# Rural road design according to the safe system approach

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# Rural Road Design According to the Safe System Approach

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## 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

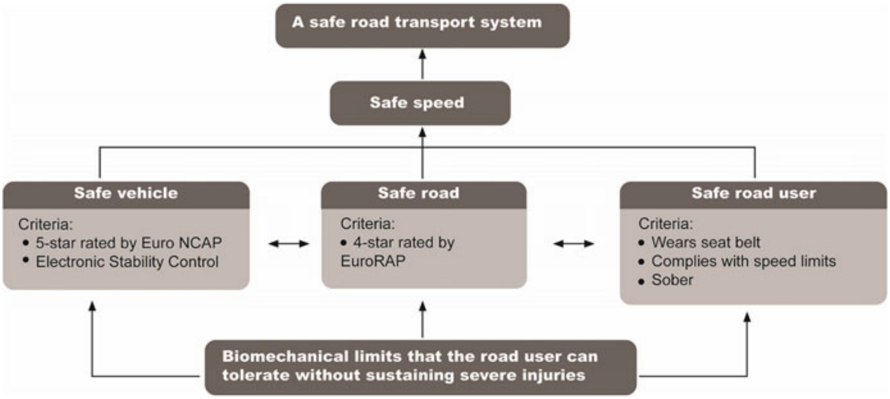

**Fig. 1** The model of a safe road transport system with criteria for the vehicle, the road and the road user reflect best practice in the present-day road transport system. (Source: Stigson 2009)

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

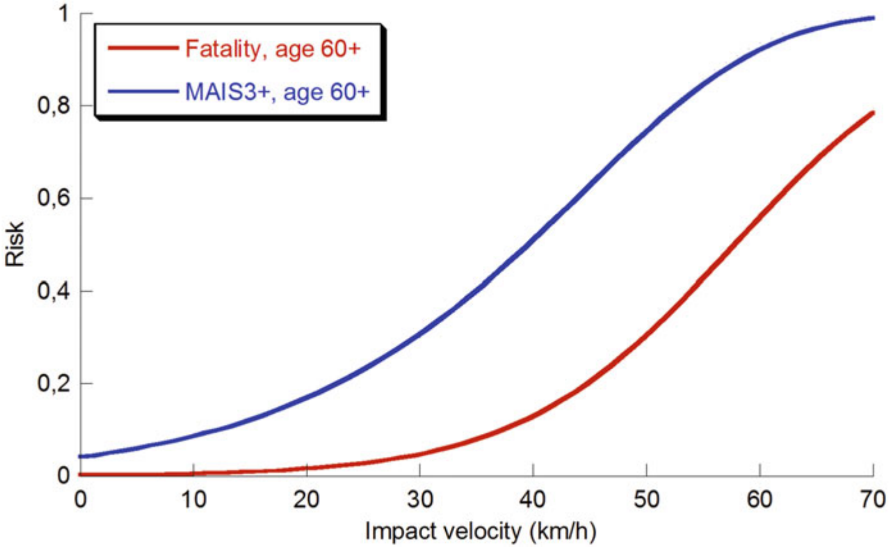

**Fig. 2** Risk for fatality and serious injury (MAIS3+) for pedestrians above 60 years age as a function of impact velocity. (Source: Stigson and Kullgren 2010)

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,

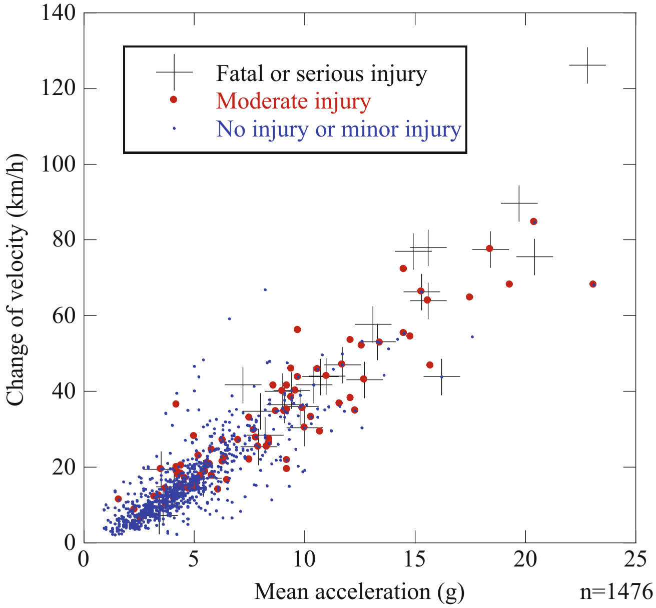

**Fig. 6** Correlation between change of velocity and mean acceleration for crashes with occupants of different injury status. (Source: Folksam)

