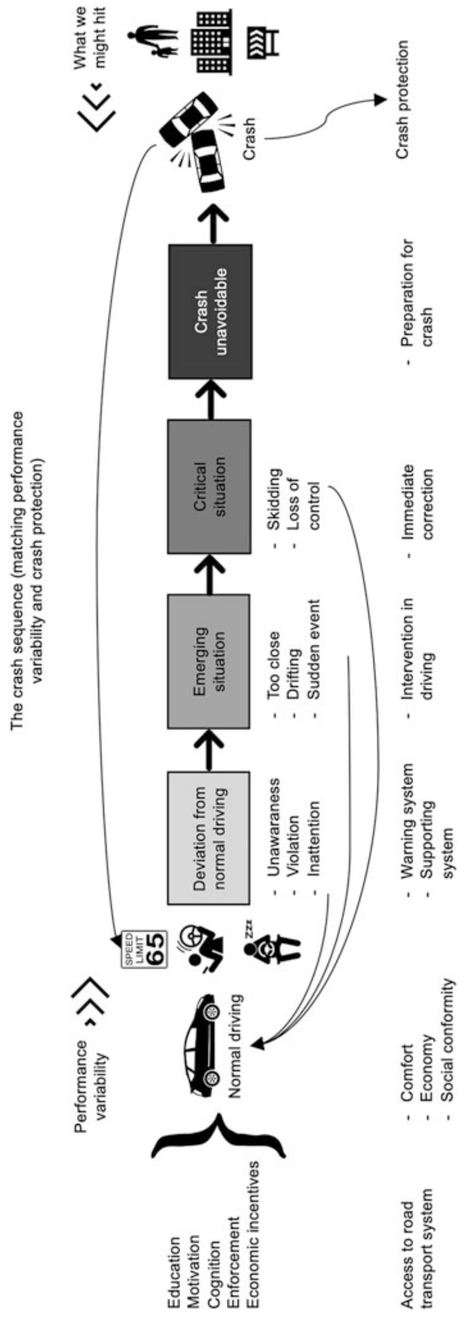

Fig. 1 The integrated safety chain. (Adapted from Tingvall et al. (2009))

The ISCR starts with an understanding of "normal" driving, which includes all the requirements of the driver to achieve this state. Moreover, conceptualizing the notion of normal driving also involves acknowledging that there is a plethora of factors which affect driver performance, such as cognition, motivation, education, police enforcement, and economic incentives. For example, drivers cannot follow a speed limit that they are unaware of or is not appropriately signed. If normal driving is too difficult to achieve, then the number of people capable of driving would be restricted, or we return to blaming the driver for not fulfilling the requirements of normal driving. In the case of distracted driving, evidence around the world shows that a requirement to never be distracted while driving is unrealistic.

The ISCR accepts that deviation from normal driving is going to occur and explains that countermeasures should be applied to correct the deviation back towards normal driving. An example of this, in the case of speeding, is a vehicular speed warning system, referred to as Intelligent Speed Adaptation (ISA; e.g., Regan et al. 2006), which would alert a driver when exceeding the speed limit. If the deviation is not corrected, and the driver finds themselves in an emerging situation, such as being too close to another vehicle or drifting out of the road lane, the ISCR recommends using the vehicle and infrastructure to help the driver regain control. For vehicles drifting out of their lane, the vehicle could automatically take control of the vehicle through electronic stability control (ESC) and lane departure assist systems to return the driver to normal driving or prepare the driver for the potential next phase. If the driver does not regain control, the next phase involves the vehicle preparing for a crash. This could take the form of the vehicle applying automatic braking and traction control. In the final stage, if a crash occurs, both vehicle and infrastructure could help reduce the severity of the consequences with systems such as vehicle airbags and road crash barriers (which serve to attenuate the force of vehicle impacts).

All the different stages from normal driving to a potential crash have the potential to prevent and mitigate the effects of distraction. The ISCR also points to the need to give equal consideration to countermeasures in vehicles as well as road infrastructure. This premise is the basis for the safe system approach which seeks to create a forgiving road environment that allows for driver variability, such as distracted driving. However, an important consideration is that all of these countermeasures need to be rigorously evaluated to prevent unintended consequences or misuse of technology. For example, it has been reported that some drivers potentially stop using their seat belt and start relying on airbags to protect them when their vehicles are fitted with them (Oviedo-Trespalacios and Scott-Parker 2018).

Most recently, prevention approaches for distracted driving have advocated for broadening the scope of intervention beyond a driver-centered approach. The long-established philosophy of the "systems approach," established by Heinrich (1931), has been proposed to achieve this. The systems approach explains that road accidents and safety (broadly speaking) are emergent properties arising from nonlinear interactions between multiple components across complex sociotechnical systems beyond the immediate road environment. In the case of distracted driving, a systems approach can help in identifying and determining the impact of the wider road system factors that moderate the relationship between distraction and error (Young and Salmon 2015). This approach broadens the scope of the ISCR which focusses on how the immediate road environment can support safe driving behavior and tolerate unsafe behavior (Young and Salmon 2015), without considering the roles that other stakeholders in the distraction ecosystem (mentioned above) have in supporting safe driving. A systems approach responds to the call for a more holistic approach to managing driver distraction, which has traditionally been dominated by a focus on driver behavior change through education and legislation (Tingvall et al. 2009).

A tool for managing road safety following a systems approach is Rasmussen's (1997) Risk Management Framework (RMF). Rasmussen's RMF is a generic framework that can be used to develop a complete picture of the factors affecting safety in any domain of interest by describing six levels of the system. In the distracted driving domain, the levels have been conceptualized as follows (Young and Salmon 2015):

- *Level 1*: *Government policy and budgeting:* At the government level, safety is controlled through the legal system and legislation including the development of behavior-regulating laws and legislation, such as bans; provision of funding for public education; and policy development.
- *Level 2*: *Regulatory bodies and associations:* At this level, legislation is interpreted and implemented into rules and regulations (e.g., vehicle design standards). This includes conversion and informing of distracted driving legislation by regulatory bodies, research organizations, and others with a financial interest in distracted driving (such as police and motor vehicle insurers).
- *Level 3*: *Local area government, planning, budgeting*: Here, government policy is developed by local councils, including general road rules related to distracted driving. These rules are later implemented in the next two levels.
- *Level 4*: *Technical and operational management:* Stakeholders at this level include other influential and authoritative bodies and organizations with a direct influence on distracted driver behavior and decision-making; for example, vehicle and mobile phone manufacturers, the outdoor advertising industry, driver training organizations, road designers, etc.
- *Level 5*: *Physical processes and actor activities:* At this level, the focus is on the drivers themselves – the psychosocial influences upon their distracted driving behavior and their actual distracted driving behavior. This level also considers other road users such as passengers, cyclists, pedestrians, etc.
- *Level 6: Equipment and surroundings:* Here, the focus is on the physical environment and surroundings in which the person drives, including the motor vehicle.

Rasmussen's RMF posits that safety is maintained through a process called vertical integration, whereby decisions made at the higher levels (i.e., government and regulatory bodies) should influence actions at the lower levels. Likewise, information about the safety performance of the transport system (i.e., driver behavior and crashes) should flow up the hierarchy and influence decision-making at the higher levels (Rasmussen 1997). Consequently, a systems approach to road safety highlights that responsibility for road safety is shared among a broad group of stakeholders, whose decisions and actions interact and affect each other.

The implementation of the systems approach for distracted driving prevention is still in its infancy. Research has highlighted that some groups of stakeholders, directly linked with distracted driving, have not assumed their responsibilities. A good example is the often-complacent roles of mobile phone manufacturers and application developers in the prevention of mobile phone use while driving (Galitz 2017).

An open question on the systems approach is whether or not the current conception of the system has sufficient breadth. As noted previously, interventions to prevent mobile phone distraction while driving have been heavily focussed on the role of the driver, while ignoring the responsibility of the wider road transport or communication authorities (Parnell et al. 2016; Parnell et al. 2017; Young and Salmon 2015). A systemic approach is more likely to succeed in preventing and mitigating the impact of mobile phone use while driving, and this is exemplified in the recent release of Australia’s National Roadmap on Driver Distraction (Department of Transport and Main Roads 2020b) developed by the Queensland Department of Transport and Main Roads in consultation with the Federal Department of Infrastructure, Transport, Cities and Regional Development, along with a wide range of stakeholders (noted above) from industry, academia, and all Australian jurisdictions. The Roadmap was developed through an extensive collaborative design process, with a focus on reducing driver distraction due to mobile devices. The Roadmap contains five overarching strategies to address the challenge of driver distraction: designing for safer interaction; mapping out the adoption of in-vehicle distraction mitigation technology; recognizing the vehicle as a workplace; encouraging greater compliance through enforcement; and changing driver behavior. The Roadmap contains a proposed forward program of work, with a range of projects aligned in support of the five main strategies. The Roadmap is likely one of very few that currently exist that have been developed in a truly collaborative manner involving all key relevant stakeholders in society responsible, directly or indirectly, for the prevention and mitigation of driver distraction.

More recently, it has been suggested that we must also consider the role of other systems, such as the healthcare system, in managing distraction. The link between problematic mobile phone use and mobile phone use while driving might require the use of clinical therapeutical interventions (Oviedo-Trespalacios et al. 2019c).

Consistent with this theme is the Human Factors Integration (HFI) process (e.g., Standards Australia 2016), which requires the specification of human factors requirements that have to be met during all stages of the lifecycle of an engineering product, system, or piece of infrastructure – from concept design through to design, build/implementation, testing, operation (including maintenance), and decommissioning. The purpose of the HFI process is to ensure products and systems are designed from a user-centered perspective to maximize safety, efficiency, user satisfaction, etc. Adherence to an HFI process, in the context of distraction, would ensure that the potential for distraction is considered and mitigated at all stages of the system lifecycle. For example, an engineering consultant, tendering for the design and construction of a new section of roadway, would be required as part of the HFI process to include in the tender a Human Factors Integration Plan that specifies in what ways the piece of road infrastructure will be designed to prevent and mitigate driver distraction during its lifecycle.

Countermeasures for Distracted Driving

Type of Countermeasures

A number of countermeasures have been developed in an attempt to prevent and mitigate distracted driving. However, there is a dearth of evaluations with regards to distracted driving countermeasures. The aim of this chapter is to systematically review countermeasures supported by empirical research, with a focus on those which have successfully reduced the occurrence or impact of distracted driving. Although there are many frameworks that can be utilized to systematically classify the interventions, this chapter will utilize the "Hierarchy of Controls" system, a widely used framework for preventing risks in socio-technical systems.

