11
Traffic safety

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11.1 INTRODUCTION

The number of road crashes, fatalities and injuries is considered unacceptably high in many countries. This is illustrated, for example, by the fact that the European Parliament in its resolution of 6 October 2021 welcomed the European Union reaffirming in its 2021–30 EU road safety policy framework (EC, 2019), the long-term strategic goal to get close to zero deaths and zero serious injuries on EU roads by 2050. In many highly developed and highly motorized countries the number of fatalities has been decreasing over the last few decades, although in recent years the speed of reduction has slowed down in most countries (OECD/ITF, 2020). The sharp drop in 2020 is related to the COVID-19 pandemic (Wegman and Katrakazas, 2021). However, so far this favourable development cannot be observed in low- and middle-income countries (WHO, 2018). The WHO report states: 'The number of road traffic deaths continues to climb, reaching 1.35 million in 2016' (WHO 2018, 16). It would not be surprising if these worldwide numbers were higher today.

Risks in road traffic are considerably higher than in other transport modes, and the number of injuries in road traffic is far higher than the numbers in train, plane or ferry transport (ETSC, 2003; Savage, 2013). Unfortunately, more recent figures are not available, but this conclusion seems to be still valid. Although crashes in these other modes attract a lot of public and media attention, road crashes kill far more people, but in a 'diluted' way, resulting in only limited media coverage and relatively limited attention from the public and politicians (Van der Meer et al., 2021). At the same time, serious road crashes are tragedies at a personal level. Road crashes can happen to everybody, anytime, anywhere, and they are unexpected. Often the lives of young people and their families are suddenly changed. Road traffic injury is now the leading cause of death for children and young adults aged 5 to 29 years (WHO, 2018).

This chapter aims to give a concise introduction to road safety. Using this chapter the reader will be able to explain basic concepts of road safety, get an insight into some recent traffic safety developments and be able to talk about a new policy vision and options for how to reduce the number of crashes and (serious) injuries. The relevance of various technologies has been discussed in Chapter 8.

Risk factors in traffic are discussed in Section 11.2. Section 11.3 deals with the subject of identifying the causes of crashes. Section 11.4 provides an explanation of three important components of road traffic when it comes to risks: transport mode, age of road users and road types. In Section 11.5 the difficulties of measuring road safety are discussed. Some developments in road safety are presented in Section 11.6. Section 11.7 explains the development in dominant thoughts about traffic safety. This section shows that the amount of knowledge on causes of road crashes and on how to implement successful policies has increased dramatically over the years. Still, the next steps for further improvements can be made. Scientific information to support this statement and one possible next step, the Safe System approach, are presented in Section 11.8. Section 11.9 focuses on vulnerable road users and Section 11.10 discusses promising options to further improve road safety. The chapter's main findings are presented in Section 11.11.

11.2 RISK FACTORS IN TRAFFIC

Taking part in traffic is a dangerous act in itself. This is due to some fundamental risk factors in traffic (sometimes also denoted as basic factors): the vulnerability of the body of road users in combination with speed levels in traffic as well as the presence of objects with large mass and/or stiffness with which one can collide. In addition, there are factors that affect driving behaviour and increase the crash risk, such as alcohol use, fatigue or distraction.

Figure 2.1 (in Chapter 2) identifies three major sources for risks to traffic safety. First are the characteristics of the transport flows – i.e., the volume, modal split and composition of traffic (including the mix between passenger and goods vehicles), division over time (including traffic jams) and distribution over space (including the use of different road types). Second is the driving behaviour, which includes speed, the acceleration and breaking behaviour, and reaction time. The third factor is technology, including especially vehicle technology (such as the adaptive cruise control) and vehicle designs that improve the safety of their occupants and other (especially vulnerable) road users. In addition, use of other technology (especially mobile devices) during travel is a risk to traffic safety. The following sections describe risk factors originating from these three sources, in order of their importance.

11.2.1 Fundamental Risk Factors

Fundamental risks are inherent to road traffic and are the basis of the lack of safety in current road traffic. These are a combination of factors such as speed and mass (and the kinetic energy in a crash) and the vulnerability of the human body.