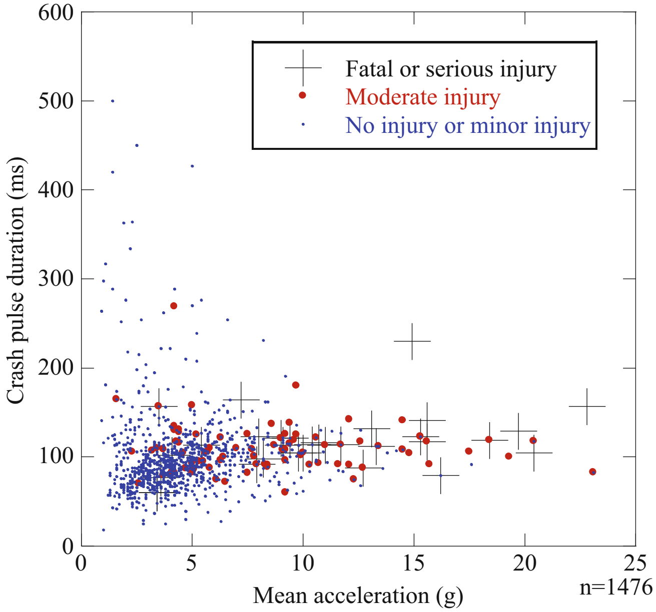

**Fig. 7** Correlation between mean acceleration and crash pulse duration for crashes with occupants of different injury status. (Source: Folksam)

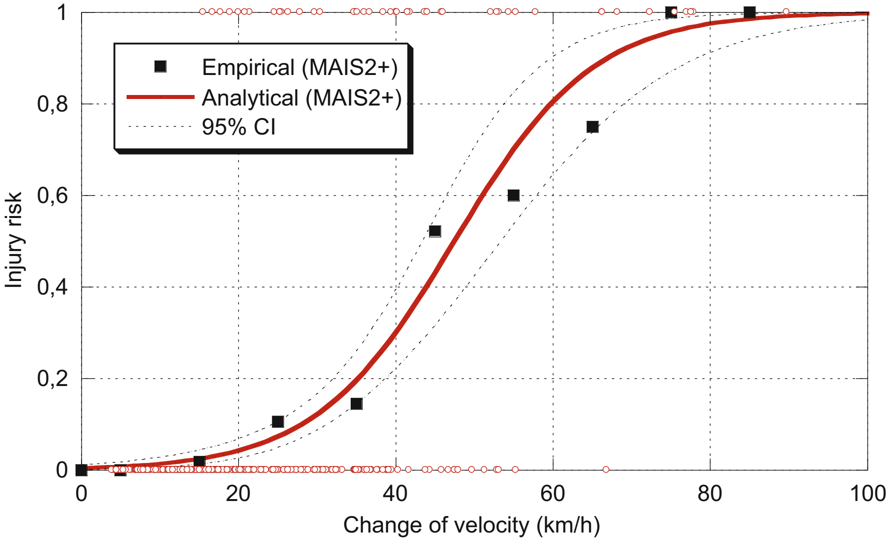

**Fig. 8** Risk of a MAIS2+ injury for front seat occupants versus change of velocity in frontal impacts (Stigson et al. 2012)