The hierarchy of controls presents different levels of solutions for the management of identified hazards and risk. In this chapter, we will use the Occupational Health and Safety Assessment Series (OHSAS 18001), which includes five main categories: elimination, substitution, engineering controls, administrative controls, and personal protective equipment (PPE), as can be seen in Fig. 2. The motivation underlying the hierarchy of controls is that more reliable control measures should be utilized rather than measures that are more likely to fail. At the top of the hierarchy is "elimination" which is traditionally considered the most effective countermeasure. Alternatively, countermeasures that rely on individuals behaving in a certain way are

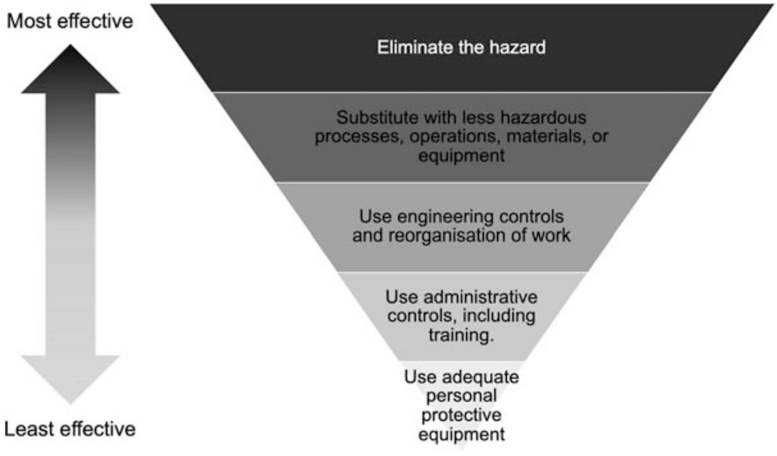

Fig. 2 Hierarchy of controls (Adapted from the National Institute of Occupational Safety and Health NIOSH)

considered less reliable. The adaptation of these five categories to consider countermeasures against distracted driving hazards is explained as follows:

- *Elimination:* Elimination is the first, most effective, control method in the pyramid. With this method, professionals suggest physically removing the hazard completely. While this is the ultimate goal, this method is potentially difficult to implement and not always possible in certain circumstances. This is particularly relevant for distracted driving from mobile phone use, where it has been demonstrated that drivers have difficulties separating from their phones (George et al. 2018). Nonetheless, this method should always be considered first and implemented before the other methods.
- *Substitution*: If elimination is impossible, the hierarchy of controls recommends moving on to the second category, known as substitution. With this method, hazardous practices/materials are replaced with an alternative, less hazardous, practice or material. This method must also be implemented in the very early phases of development, and it is crucial that the new practice or material either removes or mitigates the hazard in order to be effective. A good example of this is the integration of safer ways of interaction with the mobile phone, using technology such as "workload managers" for distracted driving (NHTSA 2016). Workload managers are driver support systems designed to limit or postpone information that is allowed to come through the phone when the driver's workload is high, or limit access to complex interactions that it supports. Specifically, when a driver's workload is high, workload managers can limit or delay information received through their mobile phone, or restrict access to complex interactions facilitated by the devices.
- *Engineering controls*: If substitution is also not possible, engineering controls are used. These include the modification or addition of physical safety features to the machinery or equipment in order to control identified hazards. For example, a workplace can provide ergonomic chairs to reduce risk of injury to the back and neck or add safeguards to prevent access to dangerous parts of a machine. In the case of distracted driving, engineering controls could involve the use of active safety technologies, such as automatic braking systems to reduce the risk of crashing, or the use of wire-rope barriers to prevent distracted drivers from veering off the roadway or into the path of other vehicles. Blocking mobile phone interactions with applications such as "do not disturb while driving" is another example of an engineering control (see Oviedo-Trespalacios et al. 2019d, for a review of applications to prevent mobile phone distracted driving).
- *Administrative controls*: The fourth control method in the hierarchy, administrative controls, involves changing the way individuals work through limiting exposure to a hazard. This can be done through installing signs, rotating jobs, etc. The parallel to driving here is driver behavioral interventions including education, legislation and enforcement, and risk awareness campaigns. Some forms of self-regulation, such as only engaging in distractions when the vehicle is stopped and not moving, could also limit exposure to the hazard (Oviedo-Trespalacios et al. 2019a). It should be noted, however, that this method is not always reliable or effective as it is prone to variability of human performance.

- *Personal protective equipment*: The fifth and final control method is the implementation of personal protective equipment (PPE), such as gloves, safety glasses, earplugs, etc. The rationale behind this method is to protect the body from injury, but it does not eliminate the hazard. Hence, PPE is deemed the least effective. In the case of distracted driving, the corollary to this would be the provision of seatbelts, airbags, and other passive safety elements to minimize the impact of a crash.

Review of Countermeasures

A review of injury countermeasures for distracted driving was undertaken by the authors using the Hierarchy of Controls for distracted driving as an organizing framework. The following table includes the control method used to minimize or eliminate distraction, a description of the method, outcome(s) from its use, and evidence of its effectiveness in achieving the outcome(s). Given that the focus of this chapter is the prevention of distracted driving, personal protective equipment controls were not included because they are post-crash treatments. Prior research studies conducted on post-crash protective measures have concluded that seatbelts, vehicle design, and emergency care can reduce the severity of crashes (Bhattacharyya and Layton 1979).

Elimination

The effectiveness of today's solutions for preventing distraction-related hazards while driving have been limited. Only fully automated vehicles operating in all conditions all of the time with SAE Level 5 automated driving features follows the elimination principle. When the automation is active, drivers do not have to control the vehicle and therefore vehicle occupants may engage in different activities unrelated to the control of the vehicle. Currently, the availability of fully automated vehicles is limited and restricted to highly controlled environments such as mining sites. It is anticipated that the safety benefits of fully automated vehicles are potentially enormous and would largely eliminate distraction-related hazards (Litman 2020).

Substitution

Regarding substitution, a countermeasure that continues to be suggested is the use of workload managers for driver distraction. Workload managers, as mentioned previously, are designed to minimize distraction by controlling, transforming, or limiting the information flow so drivers can safely manage their driving demands. The NHTSA (2016) considers that minimizing the workload associated with performing secondary tasks with a workload manager will permit drivers to maximize the attention they focus on the primary task of driving. Some of the approaches to achieve this include: (*1*) simplifying current distractions for more manageable tasks (Oviedo-Trespalacios et al. 2019d) and (*2*) only allowing drivers to be distracted at points where they can safely resume the driving task (Bowden et al. 2019). Although experimental work has demonstrated that delaying delivery of irrelevant driving-related information to drivers could reduce the impact of distraction (Teh et al. 2018), the technology needs further testing and evaluation.

Engineering Controls: In-Vehicle and Mobile Technology

Engineering controls for vehicles have been developed in increasing numbers in the form of advanced driver support systems (ADAS). ADAS are systems designed to support the driver in their driving task. The logic is that these systems are going to support the driving task by reducing the driver's demands and includes systems such as semi-automated navigation, blind spot monitors, etc. For partially automated vehicles, there is no evidence that these are going to reduce distraction-related hazards. On the contrary, it is expected that partial automation will result in more distraction due to decreased engagement with the driving task (Cunningham and Regan 2018b; Regan et al. 2020). A study in China with Tesla drivers found that drivers often engage in distracting activities while using the autopilot system (Lin et al. 2018). Similar findings have been reported in the USA, where drivers of vehicles with ADAS, such as adaptive cruise control, report engaging more in mobile phone use and texting (Dunn et al. 2019). Additionally, Matthews et al. (2019) showed that autopilot systems elicit subjective symptoms of fatigue and loss of alertness that last even after the autopilot system has been deactivated. These findings suggest that some ADAS are likely to be facilitating distracted driving.

Another issue raised is that ADAS could increase the likelihood of information overload resulting in distracted driving (Lee et al. 2020). ADAS often use auditory, visual, or a combination of auditory and visual alerts to communicate key information to drivers about the state of the vehicle and to instruct actions. However, there is growing evidence that poorly designed alert systems could increase distraction. An early experiment conducted by Biondi et al. (2014) showed that continuous exposure to auditory stimuli from ADAS negatively affects driving performance. These findings were further confirmed by a naturalistic driving study conducted in Australia, where 34 vehicles were retrofitted with collision avoidance technology which gave audio and visual warnings to drivers. The results showed that, although the system was capable of improving driving behavior, drivers did not want to continue using the system because it was too distracting (Thompson et al. 2018). A study conducted in Spain found that drivers consider GPS navigation, automatic parking systems, and lane departure warnings the most distracting ADAS (Lijarcio et al. 2019). These results highlight the need to further investigate strategies to optimize the role of ADAS as a control to reduce distraction-related hazards.

Applications to reduce mobile phone distracted driving are also engineering controls to prevent distractions. Generally, these applications restrict visual-manual and auditory interactions with the mobile phone while the vehicle is moving. A large number of applications is currently available, with different capabilities and at different stages of maturity (see Oviedo-Trespalacios et al. (2019d) for a comprehensive review of applications). Early findings from studies in Australia and Israel show that using applications aiming to block visual-manual interactions significantly reduces phone pickups and activities such as texting and browsing while driving (Albert and Lotan 2019; Oviedo-Trespalacios et al. 2020a). Nonetheless, reports from users of these applications (e.g., “Do not disturb while driving” for Apple iOS) reveal that the applications do not always stop notifications from instant message applications such as Facebook Messenger and WhatsApp (Oviedo-Trespalacios et al. 2020a). This could have negative implications for road safety given that previous research has found that unexpected incoming notifications are associated with reduced situation awareness while driving (Van Dam et al. 2020). Nonetheless, partially reducing exposure to mobile phone interactions could be a very effective countermeasure option in practice. Unfortunately, surveys in Australia and the USA have concluded that acceptance and adoption of these applications has been low, ranging from 3.8% to 20.5% (Oviedo-Trespalacios et al. 2019e, 2020c, d; Reagan and Cicchino 2018). Further work is needed to increase the effectiveness of this technology in preventing phone use while driving and the uptake of this technology.

Recent developments in in-vehicle technology also include technologies being built into the vehicle with the purpose of reducing distracted driving. A key technology that has been scientifically evaluated is feedback systems. The aim of these systems is to deliver information to drivers about their performance, on the expectation that this information will positively influence their behavior. In an experimental study conducted by Merrikhpour and Donmez (2017), it was found that feedback systems that consider parental norms (i.e., information about a parent’s performance) and real-time feedback (i.e., alarms triggered by long off-road glances) are associated with a smaller duration of off-road glances. Results from these experiments are very promising. Other in-vehicle technology such as in-vehicle interfaces that provide connectivity between smartphones, vehicle displays, and controllers (e.g., Apple CarPlay and Android Auto) has been suggested as a potential countermeasure for distraction. However, currently the potential safety benefits are unknown. Indeed, there is emerging research suggesting that there is risk of distraction from using such technology (Oviedo-Trespalacios et al. 2019f; Strayer et al. 2019; Ramnath et al. 2020).

Engineering Controls: Roads

Road and traffic engineers have considerable scope to manage distraction from some of the sources of distraction deriving from outside the vehicle that were mentioned earlier in this chapter (see section “Impact of External Distractions on Crash Risk”).

PIARC (2016) makes three primary recommendations for preventing serious crashes arising from driver distraction:

- *Lower energies through conflict points to within human tolerances* – in the event that a distraction-related crash is inevitable, infrastructure measures will generally ensure that vehicle speeds are within human tolerances for serious injury through relevant conflict points.
- *Design to provide opportunities for road users to recover from mistakes and noncompliance* – e.g., locating crash barriers further from the through traffic lanes provides an opportunity for errant vehicles to recover before hitting the barrier.
- *Design to lower the risk of a crash occurring to an “acceptable” level* – designing the road to minimize the risk of driver distraction occurring in the first place; e.g., by preventing the road from surprising the road user.

PIARC (2016) recommends the following specific road engineering treatments that can be used to mitigate the effects of driver distraction:

- *Hierarchy Level 1 treatments*. These include concrete or steel side barriers, wire rope side and median barriers, lateral shift of the road, roundabouts, grade separation at intersections and speed humps.
- *Hierarchy Level 2 treatments*. These include rumble strips, tactile line markings, speed humps, rough shoulders, and variable speed signs.

The PIARC (2016) document provides high level guidance for road design to prevent and mitigate the effects of distraction. Cunningham et al. (2017b) provide more specific guidance on managing some of the specific external sources of distraction listed earlier in this chapter (see section "Competing Activities and Sources of Distraction") that traffic engineers have some control over. For example:

- *Animals* – on road sections where roadway incursions by animals are common and distract drivers, warning signs, and perhaps barriers, can be used to minimize interaction between drivers and animals.
- *Scenery* – scenic routes and tourist roads are, by definition, distracting and are often located along winding rural roads. Traffic engineers can alert drivers to the potential for distraction along such roads and employ additional engineering control measures to prevent crashes, give drivers more time to recover from the effects of distraction, and reduce impact speeds in the event of a distraction-related crash.
- *Architecture* – there exist many buildings and monuments that have the potential to distract drivers. It may be possible for engineers to visually mask (e.g., with trees, fencing) prominent architectural structures and features that are known to distract drivers in high-risk locations.
- *Crash scenes* – so-called "rubber necking" is a common driver behavior around crash scenes. It distracts drivers and cause crashes, and often creates traffic congestion downstream. Possible countermeasures here might include routing traffic away from crash scenes, where possible, and visually masking the scene in some way from approaching traffic.
- *Traffic signs* – poorly designed traffic signs can, themselves, distract drivers. For example, if they are absent in locations where they should be (e.g., no street name on the road you are turning onto), this may encourage drivers to adopt compensatory search strategies that distract them. Similarly, if signs are poorly designed (e.g., contain too much information or are incomprehensible), this may encourage long eye glances away from the forward roadway. Poorly designed and absent road signs should be avoided.