- **Speed.** Speed is related to the risk of being involved in a crash and its severity (for an overview, see Aarts and van Schagen, 2006). Higher absolute speeds of individual vehicles are related to an exponential increase in risk, illustrating a strong link between the driving behaviour and safety (see Figure 2.1). A meta-analysis by Elvik et al. (2019) shows that both an Exponential model (basically change equals Exp(β($speed_{after}$ - $speed_{before}$)) in which β is to be determined) and a Power model (change equals $speed_{after}$/$speed_{before}^{power}$

in which the power parameter is to be determined) accurately describe by how much risk increases with increased driving speed, assuming other conditions remain the same. The models apply both to an individual operator and at the aggregate level for average speed on a road. The change in risk according to a Power model with exponent x can be calculated as (final speed / initial speed)^x – 1 (Elvik, 2013). The meta-analyses by Elvik et al. (2019) yields estimates of the exponent of the Power model of 5.5 for fatalities and 3.9 for injury accidents. For instance, an increase of driving speed by 1%, such as from 100 to 101 km/h, increases the number of fatalities by 5.6% and the number of injury accidents by 3.9%: $(101/100)^{5.5} - 1$ respectively $(101/100)^{3.9} - 1$. This is due to the kinetic energy (of which speed is an important component), which is converted into other energy forms and/or bodily damage during a crash. Injury risk (the chance of being injured in a crash) is also determined by (impact) speed level, the relative directions of crash partners, their mass differences and the protection level. Pedestrians and cyclists are about five times more likely to sustain fatal injuries in collisions with motor vehicles at a 50 km/h impact speed as compared to at 30 km/h (Nie et al., 2015). To reduce the probability of severe injuries in such crashes to approximately 10%, impact speeds need to be reduced further to around 20 km/h (Jurewicz et al., 2016).

- **Speed variance.** Speed differences at the level of road sections are also linked to increased crash risk (Aarts and van Schagen, 2006). Driving at a different speed than other traffic participants increases the risk inherently. However, the importance of speed variance also relates to the disproportionately high risk of speeding drivers as risk increases exponentially as speed increases. If two roads A and B have the same mean driving speed while road B has a greater speed variance, road B will have more fast drivers. Due to the exponential or power increase in risk as a function of speed (see above), their risk increase is much greater than the risk decrease of slow drivers who also contribute to speed variance.
- **Mass differences.** Mass differences are also fundamental risk factors. In a crash between two incompatible parties, the lighter party (smaller cars, cyclists, pedestrians) is at a disadvantage, because this party absorbs more kinetic energy and a smaller vehicle generally offers less protection to its occupants than a heavier vehicle. Mass ratio between colliding objects can be as high as 300 (a pedestrian weighing 60 kg versus a heavy goods vehicle weighing 20,000 kg). Furthermore, in view of their stiffness and structure, heavier vehicle types generally offer better protection to their occupants in the event of a crash. For occupants of vehicles with a high mass, injury risk is much lower than that of occupants of the lighter crash party. If we assume the injury risk for a crash party of an 850 kg passenger car as 1, then the injury risk for an average crash partner is 1.4 if the car weighs 1000 kg, and 1.8 if the vehicle weighs more than 1500 kg (Elvik and Vaa, 2004). Increases in vehicle masses (SUVs) will result in growing mass differences between vehicles and this might impact road safety negatively.
- **Vulnerability.** Finally, vulnerability is to be considered a fundamental risk factor. Several methods can be used to protect the human body in a crash, foremost by improving the crashworthiness of a vehicle (i.e., improving the vehicle technology; see Figure 2.1 and Chapter 8). Over the years great progress has been made to improve vehicle design to

protect car occupants. The most famous example is the use of seat belts in combination with airbags. Mbarga et al. (2018) found in their meta-analysis that seat belts reduce the risk of any major injury by 53%. Glassbrenner and Starnes (2009) estimate that seat belts reduce fatality and injury risks by more than 40%, and in combination with airbags by more than 50%. However, vulnerable road users such as pedestrians and cyclists have almost no possibilities to protect themselves from injury risk in a crash. Only a crash helmet for (motorized) two-wheelers can be considered, and some developments of airbags for motorcyclists can be seen in practice. Furthermore, modern car designers try to incorporate safety features when designing a car front, with the aim to make them safer for pedestrians and cyclists in the case of a crash.