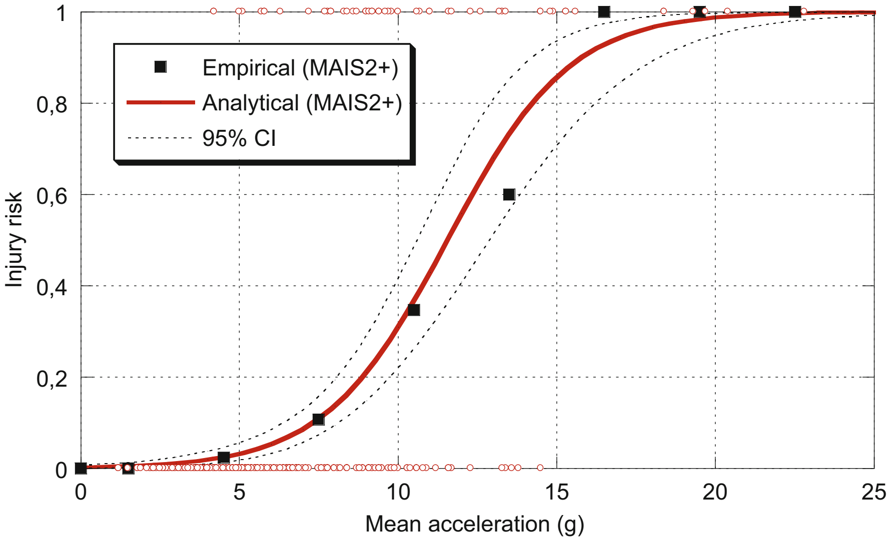

**Fig. 9** Risk of a MAIS2+ injury for front seat occupants versus mean acceleration in frontal impacts (Stigson et al. 2012)

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

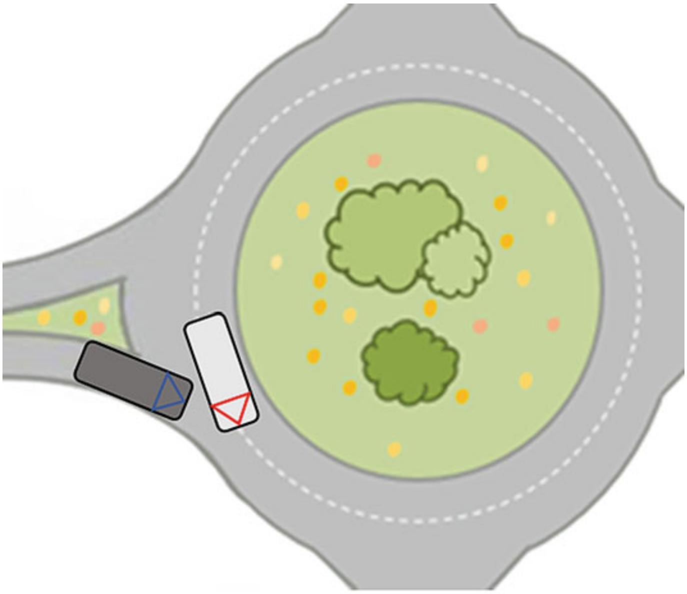

**Fig. 12** Impact angle and speed will be changed by replacing a traditional intersection with a roundabout

## 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

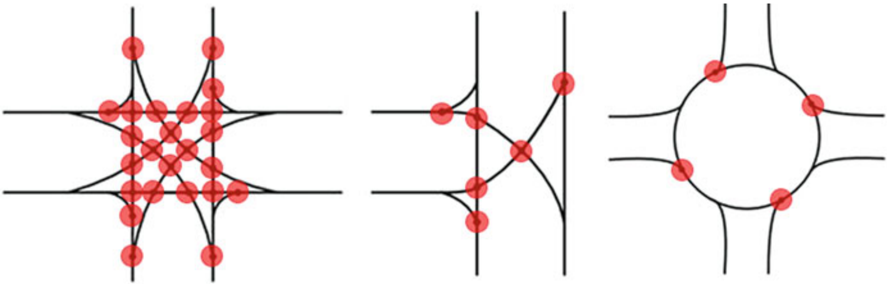

**Fig. 13** Potential conflict points of major conflict of intersections, left: four-leg crossing 24 conflict points, middle: T-junction 6 points, right: roundabout 4 points