Ultimately, the road and traffic engineer should strive for a distraction-tolerant road system such that, in the event of a distraction-related crash, no driver or other road user is killed or seriously injured (Tingvall et al. 2009; see also section of this chapter titled "Prevention of Distracted Driving").

Administrative Controls

Administrative controls cover legislation, authority enforcement of legislation, as well as education programs.

Legislation banning or restricting distraction has been a key control in the prevention of distracted driving (WHO 2011). Some of the legislative approaches target general driver performance, such as "without due care and attention," which covers a wide range of distracting behaviors. Graduated driver licensing (GDL) is a policy used to keep newly licensed young novice drivers out of harm's way by restricting driving to times and situations demonstrated to be of lower risk. In some jurisdictions, such as Queensland, Australia, the GDL bans young drivers' use of hands-free phones or loudspeaker functions while driving (Department of Transport and Main Roads 2020a), both of which are otherwise allowed among fully licensed drivers. Additionally, there is also more specific legislation targeting activities such as talking, text-messaging, or playing video games on handheld mobile phones while driving. Unfortunately, few studies have assessed the impact of legislation on distracted driving, and most of the research has been centered on mobile phone use.

Evaluations of legislation targeting mobile phone use show partial success in preventing this risky driving behavior. A common finding highlighting the positive impact of legislation is the reduction of handheld conversations among drivers after handheld mobile phone bans were implemented in the USA (Rudisill and Zhu 2017; Rudisill et al. 2019b). More recently, an analysis of the 2011–2014 Traffic Safety Culture Index surveys showed that handheld calling bans were associated with fewer calling behaviors overall and in all demographic subgroups. Evaluations of distracted driving legislation in New Zealand (Wilson et al. 2013) and the UK (Johal et al. 2005) have also reported reduced mobile phone use post legislation.

However, in other cases, legislation seems to have had a minimal effect on behaviors, such as texting on a mobile phone. In the USA, for example, Rudisill et al. (2019b) found that universal texting bans were not associated with less distraction. In Europe, Jamson (2013) documented that drivers in the most highly regulated country with respect to mobile phone legislation (Italy) report texting as frequently as those in countries with no legislation. Furthermore, the effect of legislation seems to be heterogenous among different groups of the population. An analysis of research in the USA concluded that phone legislative restrictions have no long-term effect on the prevalence of mobile phone use among novice drivers (Ehsani et al. 2016). Rudisill and Zhu (2017) found that, although there are net reductions in handheld interactions, mobile phone use was higher overall among females, younger age groups, and African Americans.

These mixed results on the effectiveness of the legislation can be partially explained by challenges associated with the enforcement of the legislation. Law compliance frameworks, such as deterrence theory, have shown that drivers are motivated to avoid harmful behavior by fear of negative consequences. Thus, breaking the law is more likely to occur if the swiftness, certainty, and severity of punishment are low (Homel 1988). Thus, sustained police enforcement programs are a key element to guarantee a reduction of distracted driving through legislation.

Studies in the USA have demonstrated that handheld mobile phone bans require robust enforcement to have the desired effect on driver behavior in the long term (McCartt and Hellinga 2007; McCartt et al. 2010). Specifically, high-visibility enforcement programs (i.e., visibility elements and a publicity strategy to educate the public and promote compliance with the law) targeting drivers who use handheld mobile phones have been trialled successfully. In California and Delaware, handheld mobile phone use dropped nearly 33% as a result of high-visibility enforcement (NHTSA 2016). Importantly, there is growing evidence that capacity to enforce mobile phone bans is restricted unless technological and legislative innovations take place. Different evaluations of distracted driving law enforcement have found several important barriers to enforcement of distracted driving legislation (Nevin et al. 2017; Rudisill et al. 2019a):

- *Societal factors*: Mobile phones often have a utilitarian function in supporting driving, such as through provision of GPS or maps, which makes it difficult to identify distracted driving. Also, mobile phones experience rapid technological change that is often faster than policy cycles.
- *Contextual factors*: The ability of police to conduct traffic stops safely is often limited and dangerous (i.e., weaving through cars or high-speed traffic).
- *Organizational factors*: Police functions are diverse, and resources limited, resulting in low prioritization of distracted driving legislation. Additionally, the lack of clear and enforceable polices is also one of the main difficulties: that is, officers cannot always be sure if a driver was texting or using the GPS while enforcing texting bans.
- *Interpersonal factors*: Many drivers who challenge police officers during traffic stops increase the difficulty of enforcement operations, and there is not sufficient dialogue among police forces regarding distracted driving.
- *Individual factors*: Police officers largely report engaging in distracted driving themselves and believe that drivers can safely multitask. Thus, the enforcement of distracted driving legislation might be unprioritized and perceived as not legitimate. Also, it was reported that, in many circumstances, detecting distracted driving is difficult without technology.

Another key factor undermining the effectiveness of enforcement operations targeting distracted driving-hazards is behavioral adaptation by drivers aiming to conceal or avoid police enforcement. Drivers have reported scanning the environment, searching for police, covering the phone all the time with their hand, and using the phone on their laps (Oviedo-Trespalacios et al. 2017b). Moreover, Oviedo-Trespalacios (2018) found that drivers who often engage in these behavioral adaptations also report higher engagement in distractions such as texting and browsing on a mobile phone. Alternatively, research has increasingly reported that drivers are using in-vehicle information systems (IVIS) to engage in texting with their mobile phones, making enforcement of mobile phone use legislation more difficult (Oviedo-Trespalacios et al. 2019f). Concerningly, IVIS are distracting even when interfaces such as Apple CarPlay and Android Auto are used (Oviedo-Trespalacios et al. 2019f;

Strayer et al. 2019; Ramnath et al. 2020). The fact that drivers are using these behavioral adaptations to avoid police enforcement undermines the effectiveness of this administrative control and must be addressed in the planning of future legislation and enforcement schemes.

The next group of administrative controls reported in the literature are related to Workplace Health and Safety (WHS) controls to prevent mobile phone use while driving. This is a very important group of controls because employment demands have been consistently linked with distracted driving, during both work-related and non work-related driving (Engelberg et al. 2015). Unfortunately, WHS efforts to prevent distracted driving are relatively new and only a few isolated cases have been evaluated. The main work identified confirmed that truck and bus drivers working for organizations that enforced texting bans have lower texting and driving prevalence in comparison to companies without bans (Hickman et al. 2010). Furthermore, additional research on work-related driving has concluded that implementing WHS policies to prevent distracted driving might not be sufficient to prevent this behavior, needing strict enforcement and sanctions to create a safety culture (Swedler et al. 2015a). Truck drivers in Swedler et al. (2015b) study listed the following examples that could be effective in reducing distracted driving:

- Better procedures for communicating with drivers – delivering a noninvasive signal over dispatch devices to indicate that the driver received a message.
- Enforcing bans on distracted driving activities.
- Video-monitoring to observe drivers engaging in distracted driving.
- Monitoring cell-phone usage if driver is using a company-provided phone.
- Locking out devices while vehicle is in motion.
- Automatically updating package delivery drivers' routes, so drivers do not have to make scheduling/routing decisions while driving.

There is great potential in the WHS space to reduce distracted driving, particularly among people who drive for work. The development of organizational guidelines could provide a great opportunity to increase road safety. Key guidelines to support this process have been developed in Australia by The National Road Safety Partnership Program (NRSPP 2016): "A guide to developing an effective policy for mobile phone use in vehicles." The process considers elements that can influence distracted driving in organizational settings, such as the current engagement in distracted driving, leadership, education, training, collection, monitoring and analysis of critical incident data, enforcement, mobile phone design, and vehicle purchase and design. There is a need to consolidate and increase the uptake of good road safety practices about distracted driving in the corporate sector.

Education programs have been developed in an effort to reduce and/or prevent drivers from using their mobile phones while driving. A number of interventions have been identified with significant gains in preventing distracted driving. In the USA, the telecommunications company AT&T launched the "It Can Wait" campaign. As part of the program, drivers are encouraged to sign a pledge on their website, encouraging them to make a commitment to never drive distracted (e.g., “I pledge to always drive distraction free.”). In addition, drivers installed an application capable of detecting when a vehicle is moving more than 25 mph and prevent mobile phone notifications. Furthermore, the campaign also launched a virtual reality experience on their website that helps users experience the dangers of distracted driving. As young adults were the primary target audience for this campaign, AT&T started social media campaigns (i.e., “#ItCanWait” hashtag on Twitter) and released a documentary (i.e., “From One Second to the Next”) to raise awareness about dangerous phone use while driving. The campaign evaluation showed a reduction in road crashes and larger awareness of distracted driving risk (Carter 2014). Unfortunately, studies aiming to replicate these results using similar strategies to those in the campaign have not shown the same success. Fournier et al. (2016) reported that neither the distribution of flyers and thumb bands with fear-based slogans (e.g., “It Can Wait”) nor the encouragement of drivers to sign a pledge seemed to reduce overall mobile phone distracted driving. Interestingly, however, the type of mobile phone use behavior did change, as drivers were found to decrease calling behavior but increase texting behavior while behind the wheel (Fournier et al. 2016). This apparent replacement of a risky driving behavior with an even riskier driving behavior highlights the need for more research to investigate the actual effectiveness of this campaign (Fournier et al. 2016).

Some educational campaigns have been aimed at specific groups of the transport system, such as employees (i.e., “It Can Wait” educational program) and parents of young drivers (i.e., “Steering teens safe” educational program). Tailored educational programs involve the use of workshops, lectures, and demonstrations about distracted driving. The “It Can Wait” educational program showed that these activities could be extremely useful in increasing awareness about distracted driving risk and road rules (Hill et al. 2020). In the case of the “Steering teens safe” educational program, parents were trained to use motivational interview frameworks to use with their teens besides being given relevant road safety knowledge so they could improve their communication with their teens (Peek-Asa et al. 2014). Although a reduction of distracted driving behaviors was reported, the success of these educational interventions has been limited. Given the importance of considering the role of additional actors, such as employers, parents, and friends, among others, in the prevention of distracted driving, future developments are needed in this space.

Emergent approaches to education of drivers do not seek to prevent distraction but to upskill drivers to engage safely in distracting behaviors. An innovative example of this is the “FOrward Concentration and Attention Learning (FOCAL)” educational program developed by Unverricht et al. (2019). FOCAL educational training develops the driver’s capacity to self-regulate off-road glances. Experiments conducted after the training confirmed its effectiveness in reducing the severity of distraction. Specifically, drivers who received the FOCAL training engaged in fewer in-vehicle glances longer than 2 s than drivers who received traditional education on distraction-related risks and road rules (Unverricht et al. 2019). Although evidence is limited, and no inferences about crash risks can be reliably made, this is a very innovative approach with the potential of changing the way we train drivers in the future.

Distraction and Vehicle Automation

New technologies are emerging that are capable of supporting and automating many of the functional driving activities performed traditionally by human drivers. These new technologies have been classified by the Society of Automotive Engineers International (SAE International 2018) as falling into two general categories that span six levels of automation:

- *Driver support features* (also known as advanced driver assistance systems) that provide momentary assistance and warnings (Level 0), steering or brake/acceleration support (Level 1), or both steering and brake/acceleration support combined (Level 2).
- *Automated driving features (ADF)* that (a) can drive the vehicle under limited conditions but require the driver to either take control when required (Level 3), (b) can drive the vehicle under limited conditions but do not require the driver to take back control (Level 4), and (c) can drive the vehicle under all conditions all of the time without human intervention (Level 5; SAE International 2018).

With increasing technological support and automation, the driving functions and tasks performed by drivers will change, and this will change the repertoire of knowledge, skills, and behaviors required by drivers to maintain safe driving performance (Casner and Hutchins 2019; Fisher et al. 2020; Regan et al. 2020; Spulber 2016). Even now, a modern driver has a unique skill set compared to drivers two or three decades ago; many drivers today have never driven a manual transmission vehicle or have been required to pump their brakes on slippery roads (Spulber 2016). As vehicles become increasingly supportive and automated, so too will the impact that distraction has on activities critical for safe driving. This is because the activities critical for safe driving will themselves change and, ultimately, in vehicles equipped with Level 5 ADFs, there will be no requirement for the driver to perform them at all. But will distraction, as a road safety issue, disappear when there is no requirement for humans to perform any activities critical for safe driving? We briefly explore this and related issues in the sections that follow, drawing on some recent thinking and empirical findings reviewed in Cunningham and Regan (2018a) and Lee et al. (2020) (and see also Kanaan et al. 2020).