11.2.2 Risk-Increasing Factors

In addition to these fundamental risk factors, road traffic has to contend with risk-increasing factors caused by road users (see also the link from driving behaviour in Figure 2.1):

- **Lack of driving experience.** Lack of driving experience results in higher risks. The effect of (lack of) driving experience on crash risk is strongly linked to age effects. Since driving experience is strongly correlated with age and as both factors are associated with specific characteristics which increase risk, it is difficult to separate the effects of age and experience. For Dutch road traffic, it is estimated that about 60% of the (relatively high) crash risk for novice drivers (broadly speaking, people who have driven less than 100,000 kilometres) can be explained by lack of driving experience, and the other 40% is age related (see Wegman and Aarts, 2006). Male novice drivers especially run an additional risk (a factor of 10) compared to more experienced drivers (male and female) and compared to female novice drivers (a factor of 2.5). The increased crash risk for novice drivers decreases rapidly within the first year after passing a driving test (Vlakveld, 2005; Curry et al., 2017).
- **Psycho-active substances: alcohol and drugs.** Alcohol consumption by road users is one of the most important factors that increase crash risk in traffic. This increases exponentially with increased blood alcohol content (BAC). Compared to sober drivers, the crash risk is a factor of 1.3 with a BAC between 0.5 and 0.8 per mille, a factor of 6 with a BAC between 0.8 and 1.5 per mille and a factor of 18 above 1.5 per mille (Blomberg et al., 2005). A BAC of 0.5 per mille means 0.5 gram of alcohol per litre blood. The crash risk of road users under the influence of psycho-active substances (Walsh et al., 2004) can be about 25 times higher. This risk can even increase up to a factor of 200 with the combined use of alcohol and drugs, relative to sober road users, also depending on the quantity of alcohol consumed (Schulze et al., 2012). Drugs in traffic is not a very mature area of research and policy-making; it has, however, received quite a lot of (political) attention recently with the trend in most nations toward enforcement of zero-tolerance laws (Jones et al., 2019). Roadside surveys show a reduction of drunk driving over time in countries having longitudinal data, while use of non-alcohol drugs increases (Christophersen et al., 2016).

- **Fatigue.** Fatigue is probably a much more important risk factor than data from police reports shows. Participating in traffic whilst fatigued is dangerous because, in addition to the risk of actually falling asleep behind the steering wheel, fatigue reduces the general ability to drive (e.g., keeping course), reaction time and motivation to comply with traffic rules. Research shows that people suffering from a sleep disorder or an acute lack of sleep have a three to eight times higher risk of injury crash involvement (Connor et al., 2002). A review by Moradi et al. (2019) shows the odds of a crash is 1.3 times higher in fatigued drivers than in other drivers.
- **Distraction.** Like fatigue, distraction is probably a much more frequent crash cause than reported police data shows (Regan et al., 2009). Currently, common sources of distraction are talking and texting on the mobile phone while driving or cycling (De Waard et al., 2015; Lipovac et al., 2017). Dingus et al. (2019) studied the impact of secondary tasks by a Naturalistic Driving study in which drivers were monitored using in-vehicle cameras, GPS, accelerometers, etc. Overall, they found a small but significant increase in crash risk due to cognitive secondary tasks. Tasks that require the eyes to be directed away from the road such as manipulating a cell phone to browse or dial increase the risk the most, i.e., roughly 2 to 3.5 times compared to model driving.