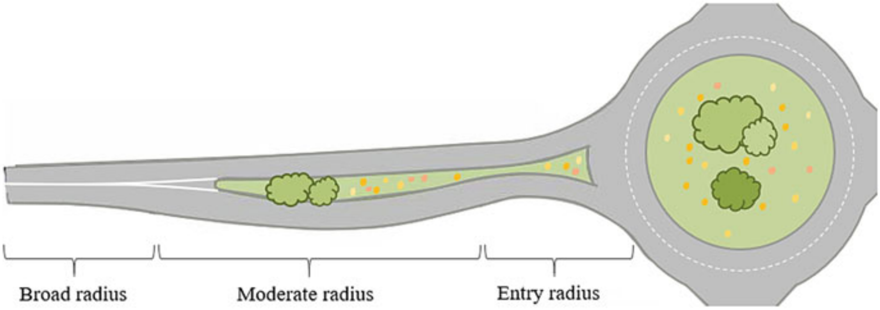

**Fig. 14** An example of chicanes at roundabout approach aimed to reduce entrance speed

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 $\geq 0.5$ 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 | | | $\geq 12$ |
| 110 | F/H | | | $\geq 11$ |
| | DR | New | $> 8000$ | $\geq 11$ |
| | DR | | $\leq 8000$ | $\geq 10$ |
| | DR | Redesigned | | $\geq 10$ |
| 100 | DR | | $> 4000$ | $\geq 10$ |
| | DR | | $\leq 4000$ | $\geq 9$ |
| | DR | Redesigned | | $\geq 9$ |
| | 2-lane | New | $\leq 1500$ | $\geq 9$ |
| | 2-lane | Redesigned | | $\geq 9$ |
| 80 | 2-lane | New | $> 8000$ | $\geq 8$ |
| | 2-lane | New | 4000–8000 | $\geq 7$ |
| | 2-lane | Redesigned | 2000–4000 | $\geq 7$ |
| | 2-lane | Redesigned | 1000–2000 | $\geq 6$ |
| | 2-lane | Redesigned | $\leq 1000$ | $\geq 5$ |

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.

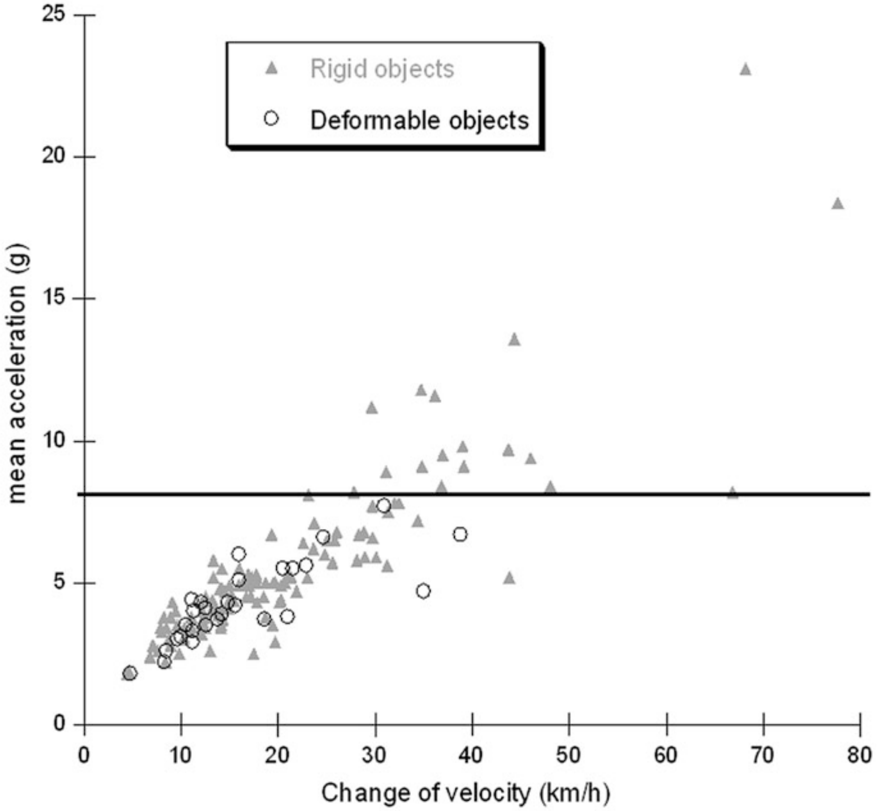

**Fig. 15** Distributions of vehicle mean acceleration in crashes with rigid and deformable objects, from (Stigson 2009)

**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

## References

Agerholm, N., Knudsen, D., & Variyeswaran, K. (2017). Speed-calming measures and their effect on driving speed – Test of a new technique measuring speeds based on GNSS data. *Transportation Research Part F: Traffic Psychology and Behaviour, 46*, 263–270. https://doi.org/10.1016/j.trf.2016.06.022.

Berg, F. A., Rücker, P., & König, J. (2005). Motorcycle crash tests — An overview. *International Journal of Crashworthiness, 10*(4), 327–339. https://doi.org/10.1533/ijcr.2005.0349.