Automation Creating Distraction

As vehicles become more automated, the technologies that drive them may, themselves, become a source of distraction for drivers. Evidence already exists showing that automation actions and alerts that are unexpected, because of a lack of training, lack of situational awareness, or some other mechanism, may create “automation surprises” (Hollnagel and Woods 2005), and, in doing so, distract drivers. Even routine alerts and indicators in vehicles equipped with existing driver support features may draw attention away from the road at inopportune moments in time (Lee et al. 2020).

As noted, vehicles equipped with Level 3 automated driving features are classified by the SAE (SAE International 2018) as being capable of driving the vehicle, but only in limited conditions. At this level of automation, the driver is expected to resume control if requested by the vehicle (e.g., if the automation fails or drifts out of its operational design domain). Here, the frame of reference for distraction may become different in the mind of the driver; the requirement to supervise the vehicle automation could itself become a source of driver distraction (Hancock 2009; Lee et al. 2020).

It is well documented that drivers tend to engage in secondary activities when supported by vehicle automation (Lee et al. 2020). Evidence for this has been found both in driving simulators (e.g., Carsten et al. 2012; Jamson et al. 2013) and in instrumented vehicles driven on test tracks (e.g., Llaneras et al. 2013; Dingus et al. 2016). The propensity to do so tends to be greater for technologies that provide higher levels of automation.

More generally, as vehicles become increasingly automated, the role of the driver is expected to shift from being that of an active controller of the vehicle to that of a more passive supervisor of the automated driving system (Desmond and Hancock 2001). There is evidence that this reduction in task engagement can induce “passive fatigue” (reduced attentional capacity arising from driving task demands which are too low (Desmond and Hancock 2001; Saxby et al. 2013) and, in turn, driver inattention (Saxby et al. 2013; Körber et al. 2015). Here, inattention is brought about not by distraction, per se, but by other mechanisms.

Thus, drivers may be distracted either because automation demands their attention at inopportune moments in time or it induces drivers to engage more often and more deeply in non-driving activities (Lee et al. 2020).

Distraction and Takeover Ability

In vehicles equipped with SAE Level 0–2 driver support features, the driver is considered to be driving the vehicle and is supported in performing activities critical for safe driving by a variety of technologies (e.g., Autonomous Emergency Braking; Adaptive Cruise Control). While distraction, when it occurs, may impair the performance of activities critical for safe driving, the technologies themselves may help to mitigate any detrimental impacts this distraction may have (Tingvall et al. 2009), as noted previously.

In vehicles equipped with SAE Level 3 ADFs, in which automation is capable of driving the vehicle in limited conditions, the automation is considered to be driving the vehicle (SAE International 2018). The driver is, however, expected to resume control of the vehicle if requested by the vehicle; e.g., if the automation fails or the vehicle is driven outside of its operation design domain. There is evidence that takeover quality in vehicles equipped with automated driving features is impaired when drivers are distracted (e.g., Merat et al. 2014). Interestingly, however, the speed of the motor actions required to commence the takeover (e.g., to reach for the steering wheel or apply the brakes) appears to be little affected (Zeeb et al. 2015, 2016). Some evidence also exists showing that manual driving performance may be compromised for a considerable period of time after the handover of control to the driver has been completed (e.g., Merat et al. 2014; for reviews, see Cunningham and Regan 2018a and Fisher et al. 2020).

Self-Regulation and Individual Differences

Drivers of manually controlled vehicles often, as noted earlier, self-regulate their behavior in an attempt to manage distraction (e.g., Bastos et al. 2020; Oviedo-Trespalacios et al. 2019a, 2020b; Ortiz-Peregrina et al. 2020; Tivesten and Dozza 2014). There is also some evidence that they self-regulate their behavior in automated vehicles. Jamson et al. (2013), for example, found that drivers supported by automation self-regulated their behavior in conditions of high traffic density in order to reduce the likelihood of them diverting their attention away from the forward roadway.

Large individual differences have been found in the nature and frequency of engagement in secondary activities when driving automated vehicles (e.g., Llaneras et al. 2013; Clark and Feng 2017; see also Fisher et al. 2020). Clark and Feng (2017), for example, investigated the impact of driver age on secondary task engagement during automated driving periods. They found that both younger and older drivers engaged in secondary activities when supported by automation. However, younger drivers mostly used an electronic device, while older drivers mostly conversed. Körber and Bengler (2014) reviewed a number of individual differences that may moderate the involvement and impact of driver distraction in automated vehicles. These include complacency and trust in automation, driver experience, and the propensity to become bored and daydream.

"Vehicle Distraction and Inattention"

Will driver distraction remain an issue in vehicles equipped with SAE Level 4 and 5 automated driving systems that obviate the need at all for a human driver to intervene? After all, in these vehicles, so equipped, there would be no controls, no driver, and the vehicle occupant could simply sit back and let the vehicle do all the driving.

This question highlights again the frame of reference through which distraction is conceptualized. Cunningham and Regan (2018a) speculate that, if there are only a few SAE Level 3, 4, and 5 vehicles in the community fleet, which mix with SAE Level 1 to 2 vehicles, then there may emerge a new frame of reference for distraction. Here, it is possible that drivers of vehicles being operated manually might be distracted by the behavior of vehicles operating autonomously if the latter have been programmed to drive in ways that violate drivers' expectations; in much the same way that drivers are distracted by the behaviors of others who drive or ride erratically in traffic flows.

If it is the responsibility of vehicles equipped with SAE Level 4 and 5 technologies to perform automatically all activities critical for safe driving, is it possible for such self-driving vehicles themselves to be distracted? Regan (in Lee et al. 2020) has labelled this “vehicle distraction.” Here, again, the frame of reference for conceptualizing distraction will change. But what competing activities, if any, could divert a vehicle’s “attention” (or computational resources), more generally, away from activities critical for safe driving? In fact, what might it mean for a vehicle driving autonomously to be inattentive and, if it was, what might be the mechanisms of inattention? (Cunningham and Regan 2018a, b).

These are interesting questions. For a vehicle to be attentive to activities critical for safe driving, its algorithms will need to be programmed such that the vehicle knows, from moment to moment, to which activities critical for safe driving it should be attending. If so, it will become necessary to specify – a priori – what these activities critical for driving will be, and they will presumably be a subset of the higher-level functional driving activities specified by Brown (1986), referred to earlier. They will change from moment to moment, along any given stretch of road.

But how do software programmers know what activities, critical for safe driving a vehicle operating autonomously, they should pay attention to from moment-to-moment along a stretch of roadway when the research community has not yet itself agreed on what we, as human drivers, should be paying attention to from moment-to-moment (Kircher and Ahlstrom 2016)? For those who have thought deeply about what activities are critical for safe driving (Engstrom et al. 2013; Hallett 2013), we know that this is not a trivial task.

Nevertheless, it is interesting to speculate on by what mechanisms, if any, a vehicle equipped with SAE Level 4/5 automation technology operating autonomously might become inattentive to activities critical for safe driving? The taxonomy of inattention proposed by Regan et al. (2011), noted earlier (see Table 1), is also useful in stimulating thought about the mechanisms by which an SAE Level 5 equipped vehicle might itself become inattentive to activities critical for safe driving. Regan (in Lee et al. 2020; see also Cunningham and Regan 2018a) has speculated on what “vehicle inattention” might mean for each of the five mechanisms of inattention proposed by Regan et al. (2011):

- *Driver restricted attention*: For a Level 4 or 5 equipped vehicle, this category of inattention might describe a vehicle that “goes to sleep,” so to speak, if, for example, there is a system failure, or some or all vehicle sensors suddenly become incapable of seeing. Here, the vehicle may become inattentive to some or all activities critical for safe driving.
- *Driver neglected attention:* This category of inattention would seem to be less relevant to the design of vehicles when driven by automation given that, unlike, humans, they will not be prone to the kinds of attentional biases, expectations, and limitations that humans are.
- *Driver mis-prioritized attention*: For a vehicle driving itself, this category of vehicle inattention might come about if the computer algorithms that drive it fail, through inadequate design, to give attentional priority to the most critical

competing activities critical for safe driving at a given moment in time. Even though vehicles when driving themselves will not have the limited attentional capacity of humans, software engineers will nevertheless need to program the vehicle to prioritize who and what the vehicle should pay attention to at any given moment in time during a trip.
- *Driver cursory attention*: For a vehicle driving itself, this is about not providing enough attention to activities critical for safe driving. Again, this category of inattention may be less relevant to the design of highly automated vehicles given that, unlike humans, they will not have the same limited attentional capacity. Nevertheless, it is incumbent on software engineers to ensure that vehicles driven by automation allocate enough attention (computational resources) to activities critical for safe driving to ensure that they are successfully and safely completed.
- *Driver diverted attention*: For a self-driving vehicle, this is about distraction. But is it possible for a vehicle operating autonomously to be distracted? It is probable that, if demanded by consumers, vehicle manufacturers may give drivers the option of operating self-driving vehicles manually. Current evidence suggests that there will be some demand from consumers (Cunningham et al. 2019). In this case, it is possible that drivers themselves could become sources of "vehicle distraction." This might occur, for example, if they attempt to take back control of a fully automated vehicle when they should not, in which case, vehicle "attention" may be diverted by the driver, at least temporarily, away from what the vehicle considers at that point in time to be the activities critical for safe driving to which it must attend. Vehicle distraction might also occur if people elect to drive self-driving vehicles manually (if allowed) in a way that violates the pre-programmed expectations of vehicle algorithms in other vehicles that are being controlled by automation. Here, self-driving vehicles might be seen as being distracted by the behaviors of other self-driving vehicles being operated manually.

The whole issue of what distraction and inattention, more broadly, might mean for self-driving vehicles in future is a fascinating one. The different frames of reference through which distraction may be conceptualized makes it highly unlikely that it will ever disappear as a road safety issue. For vehicles with higher levels of automation, then, countermeasure development will need to focus in future on a somewhat different set of distraction-related issues:

- The prevention of automation surprises (for Level 3 ADFs).
- Support for quality takeover and rapid gaining of control by drivers when requested by vehicle automation (for Level 3 ADFs).
- Prevention and mitigation of secondary-task engagement at inappropriate moments in time when automation is engaged (for Level 3 ADFs).
- Prevention and mitigation of passive fatigue induced by low workload during prolonged periods of automation (for Level 3 ADFs).

- The programming of automated driving features in a way that ensures that the vehicles they control do not violate the expectations of other road users (for Levels 3–5 ADFs).
- The prevention of "vehicle distraction and inattention" (for Levels 3–5 ADFs).

Countermeasure development for driver distraction at higher levels of automation is, however, in its infancy. Those countermeasures known to have been proposed have focussed on a limited number of areas: education and training for maintenance of vigilance of the driving environment and for understanding ADAS/ADF modes and vehicle performance (e.g., Casner and Hutchins 2019; Noble et al. 2020; Regan et al. 2020); human-machine interface design to minimize automation surprises and support safe resumption of manual control (e.g., Carsten and Martens 2019; Campbell et al. 2020); human factors considerations around policy and regulation for vehicle automation (Burke 2020); and use of driver state monitoring technologies and driver feedback to detect distraction and reorient driver attention (e.g., Lee et al. 2009; Lenné et al. 2020).

Conclusion and Strategies Moving Forward

In this chapter, we have introduced the reader to the field of driver distraction: its definition and mechanisms, its impact on driving performance and safety, prevention approaches, countermeasures, and new frames of reference for conceptualizing distraction as traditional driving functions become increasingly automated.

The focus of the chapter has been on driver distraction, although we acknowledge that there are other road users vulnerable to the effects of distraction, including bicycle riders and pedestrians. To our knowledge, there has been no systematic attempt to define distraction from their frames of reference and to define and classify the sources and mechanisms of distraction that lead to interference with activities critical for safe riding or walking. Furthermore, relatively little research has been done to understand the impact of distraction on their performance and safety (Oviedo-Trespalacios et al. 2019b). Prevention and mitigation strategies for these road user groups are, hence, at a relatively early stage of maturity.