Brüde, U., & Björketun, U. (2006). *Samband mellan EuroRAP och DSS-kvot - Sammanfattning/slutsatser (Correlation between EuroRAP and KSI)* (Projekt 50585). Retrieved from Linköping, Sweden

Brüde, U., & Vadeby, A. (2006). *Junction design – a review*. Retrieved from Linköping, Sweden: http://www.vti.se/EPiBrowser/Publikationer/R554.pdf

Carlsson, A. (2009). *Evaluation of 2+1-roads with cable barrier - Final report*. Retrieved from Linköping, Sweden: https://www.vti.se/sv/publikationer/publikation/evaluation-of-21-roads-with-cable-barriers_670552

Carlsson, A., & Brüde, U. (2005). *Uppföljning av mötesfria vägar (Follow-up of midseparated roads)*. Retrieved from T. S. N. R. a. T. R. I. (VTI): Linköping, Sweden

CROW. (2007). *Design manual for bicycle traffic*. Retrieved from https://www.crow.nl/publicaties/design-manual-for-bicycle-traffic

Daniels, S., Brijs, T., Nuyts, E., & Wets, G. (2010). Explaining variation in safety performance of roundabouts. *Accident Analysis and Prevention, 42*(2), 393–402. https://doi.org/10.1016/j.aap.2009.08.019.

Delaney, A., Langford, J., Corben, B., Newstead, S., & Jacques, N. (2003). *Roadside Environment Safety, Report to RACV.* Retrieved from Melbourne, Victoria: DfT. (2005). *Road casualties Great Britain: 2004 – Annual Report,* (ISBN 0-11-522703-6). Retrieved from http://www.travelindependent.org.uk/files/adcasualtiesgreatbritain2004.pdf

Ding, C., Rizzi, M., Strandroth, J., Sander, U., & Lubbe, N. (2019). Motorcyclist injury risk as a function of real-life crash speed and other contributing factors. *Accident Analysis and Prevention, 123*, 374–386. https://doi.org/10.1016/j.aap.2018.12.010.

Dozza, M., Schindler, R., Bianchi-Piccinini, G., & Karlsson, J. (2016). How do drivers overtake cyclists? *Accident Analysis and Prevention, 88*, 29–36. https://doi.org/10.1016/j.aap.2015.12.008.

Durisek, N. J., Tanner, C. B., Chen, H. F., & Guenther, D. A. (2004). *Vehicle characterization through pole impact testing, part I: Vehicle response in terms of acceleration pulses* (2004-01-1210).

Durisek, N. J., Tanner, C. B., Brantman, R., & Guenther, D. A. (2005). *Vehicle characterization through pole impact testing, part ii: analysis of center and offset center impacts*. Retrieved from

Elvik, R., & Vaa, T. (2004). Part III: 1. Road design and road furniture. In *The handbook of road safety measures*. Oxford: Elsevier.

ETSC. (1998). *Forgiving roadside*. Retrieved from http://archive.etsc.eu/documents/bri_road5.pdf

Evans, L. (1991). *Traffic safety and the driver.* New York: Van Nostrand Reinhold.

Folksam. (2015). *Bättre motorcykel- och räckesdesign kan rädda liv* [Improved Motorcycle and Barrier design can save lifes]. Retrieved from http://www.folksam.se/testergodarad/sakeritrafiken/mcsakerhet/sakerhetsstudie2015

Gabauer, D. J., & Gabler, H. C. (2008). Comparison of roadside crash injury metrics using event data recorders. *Accident Analysis and Prevention, 40*(2), 548–558. https://doi.org/10.1016/j.aap.2007.08.011.

Gross, F., Lyon, C., Persaud, B., & Srinivasan, R. (2013). Safety effectiveness of converting signalized intersections to roundabouts. *Accident Analysis and Prevention, 50*, 234–241. https://doi.org/10.1016/j.aap.2012.04.012.

Grzebieta, R., Bambach, M., & McIntosh, A. (2013). Motorcyclist impacts into roadside barriers: Is the European crash test standard comprehensive enough? *Transportation Research Record, 2377*(1), 84–91. https://doi.org/10.3141/2377-09.

Harvey, T. (1992). *A review of current traffic calming techniques*. Retrieved from http://www.its.leeds.ac.uk/projects/primavera/p_calming.html

Herrstedt, L. (2006). *Self-explaining and forgiving roads – Speed management in rural areas.* Paper presented at the 22nd ARRB Conference – Research into Practice, Canberra Australia.

Hydén, C., & Varhelyi, A. (2000). The effects on safety, time consumption and environment of large scale use of roundabouts in an urban area: A case study. *Accident Analysis and Prevention, 32*(1), 11–23.

IIHS. (2005). *Fatality facts 2004: Roadside hazards.* Retrieved from http://www.iihs.org/research/fatality_facts/pdfs/roadsidehazards.pdf

Johansson, R. (2008). Vision zero – Implementing a policy for traffic safety. *Safety Science, 47*, 826–831.

Johansson, R., & Linderholm, L. (2016). *VGU-guide : Vägars och gators utformning – Utformningsprocess (Design of roads – Design process)*. Retrieved from Trafikverket: Borlänge: http://urn.kb.se/resolve?urn=urn:nbn:se:trafikverket:diva-4146

Kloeden, C. N., McLean, A. J., Baldock, M. R. J., & Cockington, A. J. T. (1999). *Severe and Fatal Car Crashes Due to Roadside Hazards*. Retrieved from Adelaide, South Australia: http://casr.adelaide.edu.au/hazards/HAZARD.PDF

Kovaceva, J., Balint, A., Schindler, R., Schneider, A., Stoll, J., Breunig, S., . . . Esquer, A. (2019). *Assessment of the PROSPECT safety systems including socioeconomic evaluation*.

Krafft, M., Kullgren, A., Malm, S., & Ydenius, A. (2005). *Influence of crash severity on various whiplash injury symptoms: A study based on real-life rear-end crashes with recorded crash pulses* (Paper presented at the 19th International Conference on the Enhanced Safety Vehicles (ESV), Washington DC, USA).

Kullgren, A. (1998). *Validity and reliability of vehicle collision data: Crash pulse recorders for impact severity and injury risk assessments in real-life frontal impacts* (Phd). Stockholm: Karolinska Institutet.

Kullgren, A. (1999). Crash-pulse recorders in real-life accidents: Influence of change of velocity and mean and peak acceleration on injury risk in frontal impacts. *Journal of Crash Prevention and Injury Control, 1*(2), 113–120. Retrieved from http://www.informaworld.com/10.1080/10286589908915748.

Kullgren, A., & Stigson, H. (2011). *Report on whiplash injuries in frontal and rear-end crashes*. Retrieved from Folksam.

Kullgren, A., Rizzi, M., Stigson, H., Ydenius, A., & Strandroth, J. (2017). *The potential of vehicle and road infrastructure interventions in fatal pedestrian and bicyclist accidents on Swedish rural roads – what can in-depth studies tell us?* (Paper presented at the 25th ESV Conference, Detroit).

Kullgren, A., Stigson, H., Ydenius, A., Axelsson, A., Engstrom, E., & Rizzi, M. (2019). The potential of vehicle and road infrastructure interventions in fatal bicyclist accidents on Swedish roads-what can in-depth studies tell us? *Traffic Injury Prevention, 20*(sup1), S7–S12.

La Torre, F. (2012). *Forgiving roadsides design guide*. Retrieved from C. C. o. E. D. o. Roads): https://www.cedr.eu/download/Publications/2013/T10_Forgiving_roadsides.pdf

Lee, G., Joo, S., Oh, C., & Choi, K. (2013). An evaluation framework for traffic calming measures in residential areas. *Transportation Research Part D: Transport and Environment, 25*, 68–76. https://doi.org/10.1016/j.trd.2013.08.002.

Lie, A. (2012). Nonconformities in real-world fatal crashes–electronic stability control and seat belt reminders. *Traffic Injury Prevention, 13*(3), 308–314. https://doi.org/10.1080/15389588.2011.653842.

Mandavilli, S., McCartt, A. T., & Retting, R. A. (2009). Crash patterns and potential engineering countermeasures at Maryland roundabouts. *Traffic Injury Prevention, 10*(1), 44–50. https://doi.org/10.1080/15389580802485938.

Ohlin, M., Strandroth, J., & Tingvall, C. (2014). *The combined effect of vehicle frontal design, speed reduction, autonomous emergency braking and helmet use in reducing real life bicycle injuries* (Paper presented at the International Cycling Safety Conference, Göteborg, Sweden).

Persaud, B. N., Retting, R. A., Gårder, P. E., & Lord, D. (2001). Safety effect of roundabout conversions in the United States: Empirical Bayes observational before-after study. *Transportation Research Record, 1751*(1), 1–8. https://doi.org/10.3141/1751-01.