Just as activities critical for safe driving will continue to change as vehicles become more automated, so too will the sources of distraction drivers interact with that may impair their performance. These include new infotainment and other technologies being built into the vehicle by manufacturers, special interfaces that provide connectivity between smartphones and vehicle displays and controllers (e.g., Apple CarPlay; Android Auto), and portable devices brought into the vehicle, including smartwatches and other wearables. While there is some limited research on the effects on driver behavior and performance of interaction with these devices while driving (Oviedo-Trespalacios et al. 2019f; Strayer et al. 2019; Ramnath et al. 2020), little or nothing is known about their impact as contributing factors to crashes and increased crash risk. Similarly, we know almost nothing about the impact on crashes and crash risk of distraction created by automated driving features.

While the focus of this chapter has been on the negative impacts that distraction may have on driving performance and safety, there is evidence that distraction may in some circumstances enhance driving performance and improve safety – by, for example, counteracting the effects of fatigue (Williamson 2009; see also Olson et al. 2009). However, the specific mechanisms by which this occurs (e.g., through increased arousal; increased vigilance, etc.) have not, to our knowledge, been researched and operationalized. Further research is needed to understand under what conditions, and how, distraction can be used in a positive way to optimize driving performance.

Laws that regulate the use of particular technology devices (e.g., mobile phones, visual display units) are becoming quickly outdated as new technologies and modes of interaction with them emerge. Australia's National Transport Commission (NTC) has recently advocated a shift away from technology-based road rules towards technology-neutral approaches for regulating driver distraction (National Transport Commission 2019). This approach would provide (p. 8) (a) "a clear list of high-risk behaviours and interactions that drivers must avoid regardless of the technology involved or the source of distraction" and (b) "reduced uncertainty about 'proper control' to address both the observable causes and consequences of behaviours and interactions that can impair a driver's control of a vehicle." This would seem to be a positive way forward that focuses more on those behavioral interactions known to increase crash risk (e.g., long eye glances away from the forward roadway) rather than on the technologies that induce them, and provides clearer, evidenced-based guidance to enforcement authorities on what constitutes improper control of vehicles being driven by distracted drivers.

In addition to the guidance already provided in this chapter, we provide in Table 5 some general strategies that might be considered by society in setting a coordinated agenda for the management of distracted driving going into the future. They have been categorized under headings that will be more familiar to road transport agencies: data collection and evaluation, education and training, employers, legislation and enforcement, licensing, public education, research, road and traffic engineering and design, roadside advertising, stakeholder consultation, technology design, and vehicle design. These strategies derive from material presented in this chapter, our own thinking and some other sources (Regan et al. 2009; European Commission 2015; NRSPP 2016; PIARC 2016; Imberger et al. 2020; Regan et al. 2020; Department of Transport and Main Roads 2020b). It is our hope that the material presented in this chapter, along with the general strategies outlined in Table 5, will go some way towards informing the future management of distracted driving.

Until all vehicles can drive themselves, in all conditions, all of the time, it is unlikely that we will achieve Vision Zero for distracted driving, and even then, self-driving vehicles may themselves be vulnerable to its effects. In the meantime, however, there is much that can be done to prevent and mitigate the effects of driver distraction as we strive, collectively, to achieve Vision Zero.

Table 5 Strategies moving forward to manage driver distraction

	Strategies
Data collection and evaluation	Adopt a common definition of distraction that can be operationalized and used to code crash and incident data. Standardize the way in which distraction data are collected and coded in crash and incident databases. Provide training for police and crash investigators to detect distraction as a contributing factor in crashes and distinguish it from other mechanisms of inattention. Undertake regular studies of driver exposure to distracting activities. Continue to undertake naturalistic driving studies that enable estimates of crash risk to be established for driver interaction with emerging sources of distraction. Evaluate the effectiveness of all distraction prevention and mitigation strategies that are implemented; design them from scratch in a way that allows them to be properly evaluated.
Education and training	Develop a shared national and international narrative for driver distraction. Align stakeholder educational campaigns to drive cultural change and awareness of distracted driving. Provide distraction management education and training for drivers of all ages. Provide drivers with education and training in the use of vehicles equipped with ADAS and automated driving features focussed on distraction. Make driving instructors aware of driver distraction management competencies that should be covered in their driver training programs. Leverage personalized insurance pricing for safe drivers, with an emphasis on distraction mitigation. Educate consumers to make wiser choices regarding their purchases in terms of technology that minimize distraction while driving. Develop new educational models and leverage the potential of new technologies such as virtual reality to create more effective education.
Employers	Develop an understanding of the relationship between job demands and distracted driving. Encourage employers to develop and implement best practice policies for managing distraction – for both professional and nonprofessional drivers. The NRSPP (2016) "Guide to Developing an Effective Policy for Mobile Phone Use in Vehicles" is a good example. Consider insurance as a lever for corporate vehicle fleets – as a mechanism for incentivizing the implementation of best-practice policies for managing distraction and safer driving technologies.
Legislation and enforcement	Evaluate relevance and effectiveness of existing distraction regulations and penalties for driver distraction – monitor Australia's move towards technology-neutral regulations. Optimize deterrence models to consider legal sanctions, social sanctions, and new road policing activities.

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Table 5 (continued)

	Strategies
	Develop and implement technologies that support police enforcement of regulations for driver distraction. Develop a data platform that enables investigation, tracking, and sharing of crash and infringement data resulting from driver distraction.
Licensing	Incorporate information about distraction in licensing programs. Incorporate into computerized testing driver knowledge of distraction and ability to manage it. Incorporate into on-road testing, criteria for assessing driver ability to manage distraction.
Research	Following an extensive, evidence-based review of the nature and size of the distraction problem in the EU, the European Commission (European Commission 2015) identified the following priorities for distraction research (p. 5): • “Voice recognition: How should such systems be designed? • “Night vision: Can such systems present extra information to drivers in such a way as to alert the driver to potential risks, but without being too distracting?” • “Biometry: Can systems spot inattention quickly enough to permit useful intervention or alerts? Can they be reliable enough to avoid drivers wanting to turn the systems off (e.g., false alarms)?” • “Legislation of usage conditions: How should legislation be designed and worded with the pace of technology development (e.g., new input and output modes) being so quick?” • “Public information campaigns: What is needed in such campaigns beyond the provision of information? How can behavioural change techniques help?” • “Auditory/vocal (cognitive) distraction and how it relates to driver performance and crash risk.” • “Sociological aspects of distraction: What makes drivers willing to take part in distraction activities? How do social norms play a role? Does the need for ‘connectedness’ outweigh risks in the perception of drivers?” • “Views of young drivers on driving and distraction: What makes young drivers particularly susceptible to distraction by devices? Which sub-groups of young drivers are particularly at risk?” • “Effects of countermeasures: Which countermeasures can be shown to really work? What are the relative benefits of enforcement approaches? Can behaviour change” approaches to work to reduce exposure to distraction?” • “Pedestrian distraction studies: What is the exposure of pedestrians to distraction? What behaviours other than crossing the road are affected? How does the increased risk for pedestrians (per unit of travel) compare with that of other road users?” • “Distraction/alertness in the transition to automated driving: How long do people need to move from a distracting task to taking

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Table 5 (continued)

	Strategies
	over control of an automated vehicle? What are the best ways of alerting drivers in this situation?” • “Self-regulation of road users and good driving behaviour: Does behavioural adaptation (e.g., reduced speed) actually reduce risk for some distracting tasks? What are the distraction tasks that cannot benefit from behavioural adaptation?” • “Future trends and challenges in distraction: Does the ageing population represent an increased distraction risk? Will ‘wearable technology’ improve the situation or make things worse?” • “New vehicles and distraction: Will new vehicles with different behavioural profiles (e.g., electric bicycles with higher speeds) reduce distraction-related safety margins?” • “Business models and eco systems of new distraction-preventing technologies: How can countermeasures be built into the business case? Who will pay for distraction-reducing technologies?” Although many of these strategies are specific to the context of driving, researchers and practitioners should also consider the role of distraction among other road users such as pedestrians, cyclists, motorcyclists, etc. The impact of distraction on the performance and safety of other road users has been under-researched.
Road and traffic engineering and design	Identify which road and roadside objects, events, and activities distract drivers and other road users, and contribute most to crashes and crash risk. Design the road environment to prevent distraction-related crashes, including infrastructure that guides and nudges road users to stay focussed on the driving task. Design the road environment to provide opportunities for road users to recover from mistakes and noncompliance arising from distraction. Design the road environment to lower energy exchange through conflict points to within human tolerances. Develop and implement guidelines and standards for the design of the road and traffic environment to reduce distraction. Develop and implement criteria and test methods for rating the road and traffic environment for its potential to distract drivers that could be incorporated in road safety audits and roadway star rating systems (e.g., IRAP).
Roadside advertising	Promote independent research on the impact of roadside advertising on the safety of all road users. Develop standardized criteria and methods for assessing the suitability of a road site for the erection of advertising signage. Develop standardized criteria and research methods for evaluating the impact of advertising billboards on driver performance and safety. Develop guidance for planning authorities for assessing development applications for advertising on private premises

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Table 5 (continued)

	Strategies
	adjacent to roads to ensure greater consistency with advertisements in the road corridor. Proactively evaluate the impact of new advertising models and technologies on road safety.
Stakeholder coordination	Promote cross-sectoral stakeholder cooperation and coordination led by national and international bodies. Guarantee active participation of major stakeholders such as government, industry, drivers, technology developers, etc. Recognize the role that non-transport stakeholders such as the healthcare system or entertainment industry have in distracted driving. Adopt Human Factors Integration processes to ensure that products and systems are user-centered designed to prevent and mitigate distraction
Technology design	Persuade companies that already develop technologies to use smart phones in vehicles more safely to adopt common HMI design guidelines to further reduce road user distraction. Promote standardization of interfaces for the secure placement, mounting, and powering of nomadic devices on vehicle dashboards to prevent distraction induced by sliding and dislodgement of devices. Develop and implement mobile and wearable design guidelines, standards and features that facilitate safe interactions and prevent unsafe ones. Stimulate demand for other technologies (such as phone blocking, distraction warning systems, and workload managers) where proven to prevent and mitigate (directly) the effects of distraction. Develop and implement technologies that support police enforcement of regulations relating to driver distraction.
Vehicle design	Provide incentives for manufacturers to equip vehicles with technologies that prevent and mitigate the effects of distraction. Stimulate societal demand for advanced driver assistance systems already known to prevent and mitigate the effects of distraction. Develop and implement guidelines and standards for minimizing distraction in current and future generation vehicles. Develop assessment protocols for rating vehicles for their potential to distract drivers that could be incorporated in new car assessment programs (e.g., NCAPS) to encourage improved human-machine interface design.

Cross-References

- ▶ Automated Vehicles: How Do They Relate to Vision Zero
- ▶ Vision Zero: How it All Started

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Appendix

A Review of countermeasures against distracted driving hazards following the "Hierarchy of Controls."

Level of control	Countermeasure	Description	Evidence of Effectiveness
Elimination	Fully Automated Vehicles (FAV) SAE Level 4–5	FAV use sensors and software to drive the vehicle. Drivers are not required to take control or monitor the vehicle.	As drivers are not required to take control, this raises the question as to whether or not drivers can engage in distracted driving (e.g., eating, mobile phone use, etc.) without any repercussions. Automated vehicles are already being used in controlled road networks such as mining sites (Gershgorn 2016). Projected benefits from such vehicles are only likely to be observed in 25–30 years, mostly due to challenges in infrastructure, legislation, etc. (Dia 2015; Clark et al. 2016)
Substitution	Workload managers	Presenting driving and non-driving related information in such a way that road users are not distracted. Workload managers help drivers to focus on driving when it is needed.	Experimental research has shown that the technology could have a positive impact on safety in reducing distraction from ADAS (driving-related information) (Teh et al. 2018). The effectiveness of this approach to manage non-driving related information is unknown.
Engineering controls	Partially Automated Vehicle SAE Level 3 (also known as autopilot)	Partially automated vehicles involve automation of key vehicle control tasks, e.g., lateral and longitudinal vehicle control. However, drivers are supposed to maintain their hands on the steering wheel and be supervising the	Drivers are likely to engage in distraction while driving partially automated vehicles (Lin et al. 2018), which could result in road crashes.