Persaud, B. N., Retting, R. A., & Lyon, C. A. (2004). Crash reduction following installation of centerline rumble strips on rural two-lane roads. *Accident Analysis and Prevention, 36*(6), 1073–1079. https://doi.org/10.1016/j.aap.2004.03.002.

Polders, E., Daniels, S., Casters, W., & Brijs, T. (2015). Identifying crash patterns on roundabouts. *Traffic Injury Prevention, 16*(2), 202–207. https://doi.org/10.1080/15389588.2014.927576.

Pucher, J., Dill, J., & Handy, S. (2010). Infrastructure, programs, and policies to increase bicycling: An international review. *Preventive Medicine, 50*(Suppl 1), S106–S125. https://doi.org/10.1016/j.ypmed.2009.07.028.

Rajamaki, R. (2010). Impact of rumble strips on road accidents. *Research reports of the Finnish Transport Agency*(41), online-online. Retrieved from http://dx.doi.org/

Rechnitzer, G., & Grzebieta, R. H. (1999). *Crashworthy systems – A paradigm shift in the road design (part II)*. Paper presented at the "Aus Top Tec" Topical Technical Symposia, Society of Automotive Engineers Australia, Melbourne, VIC.

Retting, R. A., Persaud, B. N., Garder, P. E., & Lord, D. (2001). Crash and injury reduction following installation of roundabouts in the United States. *American Journal of Public Health, 91*(4), 628–631. https://doi.org/10.2105/ajph.91.4.628.

RISER. (2005). *European best practice for roadside design: Guidelines for roadside infrastructure on new and existing roads*. Retrieved from https://ec.europa.eu/transport/road_safety/sites/roadsafety/files/pdf/projects_sources/riser_guidelines_for_roadside_infrastructure_on_new_and_existing_roads.pdf

Rizzi, M. (2016). *Towards a safe system approach to prevent health loss among motorcyclists – The importance of motorcycle stability as a condition for integrated safety.* (PhD PhD). Chalmers university of Technology, Gothenburg. (ISBN 978–91–7597-376-0)

Rosén, E., & Sander, U. (2009). Pedestrian fatality risk as a function of car impact speed. *Accident Analysis and Prevention, 41*(3), 536–542. https://doi.org/10.1016/j.aap.2009.02.002.

Rosen, E., Kallhammer, J. E., Eriksson, D., Nentwich, M., Fredriksson, R., & Smith, K. (2010). Pedestrian injury mitigation by autonomous braking. *Accident Analysis and Prevention, 42*(6), 1949–1957. https://doi.org/10.1016/j.aap.2010.05.018.

Rosén, E., Stigson, H., & Sander, U. (2011). Literature review of pedestrian fatality risk as a function of car impact speed. *Accident Analysis and Prevention, 43*(1), 25–33. https://doi.org/10.1016/j.aap.2010.04.003.

Sayed, T., deLeur, P., & Pump, J. (2010). Impact of rumble strips on collision reduction on highways in British Columbia, Canada: Comprehensive before-and-after safety study. *Transportation Research Record, 2148*(1), 9–15. https://doi.org/10.3141/2148-02.

STA (2019). *Saving lives beyond 2020: The next steps recommendations of the academic expert group for the third ministerial conference on global road safety 2020*. Retrieved from

STA (2020) *VGU, Vägar och gators utformning – Krav, 2020:029*. Design of roads. Retrieved from Trafikverket: https://trafikverket.ineko.se/se/krav-vgu-v%c3%a4gars-och-gators-utformning

Steffan, H., Hoschkopf, H., Geigl, B., & Moser, A. (1998). *Development of new crash-cushion concept for compatibility purposes of rigid obstacles near the road* (Paper presented at the 16th Int. Techn. Conf. on ESV, Winsor, Canada).

Sternlund, S. (2019). The effectiveness of centerline rumble strips (CLRS) on two-lane carriageways in Sweden on injury accident risk for cars equipped with electronic stability control (ESC) and cars without ESC. *Traffic Injury Prevention, 20*(8), 880–885. https://doi.org/10.1080/15389588.2019.1669790.

Stigson, H. (2009). *A safe road transport system – Factors influencing injury outcome for Car occupants* (PhD). Stockholm, Sweden: Karolinska Institutet. ISBN 978-91-7409-433-6.

Stigson, H., & Hill, J. (2009). Use of car crashes resulting in fatal and serious injuries to analyze a safe road transport system model and to identify system weaknesses. *Traffic Injury Prevention, 10*(5), 441–450. https://doi.org/10.1080/15389580903081057.

Stigson, H., & Kullgren, A. (2010). *Fotgängares risk i trafiken - Analys av tidigare forskningsrön*. Retrieved from Folksam Stockholm.

Stigson, H., Krafft, M., & Tingvall, C. (2008). Use of fatal real-life crashes to analyze a safe road transport system model, including the road user, the vehicle, and the road. *Traffic Injury Prevention, 9*(5), 463–471. https://doi.org/10.1080/15389580802335240.

Stigson, H., Ydenius, A., & Kullgren, A. (2009). Variation in crash severity depending on different vehicle types and objects as collision partner. *International Journal of Crashworthiness, 14*(6), 613–622.

Stigson, H., Kullgren, A., & Krafft, M. (2011). *Use of car crashes resulting in injuries to identify system weaknesses* (Paper presented at the 22th International Conference on the Enhanced Safety Vehicles (ESV) Washington, DC).

Stigson, H., Kullgren, A., & Rosen, E. (2012). Injury risk functions in frontal impacts using data from crash pulse recorders. *Annals of Advances in Automotive Medicine, 56*, 267–276.

Sunnevång, C. (2016). *Characteristics of nearside car crashes – An integrated approach to side impact safety* (PhD). Umeå: Umeå Universitet.

Sunnevång, C., Rosén, E., & Bostrom, O. (2009). Real-life fatal outcome in car-to-car near-side impacts–implications for improved protection considering age and crash severity. *Traffic Injury Prevention, 10*(2), 194–203. https://doi.org/10.1080/15389580802594127.

Tingvall, C. (2008). Distraction from the view of governmental policy making. In M. U. Kristie Young, (Ed.), *Driver distraction: Theory, effects, and mitigation* Clayton, Victoria, Australia; John D. Lee, University of Iowa, USA; Michael A. Regan, French National Institute for Transport and Safety Research (INRETS), Lyon, France / Monash University, Accident Research Centre, Melbourne, Australia.

Tingvall, C., Lie, A., & Johansson, R. (2000). *Traffic safety in planning - a multi-dimensional model for the Zero Vision* (Paper presented at the In Transportation, Traffic safety and Health. New Mobility. Second International Conference, Berlin).

Tingvall, C., Stigson, H., Eriksson, L., Johansson, R., Krafft, M., & Lie, A. (2010). The properties of safety performance indicators in target setting, projections and safety design of the road transport system. *Accident Analysis and Prevention, 42*(2), 372–376. https://doi.org/10.1016/j.aap.2009.08.015.

Vadeby, A. (2016). *Traffic safety effects of narrow 2+1 roads with median barrier in Sweden* (Paper presented at the 17th International Conference Road Safety On Five Continents (RS5C 2016), Rio de Janeiro, Brazil, 17–19 May 2016., Linköping). http://urn.kb.se/resolve?urn=urn:nbn:se:vti:diva-10267

Visser van der Meulen, J., & Berg, S. (2018). *Fördjupat experiment med 2–1-vägar Bygdeväg*. Retrieved from S. T. Administration: https://www.trafikverket.se/contentassets/9ef5bb1681b145e89dcbc35732bede6f/fordjupat-experiment-med-2_1_vagar.pdf

Wegman, F. (2003). *Fewer crashes and fewer casualties by safer roads* (Paper presented at the International symposium 'Halving Road Deaths' Association of Traffic and Safety Sciences, Tokyo, November 28).

WHO. (2008). *Speed management: A road safety manual for decision-makers and practitioners*. Geneva, Switzerland: Global Road Safety Partnership.

Ydenius, A. (2002). *Influence of Crash Pulse Duration on Injury Risk in Frontal Impacts Based on Real Life Crashes* (Paper presented at the International IRCOBI Conference on the Biomechanics of Impact, Munich, Germany).

Ydenius, A. (2010). *Integration of car and road infrastructure design : Crash severity and occupant injury risk evaluations in frontal real-world crashes* (PhD). Stockholm: Karolinska Institutet.

Ydenius, A., Kullgren, A., & Tingvall, C. (2001, June 4–7). *Development of a Crashworthy System: Interaction Between Car Structural Integrity, Restraint System and Guardrails* (Paper presented at the 17th International Conference on the Enhanced Safety of Vehicles (ESV), Amsterdam, Netherlands).