(continued)

Level of control	Countermeasure	Description	Evidence of Effectiveness
		vehicle. Also, drivers must be available to take over control of the vehicle at all times.	
Engineering controls	Advanced driver-assistance systems (ADAS) including crash warning system [available in SAE Level 1–2 vehicles]	ADAS support drivers with features such as cruise control, blind spot monitors, lane centering, etc. ADAS also include systems that provide warnings for upcoming collisions.	Early warnings helped decrease drivers' reaction times, thus avoiding more conflicts and collisions (Lee et al. 2002; Bao et al. 2012). However, ADAS might not compensate for the effects of distraction on drivers' performance (Sieber et al. 2015). ADAS could increase distraction by means of poorly designed warnings/alarms (Biondi et al. 2014; Thompson et al. 2018; Li et al. 2020b). The spread of in-vehicle information systems (IVIS) increases the capabilities and often licit means to engage in non-driving tasks (Oviedo-Trespalacios et al. 2019f). IVIS are often used as an interface for ADAS.
Engineering controls	Blocking technology for mobile phone distractions	There are two main technologies: mobile phone applications and hardware which seek to block mobile phone use while driving (Oviedo-Trespalacios et al. 2019d)	Mobile phone applications and hardware-based technologies to block mobile phone technologies are effective in reducing mobile phone use while driving (Oviedo-Trespalacios et al. 2020a; Albert et al. 2019). However, there are concerns that some applications will not fully prevent high-risk mobile phone interactions. A field study using

(continued)

Level of control	Countermeasure	Description	Evidence of Effectiveness
			hardware-based blocking technologies in Australia showed a reduction on mobile phone use while driving (Ponte et al. 2016). Acceptance of blocking technologies is low among drivers which limits adoption of the technology (Oviedo-Trespalacios et al. 2019e, 2020c; Ponte et al. 2016; Reagan and Cicchino 2018).
Engineering controls/ administrative controls	Feedback systems [*Targeting young drivers*]	Feedback systems deliver information to drivers on their performance. Three main different feedback systems have been established (Merrikhpour and Donmez 2017): Social norms feedback that provided a report at the end of each drive on teens' distracted driving behavior, comparing their distraction engagement to their parents. Post-drive feedback that provided just the report on teens' distracted driving behavior without information on their parents Real-time feedback in the form of auditory warnings based on eyes-off-road time	Feedback systems that consider parental norms and real-time feedback are associated with a smaller duration of off-road glances, with parental norms feedback outperforming real-time feedback (Merrikhpour and Donmez 2017). Post-drive feedback showed no significant effect (Merrikhpour and Donmez 2017).
Administrative controls	Legislation	Legislation banning the use of mobile phone devices while driving	There are mixed reports about the effectiveness of bans across jurisdictions. In the USA, universal handheld calling bans are associated with lower self-reported

(continued)

Level of control	Countermeasure	Description	Evidence of Effectiveness
			handheld conversations for adult drivers (Rudisill et al. 2019b) as well as a reduction in motor vehicle crash (MVC)-related emergency department (ED) visits (Ferdinand et al. 2019). Alternatively, Rudisill et al. (2019b) found that universal texting bans were not associated with lower texting. A US literature review found that nearly none of the restrictions targeting young distracted drivers sustainably prevented mobile phone use while driving (Ehsani et al. 2016). In Europe, Jamson (2013) found that drivers in the most highly regulated country (Italy) reported texting while driving as frequently as those in countries with no legislation.
Administrative controls	Police enforcement	Police operations to increase compliance of legislation banning different forms of mobile phone use while driving.	Reductions of mobile phone use while driving are observed with resource-intensive police operations (McCartt et al. 2010). However, there are doubts of the long-term impact of the bans on safety (McCartt et al. 2014). The effect of police enforcement of mobile phone bans is limited. Research has shown that police officers are unable to correctly enforce legislation in many circumstances due

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Level of control	Countermeasure	Description	Evidence of Effectiveness
			to lack of resources, poor visibility inside vehicle, unenforceable legislation, among others (Rudisill et al. 2019a; Nevin et al. 2017). Additionally, drivers can engage in police-avoidance strategies such as concealing their mobile phone which further reduce effectiveness of police operations (Oviedo-Trespalacios 2018).
Administrative controls	Organizational procedures/ policies *[Targeting driving for work]*	Implementation of Workplace Health and Safety (WHS) organizational procedures/policies to reduce distracted driving and enhance safety of drivers.	Truck and bus drivers working for organizations that enforced texting bans have lower texting and driving prevalence in comparison to companies without bans (Hickman et al. 2010). Participants in Swedler et al. (2015b) study emphasized the importance of implementing policies that are clearly and strictly enforced. In addition, a participant in the study mentioned that a texting ban would help create an organizational safety culture that does not normalize distracted driving. Truck drivers in Swedler et al. (2015b) study listed the following examples that could be effective in reducing distracted driving: Better procedure for communicating with driver – delivering a noninvasive signal over dispatch device to

(continued)

Level of control	Countermeasure	Description	Evidence of Effectiveness
			indicate that the driver received a message Enforcing bans on distracted driving activities Video-monitoring to observe drivers engaging in distracted driving Monitor cell-phone usage if driver is using a company-provided phone Locking out device while vehicle is in motion Automatically updating package delivery drivers' routes so drivers don't have to make scheduling/routing decisions while driving
Administrative controls	"It Can Wait" educational program	In 2010, AT&T launched the "It Can Wait" campaign across the USA to educate drivers on the dangers of texting and driving. The campaign involved: Signing an online pledge to encourage drivers to make a commitment to never drive distracted (e.g., "I pledge to always drive distraction free.") A mobile app called "AT&T DriveMode," which detects when a vehicle is moving more than 25 miles an hour. If a driver receives a text message or email when the vehicle is in motion, the app is capable of sending an automatic reply to notify them that the user is currently driving (AT&T 2012). A virtual reality experience on their	AT&T evaluated the program after its launch, and found strong, positive, relationships between the campaign activities, particularly social media sharing, pledging, and mobile apps, and the projected reduction in crashes that would have taken place across the USA over a 1-year period (Carter 2014).

(continued)

Level of control	Countermeasure	Description	Evidence of Effectiveness
		website that helps users experience the dangers of distracted driving	
Administrative controls	"Steering teens safe" educational program	Educational intervention targeting parents of teen drivers. The intervention included: Parents received a workbook that identified 19 safety lessons divided into 4 topics: basic safety principles (including distracted driving); safe driving skills; rural driving; and special situations. Parents were upskilled on motivational interviewing in an initial 45-minute session. Parents received three 30-minute follow-up phone calls to provide additional intervention support	The intervention had a weak but positive effect, enhancing risky driving and parent-teen communication about road safety (Peek-Asa et al. 2014).
Administrative controls	"Just Drive—Take Action Against Distraction" educational program *[Targeting driving for work]*	An education program designed to increase awareness of the dangers of distracted driving and to encourage employees to be safe and responsible drivers. The program included presentations, group activities, and a "pledge card" to document the planned behavioral changes. The target group were businesses and organizations in San Diego County as part of employee safety and wellness programs.	The program was well received among the participants and resulted in positive changes in short-term intention and medium-term behaviors. Additionally, participants showed increased knowledge regarding distracted driving legislation and risks (Hill et al. 2020).
Administrative controls	"FOrward Concentration and Attention Learning (FOCAL)" educational program	The FOCAL program is a research-led training that consists of three stages: Pretest: Trainees watch four video clips while	Driver who received the FOCAL training engaged in fewer in-vehicle glances longer than 2 s by roughly 25 percentage

(continued)

Level of control	Countermeasure	Description	Evidence of Effectiveness
		having to switch between viewing the forward roadway and a map via keyboard. Trainees were asked to find the location of a street while also limiting glances away from the road to less than two seconds. Participants hit the space key on the keyboard to switch between the viewing the forward roadway and the map Training: This stage included feedback, timer, 3-second in-vehicle glance training, and 2-second in-vehicle glance training. Posttest: Trainees finished the program by watching four new video clips and completing the same task as in the pretest.	points when compared to the placebo group (Unverricht et al. 2019).

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34 Automated Vehicles: How Do They Relate to Vision Zero

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Contents

Abstract

The ideas to develop and introduce partially or fully automated vehicles are not recent but are not used on any larger scale at this moment. It is though likely that automating different functions, or moving vehicles driverless, will be common sooner or later. In this text, it is discussed how Vision Zero principles relate to the automation of the road transport system. Key findings are that automated vehicles

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will have to be better than human drivers and their safety system horizon will be key to limiting their functionality. The road transport system will have to be adapted to both failing humans and failing automated vehicles.

Keywords

Vision Zero · Automated vehicles · Model for safe traffic · Rules around automated vehicles

Introduction

Automation is entering the road transport system. This both as automated safety systems but also, being more challenging, as fully or partially automated vehicles. Vision Zero can be an important cornerstone when setting demands on automated vehicles. The safety requirements put on automated vehicles will probably be high, higher than the demands on human drivers. Models and approaches will have to be developed.

The ideas to develop and introduce partially or fully automated vehicles are not recent but not used on any larger scale at this moment. It is though likely that automating different functions, or moving vehicles driverless, will be common sooner or later. In this text, it is discussed how Vision Zero principles relate to automation of the road transport system.

Automation of vehicles can be seen as a stepwise migration of different driving tasks from the human driver to the vehicle. There is a migration of both normal driving tasks and driver actions in crash-related critical situations. There are several scales, but the Society of Automotive Engineers (SAE) seems to have developed the most widespread definitions of the levels between no automation and full (autonomous) automation (SAE 2018). A more simplified scale is a to go from "feet off" via "hands off" to finally "eyes off" representing the steps from automation of longitudinal control of speed to control of lateral positioning to finally let the technology take over all strategic, tactical, and operational driving tasks. In the highest level, full automation, the vehicle is "driverless" and could drive without human interactions. In between the steps, we have temporary situations, from milliseconds to infinite time, when the technology control some functions of the vehicle. This could be triggered as a safety function, like electronic stability control (ESC) or autonomous braking (AEB). They could also be more comfort oriented like adaptive cruise control (AICC). We can also see remote control of vehicles like geofencing of speed or "radio control R/C" with remote driving as some kind of automation, i.e., taking control of the driving task from the driver in the vehicle. A second development route is the one where low-speed vehicles operate along predefined route. These vehicles are seen already today. As they develop they will be able to incrementally manage more complicated situations.

The Vision Zero Concept

When first introduced around 1994, the Vision Zero contained a shift in focus in many traffic safety areas. One important and significant shift was in the new responsibility balance between the road users and system designers. System designers were defined as the bodies in society that design, operate, and use the road transport system. Vision Zero is stating that the system should be adapted to the failing human – a relatively dramatic shift from the common approach that road users should take the burden of a dangerous and non-error-tolerant road traffic system.

1. **The designers of the system are always ultimately responsible for the design, operation, and use of the road transport system and thereby responsible for the level of safety within the entire system.**
2. **Road users are responsible for following the rules for the safe use of the road transport system set by the system designers.**
3. **If road users fail to obey these rules due to lack of knowledge, acceptance, or ability, or if injuries still occur, the system designers are required to take necessary further steps to counteract people being killed or seriously injured.**

Vision Zero's shared responsibility concept

Vision Zero is further focusing the road traffic safety challenge to the most severe injuries, the impairing injuries and the fatalities. The development and introduction of Vision Zero resulted in a change in the Swedish Road Administration that up until Vision Zero mainly used accident reduction as the key target. Shifting focus and targets from accidents to the most severe cases changes what solutions are prioritized.

Illustrations about 2+1 roads and roundabouts (Swedish Transport Administration 2019)

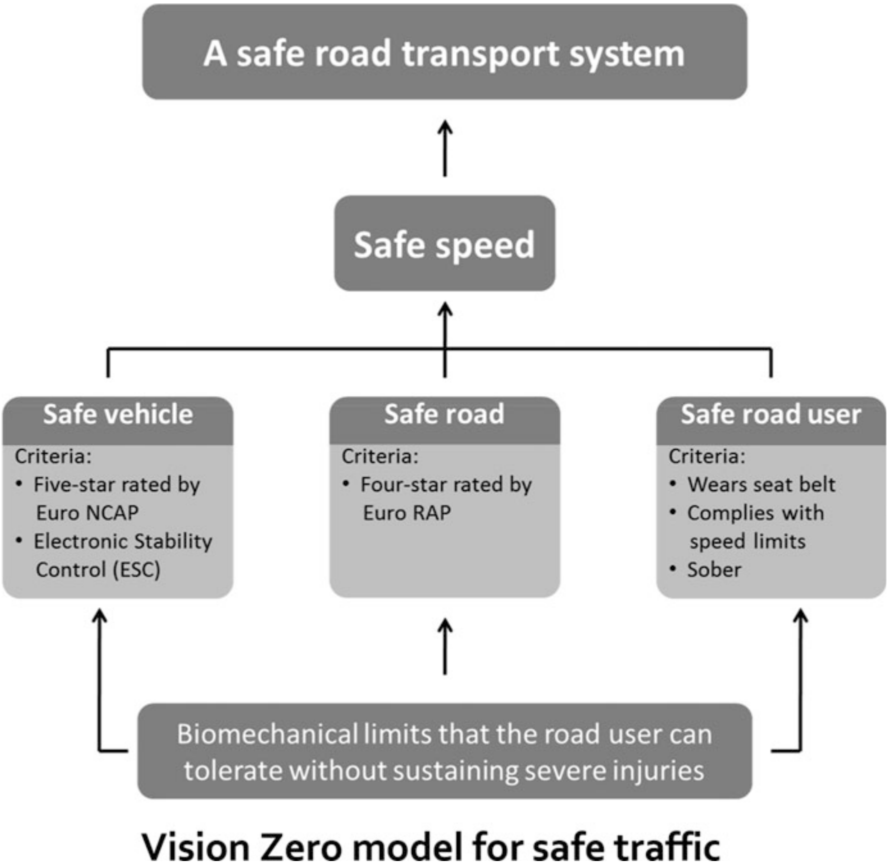
The safety core of Vision Zero is very much to design for the failing, non-perfect human – the human making misjudgments, errors, and mistakes. This is in strong contrast with the idea of perfect humans in traffic. The National Highway Traffic Safety Administration (NHTSA) in the USA finds that 94% of accidents are because of human error. This illustrates that the road traffic system is not designed for humans with the capabilities and weaknesses they have. The 94% human error problem, as described by NHTSA, can lead to the conclusion that we must develop driver further. In Vision Zero, the main focus is to develop the road transport system to absorb human failures to avoid fatalities and serious injury. However, we must bear in mind that humans are relatively good at driving.

As previously stated, Vision Zero is not aiming for a crash-free road transport system. It is aiming at a system without crashes that risk to result in loss of life or loss of long-term injuries. This is leaving the system designers with the possibility to manage the energy in crashes to levels that are survivable and not resulting in long-term harm. Energy control becomes essential and would include not only limiting kinetic energy but also using barriers, dampers, and filters outside and inside vehicles or directly protecting the human body through helmets and other protective gear.

Vision Zero Models for Safe Traffic

Vision Zero is using a holistic approach to road traffic safety. The capabilities of the road users and the performance of vehicles and roads together with the energy levels (speed) in the system can be balanced to deliver an efficient and safe system. High and safe travel speeds are possible with good cars on good roads and when no vulnerable road users are at risk in the system. With today's vehicle safety systems, speeds must be under 30 km/h when vulnerable road users and cars interact.

To illustrate how the components of the system interact, a Vision Zero model for safe traffic was developed. The Vision Zero model for safe driving can help in the planning process of a management system for traffic safety, especially in the design parameter setting and in the understanding of potential crashes.



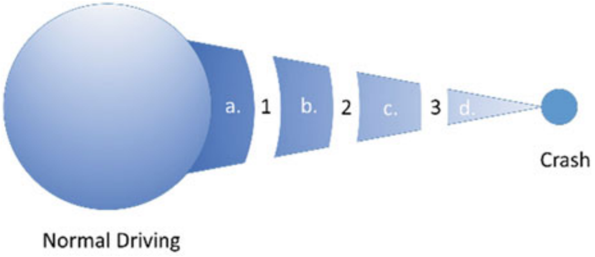
Vision Zero model for safe traffic

An example of the use of elements and criteria is how the factor "Safe vehicle" contains the element vehicle safety as measured by Euro NCAP and the criterion 5 stars. Another example is in the factor "Safe road user" that is having "Wears seatbelt" as element and 100% fulfillment as criterion. Stigson et al. have used this model to evaluate the safety on Swedish roads (Stigson 2009). By setting the criteria, a "safe" speed limit can be defined. Volvo Cars and the Swedish Transport Administration made a joint effort in 2011 to define "safe speed limits" (Eugensson et al. 2011). The basis was the existing levels of crash safety and accident avoidance technologies. The exercise indicated that at road without a median guard rail and safe management of the side areas, the maximum speed could be 80 km/h. The assumption was that the best cars could brake away 20 km/h before the crash and that a crash with a change of velocity of 60 km/h could leave the passengers without life-threatening injuries. The implication is that at speed higher than 80 km/h, significant investment in the road infrastructure is essential. At lower speeds much of the safety can be vehicle based. For vulnerable road users, a similar discussion was held and showed that travel speed of 40 km/h could be considered safe if the vehicles could brake 10 km/h before a crash and assuming a crash with a vulnerable road user is "safe" at 30 km/h. The numbers presented illustrate well how the human biomechanical limits, the protection in and of cars, the potential pre-impact braking, and the speed limit together can be used to calculate risk.

The reasoning above can be illustrated as a chain of processes potentially leading up to a crash and a serious injury or fatality.

The Vision Zero Integrated Safety Chain Model

To understand how crashes and injuries occur, the Vision Zero integrated safety chain model was developed (Tingvall 2008). It is describing crashes as a process spanning from normal driving to a crash and post-crash care and rehabilitation.



The integrated safety chain model

In the normal driving phase, most of the driving is done. The parameters from the Vision Zero model for safe traffic apply. The speeds should be at levels that ensure that potential crashes don't result in severe injuries of fatalities. If all drivers were perfect, the story would stop here. Everyone would be in the envelope of normal driving all the time. But when we design for failing humans, we must plan for events where road traffic users sometimes make errors, misjudgments, and mistakes. It is, however, important to remember that humans in a larger perspective are extremely good at driving and managing traffic. Most of us stay in the normal driving phase for hours and hours also in complicated traffic situations.

Even if normal driving is common and to a large degree regulated, human drivers often leave the normal driving and enters critical situations. Illegal speeding, driving too close, and not being able to stop in time are all examples of such situations.

For a multitude of reasons, drivers sometimes leave the normal driving or critical envelope and approach a critical situation (b). At this stage soft methods can be used to get the driving back into normal. This could be in the form of lane departure warnings, electronic stability control, or the warning element of emergency braking systems. In this early phase, the driver can still be part of the control and get the vehicle back into normal driving. One can expect that drivers are in these critical situations several times every year.

If the potential crash passes barrier level 2, one can no longer expect the driver to manage the situation. In phase c automated emergency braking is today such a system. In the future automated emergency steering can avoid potential crashes. In phase c reversible crash safety systems can also be activated. Reversible seatbelt pretensioners are one relevant example.

If the event is passing barrier 3, the crash can no longer be avoided. However it can still be mitigated by continuation of emergency braking in phase d. The consequences of the crash can in this phase be reduced by non-reversible crash safety systems.

In the crash more traditional safety systems such as seatbelts and airbags are active to protect the occupants. In a safe system, no energy can hit the human body at levels higher than the biomechanical tolerance levels for severe or fatal injuries. An ordinary driver can drive all the life without experiencing a crash going all the way to severe injuries.

In the integrated safety chain, one element is the frequency of cases going from normal driving and to a potential crash. One must be aware that very few crashes actually end up in severe and potentially life-threatening cases. An ordinary driver in a modern car can experience some ESC interventions and perhaps a few emergency brake warnings per year. Emergency braking or pre-impact deployment of safety systems is even rarer.

The integrated safety chain model is also an illustration of energy and can be read in reverse to establish safe travel speeds. Starting with the human tolerance, adding the crash safety system's performance and finally adding the crash mitigation and avoidance system's capabilities can result in a safe normal driving speed. A consequence of this is that cars with poor crash safety and few crash mitigation and avoidance safety systems have a lower "safe speed" compared to the best cars. This is what the above mentioned Volvo Cars study illustrated.

The Vision Zero work has developed two important models, the model for safe traffic and the integrated safety chain. Both models show how the human tolerance to crash impact, together with safety systems, can indicate safe travel speeds. The models also illustrate how different safety layers can support one another to generate safe traffic and that modifications would be directed to not only the vehicle but also the infrastructure.

In 1965 and 1966, Sweden had 1313 fatalities each year, the highest in Swedish history. This corresponded to around 17 fatalities per 100,000 inhabitants. Today Sweden has around 2 fatalities per 100,000 inhabitants. It is interesting to note that Sweden historically had about the same fatality rate as the world has today. According to the WHO's Global Status Report on road safety 2018, the global rate of road traffic death per 100,000 population was calculated to be 18.2 in 2016. The large reductions are a consequence of systematic work altering the components and interactions of the road transport system.

What About Automated Cars?

A question to consider is the relation between automated cars and Vision Zero. Do the Vision Zero models applicable for a fully or partially automated road transport system? There are reasons to believe so. Just as Vision Zero is defining possible speeds/energy levels based on the safety-related design properties of the road and the vehicles, an automated system must consider crash mitigation and avoidance safety properties, crash safety capabilities, and possible safe travel speeds. This approach is essential at least as long as the automated cars are used in traffic also containing manually driven vehicles and they have not proven to be crash- or incident-free.

In this paragraph the integrated safety chain will be used for a discussion about safety strategies for automated cars.

The normal driving of a fully automated car will be very different from the normal driving for humans. Automation and computers lack many of the human's weak spots. They don't get tired, they don't get drunk, they can have constant focus, etc. But potentially automated vehicles have in some aspects lower capabilities. The human eye and ear have dynamic ranges and capabilities that is a challenge to match. One can assume that the challenges for humans also are challenges for automated cars but also that automated vehicles will have unique challenges not yet well known. One can assume that humans have a unique possibility to act "approximately right" in complicated new and unexpected situations.

Sensors are very important elements since they are the basis for situational awareness. The situational awareness, mapping ego activities, the road properties, and the positions, speed, and intention of other road users are the bases for safety as the vehicle must operate in a dynamic surrounding. Humans have a very good capability when it comes to making decisions based on sparse information in a complicated situation.

Humans often bend or brake road traffic regulations. From an individual perspective, it can seem rational and beneficial. The perhaps most common is to travel faster than the regulated speed limit. But road users often break other rules and regulations as well. From a societal perspective, this is a problem and a reason for the significant road traffic problems we see. One must assume the fully automated vehicle will be law abiding, and therefore there is no variation in relation to rules and accepted practices in driving and therefore no need for bringing the car back to normal driving, i.e., the driving is always in the safe normal driving envelope. This makes the design of a safe system easier. However, for a long time we will have to design for both human driver partially automated and fully automated vehicles.

Automated vehicles will, just as human drivers, make errors and mistakes and misunderstand situations. As an effect of this, automated vehicles will at least initially need the same safety package as ordinary vehicles. If the fully automated vehicles should travel at speeds similar to vehicles driven by humans, the safety package must be the same. When designing a fully automated vehicle, there are good reasons to consider and design the safety systems as separate from the systems managing normal driving. This would add a much valued element of redundancy. A good side effect of automated cars having sophisticated crash mitigation and avoidance systems and crash safety system would probably also be further improvements to the safety pack of ordinary vehicles.

Is Performing as Good/Bad as Humans Good Enough?

The question above is probably one of the most challenging when discussing the introduction of fully automated vehicles. Here it will be discussed with an ethical approach, a legal approach, and an efficiency approach.

First of all we must define the objective of what potential outcome of incidents and unexpected events should be for a fully automated car. We could aim for the same safety ambition as Vision Zero, no fatalities or serious injuries. Or we might choose to move to "no crashes at all" or even further to avoid also incidents as to aim for security or rather the feeling of security. Cases that go beyond the target in Vision Zero would have major impact on the way a fully automated vehicle can operate. Using the chain of events approach where we limit the travel speed to what is possible to avoid fatalities and serious injuries and instead replace such a target with avoiding crashes means that we must reduce travel speed substantially. And if we would limit, say, braking to less than 0.2 g (normal and conformable braking), the travel speed would have to be further reduced. To some degree improved sensing and situational awareness could influence acceptable travel speeds but only marginally as long as errors do occur.

The road transport system kills about 1.25 million people every year. That is an alarming number, and as previously pointed out, the international society has taken action against road fatalities (United Nations General Assembly 2020). The situation has had a relatively low priority since our attitude to a large degree has been to blame the victim. An individual has done something "wrong" and is hence to blame. The fact that there is a guilty part has blinded many. The Vision Zero introduces the shared responsibility model. Road traffic users must do their best, but the system designers hold a high degree of responsibility for the design and usage of the system. It is more ethical to blame the ones having a real possibility to change the system (Hauer 2016).

Further it seems that we, both society and individuals, have a higher interest in protecting passengers than drivers. Being an innocent victim is significantly different from being an active agent, a driver. The effect of this is that safety in trains and planes is significantly higher than in cars. In aviation and for trains, there is virtually no balancing between safety and efficiency. Safety comes first. In the road transport system, such balancing is still common practice even if Vision Zero slowly is changing practice in many organizations.

For fully automated cars, it seems relevant to put the safety ambitions as high as the levels for aviation of train riding, a twentieth of the risk of today's car riding.

The Vienna Convention Article 13

The road transport system of today is running as it does, much because of driver not fully adhering to the rules. But taking the rules literary will probably be a prerequisite for partially or fully automated vehicle functions. The Vienna Convention of road traffic from 1968 is setting the framework for road regulation in most countries. One significant article in the convention is Article 13.

The key aspect is that the driver (or in the case of automated cars the control mechanism) always should adapt the speed so to be able to stop for any foreseeable obstruction. Even if the Vienna Convention isn't a regulation in itself, this article should be implemented in all national regulations in the contracting countries.

Human drivers are often not fulfilling the demand to be able to stop within the range of forward vision. This is clearly seen in the dark, rainy, or foggy traffic situations. We also often pass buses where it is well known that especially children can rush into traffic. Humans frequently take risks and bend rules in ways fully automated vehicles probably cannot accept. The risk taking of humans can to some degree make the system more efficient but at a high cost in insecurity, crashes, and severe or fatal injuries.

Combining the demands from the Vienna Convention, about being able to brake, with Vision Zero's chain of event model can reveal the new situation. The fully automated vehicle must always plan and act as to remain within the normal driving envelope. The energy level can never be higher than the allowed speed limit, but it is further restricted by the demand to be able to stop short of any foreseeable obstruction. The strict demand in the Vienna Convention about adaptation of the speed is often poorly understood or neglected by human drivers. Computer-driven vehicles should have less issues with this. The sensors and their limitations in combination with the systems situational awareness will restrict possible travel speeds. One must keep in mind that the Vienna Convention demands a crash-free system, not an injury-free traffic. The fully automated vehicle will therefore move slower than the rest of the traffic, and it may be sometimes a better idea to close off manually driven cars from some environments. The alternative is to change the rules and the behavior of the manually driven cars as well, to accommodate the principles of the Vienna Convention with regard to speed. Another alternative is to give the automated vehicles special infrastructure solutions to move within.

External or shared sensors could potentially expand the sensor horizon for automated vehicles. It can, however, be questioned whether external sensors can be reliable enough to base safety critical decisions on.

But, even if the energy levels are at the right, fully automated vehicles will be driving in environments with other vehicles and road users. Therefore it is probable that the fully automated vehicles also will crash and therefore need good systems to brake, steer, and protect in the crashes. Fully automated vehicles may be designed in ways where the passengers have seating postures different from the ones of today's vehicles. Safety demands and performance in these new seating positions must be considered. It is not likely that crash safety can be diminished for a long time to come. Further investment in crash avoidance and crash safety is an investment in higher speeds and better mobility.

Probably society will not accept fatalities and severe injuries in the fully automated transport system. As the safety demands increase, the most severe injury that is acceptable will be at lower levels than we see today. In the few and rare crashes that automated vehicles experience, the injury levels must be extremely low.

Very rare incidents and extremely few injuries are also a prerequisite for the acceptance for machine-driven vehicles from the general public. The new vehicles must act and feel like reliable and trustful traffic elements.

The demands regarding the impact of the road transport system will also gradually increase over time in such a way that even children should be able to walk or bicycle without risking any injury as a result of a conflict with fully automated vehicles. This will even more restrict automated vehicle to move in such a way that parents and the society feel secure. This means an even less obtrusive traffic.

Discussion

The development towards full or partial automation of driving functions will no doubt continue. Some of the safety technologies developed and introduced during recent years have been proven to be very effective. There are technologies available or under development that could significantly reduce illegal speeding and impaired driving, related to alcohol, fatigue, and distraction. Further, autonomous emergency braking and lane keeping aid systems have become common practice in modern cars. While these technologies do not have a 100% effect on the situations they address, they still seem to bring down the risk of fatalities to very low levels (Rizzi et al.). If they, hypothetically, would be 99% effective on fatalities, we would still have fatalities left but on a global basis go from, say, 1 million deaths per year to 10,000 deaths per year. That would be a giant step, but still not near today's safety level of rail or aviation (including only fatalities to those using train or regular aviation and excluding, for instance, car occupant fatalities in train to car level crossing crashes).

With these technologies within reach and more to come, full automation is probably not needed to solve today's safety challenges. However, regulation may be needed to ensure that all vehicles are equipped with these new technologies and that the systems are active when the vehicles are driven.

For railway, the acceptable risk for a jurisdiction is set to 10^9 fatalities per operating hours (Tingvall and Lie 2021). If we translate this level to the road transport system, the maximum number of fatalities for the European Union would be less than 185 fatalities per year which is 140 times less than the actual number (in 2018). For the USA, the corresponding figure would be 300 times lower than today's fatality number.

The risk of a fatality in a country like Sweden is already quite low on an individual basis. Calculated on cars (passenger cars, trucks, etc.), we have 200 fatalities linked to these annually, with 5 million cars exposed. This would equate on average to 1 fatality per 25,000 years for a car exposed. For serious injuries the corresponding figure would be 1 case per 2500 years. This tells us that the risk per individual car is low, but on a country level, it still becomes a large health problem.

For cars with a complete set of safety systems, much like a Volvo car of year model 2020 studied in the report by Rizzi et al., we could expect at least a 50% reduction compared to the estimates above. That would equate to 1 fatality per 50,000 years per vehicle and year and 1 per 5000 years for a serious injury. But a serious injury or a fatality would only be a tip of an iceberg, and the number of crashes with/without an injury would be many times more. While crashes without a serious injury or fatality would not be seen as a traffic safety problem, it is likely that they would constitute an unacceptable event for a fully automated car. This could be seen as the main issue surrounding the expectations for a fully automated car in comparison with a car driven by a human.

Many crashes (Rizzi et al. 2019) would be avoided or mitigated if the driver was brought to drive in accordance to general traffic rules. Driving sober, not exceeding the speed limits, and with a distance to the car in front of at least 2–3 s would no doubt have a large effect on the number of killed and serious injury. The figures given above would be significantly reduced when basic rules are followed. If every driver in Sweden did not speed, the number of fatalities would drop by at least 25%. And if no one was driving under the influence, another 25% would not be killed. If we would also add fatigue and distraction as examples, it is likely that we would end up with very few cases of fatalities. A fully automated car would not act as if the driver was intoxicated or fatigued nor drive too fast. But the technologies to detect and limit the driver to act and drive within the legal frameworks exist already. It can be seen as surprising that drivers today are given possibilities to break so many rules when there are technologies available to almost eliminate many offenses.

Given the above logics, it is hard to argue that the safety gains as they are expressed in Vision Zero would be substantial with fully automated cars. On the contrary, it might be a larger challenge to replace the human during normal driving than to only use technology when the driver is acting unsafe and/or a hazardous situation occurs. There are significant benefits in using the capabilities of human drivers and complement these with partially or fully automated functions, without making the entire driving process fully automated.

What seems to be more challenging with the fully automated car is the expectation that it would not only avoid any serious harm to a human but also not crash. It would probably even be expected to act in a nonaggressive way, meaning no harsh braking, etc. This would in turn reduce speed and increase distance to other vehicles and humans. The consequence of the fully automated car would therefore be more of a mobility issue or comfort rather than a safety issue. Furthermore, significant modifications to the road infrastructure would have to be made to improve effectiveness that otherwise would have to be solved by low travel speed. For low-speed fully automated vehicles, this could be more straightforward, especially if they only travel along predefined routes. This seems to be an issue not discussed to the extent that is needed (Sternlund 2020).

In summary, it does not seem adequate to claim that fully automated driving is the way to improve traffic safety to the level of Vision Zero. The combination of the driver and the technology of a vehicle could under certain conditions be as safe as, or even safer than, the fully automated car. But these conditions would no doubt put the same type of restrictions on the driver as we put on the automated car. Speed, fitness to drive, and distance to other road users should be the same for the car driven by a human as it would be on the fully automated car. The main difference between the automation and the manually driven car would be what we aim for – a road transport system free of death and serious injuries or a road transport system free of crashes, incidents, or fear of technology. In the end, it would be the effectiveness of the road transport system that would be the real challenge.

As human drivers will continue to play active roles in driving their vehicles while managing an increasing array of new or newly configured technologies at their disposal, they can expect to encounter more situations when they must consider, or have embraced and trusted a priori, a mix between human and automated control. These questions become tangibly real for drivers of cars equipped with advanced systems. Millions of drivers over the next 10 years will not only have to ask what their vehicle is able to handle, but be prepared and comfortable answering them with literal life-or-death certainty. Democratizing safety technology so that it benefits the greatest number of people as soon as possible is a new way of looking at our journey to full automotive autonomy. We believe that such a development can be enabled by a scalable safety approach that puts each new safety innovation wherever it can work effectively (Veoneer 2020).

It should also be stressed that the safety modeling of Vision Zero is based on modifying the road infrastructure if the conditions does not fulfill the safety requirements given the safety level of the vehicles exposed. For fully automated cars, the modifications to the infrastructure should be brought up as well. Otherwise, the entire safety challenge would have to be solved by the vehicles, and this does not seem to be rational as the travel speed of the safe fully automated car would have to be very low. In summary, it would be a mistake to believe that no modifications would have to be done to the infrastructure or to the functionality of the road transport system if we fully automate the vehicles. However we can foresee focussed action in the infrastructure if they are limited and clearly defined. An open dialogue around demands and performance would help both vehicle and infrastructure designers. We still need to bring humans, infrastructure, functions, and vehicles into the design of the future safe and secure mobility.

Partially or fully automated vehicles will be common in the future. The full potential benefits can only be gained if we understand the potential and limitations of automation. There is also an urgent need to look at automation in the systems perspective that Vision Zero has developed.

Fully automated vehicles are probably not prerequisites to achieve Vision Zero, but Vision Zero or even higher safety levels are a prerequisite for fully automated vehicles.

Conclusions

- Safety, trust, and security are critical elements when introducing partially or fully automated vehicles.
- When machines are driving, the safety demands will increase at least tenfold compared to the expectations on human drivers. They must experience fewer and less severe crashes than what we see today.
- The fully automated vehicles will have to obey traffic regulation. As a result of this, the energy allowed will be restricted by their sensor horizon, sensor reliability, situational awareness, and their stopping distance.
- Even if machines can drive safely in an ego perspective, they will have to plan for crashes by having the same safety systems as human driven cars.
- The key element of Vision Zero, the road transport system must be adapted to the failing human, is valid also for machine-driven vehicles. The system must be adapted for the failing machines.

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