11.3 CAUSE: ‘UNINTENTIONAL ERRORS’ OR ‘INTENTIONAL VIOLATIONS’?

In identifying the cause of crashes in whatever system, ‘man’ is always quoted as the most important cause of crashes in any system. People make errors, no matter how hard they try. At the same time, people do not always (consciously or otherwise) obey rules and regulations designed to reduce risks. The question arises: how serious are intentional violations or offences for road safety and with what frequency do they cause traffic crashes? This section will show that no clear picture emerges from the research of the relative contribution to crashes by intentional violations and unintentional errors.

A Canadian study looked into the relationship between violations and crashes as evidenced by driver behaviour (Redelmeier et al., 2003). The research team tracked car drivers who were convicted of causing a fatal crash and recorded the crash involvement of these offenders in the period following the conviction. The first month after the penalty, the chance of being involved in a fatal crash was 35% lower than could be expected on the basis of coincidence. The authors attributed this effect to the fact that there were fewer traffic violations immediately after the period in which the drivers were fined. However, this benefit lessened substantially over time and disappeared after three to four months. Out of the above research, a strong relationship emerges, particularly between violations and crash involvement. It must be emphasized, however, that this type of research does not prove the causality between the two phenomena.

Thus, both errors and violations (and related extreme behaviour) play a role in the cause of crashes and therefore deserve a place in road safety policies. How large the share of (unintentional) error and (intentional) violation is exactly cannot be stated, based on current knowledge. The role of (unintentional) error seems to be the more important one. Unfortunately, the information that can be extracted from police registration forms about crash causes cannot be used to identify the underlying causes of crashes. This is not surprising given that the data is gathered primarily with the objective of being able to identify the guilty party, rather than identifying precisely the underlying causes of a crash. In addition, crashes are nearly always the result of a combination of factors.

On the one hand, it is logical that unintentional errors form the lion's share of crash causes, given that intentional offending in itself hardly leads directly to a crash. Violations certainly can increase the risk of error and the serious consequences of these errors. On the other hand, there is no evidence to support the widely held opinion that anti-social road hogs are the major perpetrators of crashes. Without doubt they cause part of the road safety problem, if only because other road users cannot always react appropriately to them. However, many crashes are the result of unintentional errors that everybody can make in an unguarded moment, as illustrated by Dingus et al. (2006) and Khattak et al. (2021).

Dingus et al. (2006) concluded that, in nearly 80% of the recorded crashes driver inattention was involved just prior to the onset of the conflict. The most common human errors observed by Khattak et al. (2021) were recognition and decision errors, which occurred in 39% and 34% of crashes. In these studies drivers were followed by observation systems installed in their cars: a black box and small cameras. The idea was to observe everyday driving behaviour and to learn about the role of driver inattention and errors, which are rarely found on police registration forms. After all, who would tell the police that a cigarette fell to the floor just prior to the crash and that in a state of some panic the driver was trying to retrieve it? Therefore, it is time to rethink the widespread belief (held also by road safety professionals and decision-makers) that crashes are caused exclusively or even primarily by the traffic offences that are frequently found on police registration forms.

Two recent studies (Shinar, 2019; Hauer, 2020) doubt whether the current three primary methods for crash causation analysis – (1) post-crash clinical analysis using subjective evaluations by experts, (2) naturalistic driving studies and (3) epidemiological studies – are appropriate methods to identify crash causes. Furthermore, both studies recommend the linking of causes and countermeasures, as is being applied in the medical model of finding a cure for a disease. The framing of '90%-plus of the crashes are due to human errors or failures' is a direct consequence of how causes have been defined in the past and this approach is no longer considered to be adequate. Both authors propose to put human errors, failures and violations in the context of the environment of these behaviours and trying to change behaviour in a safe direction by adapting the environment. This insight is one of the reasons to think about a paradigm shift in road safety, as presented in Section 11.7.

11.4 RISKS FOR TRANSPORT MODES, AGE GROUPS AND ROAD TYPES

Transport modes and road types relate to the fundamental risk factors (Section 11.2): speed, mass and vulnerability, in combination with protection. Users of motorized two-wheelers, for example, have the highest fatality and injury risk in road traffic (Table 11.1), which can largely

Table 11.1 Road fatalities per one billion vehicle kilometres (2019) for a selected number of countries that made data available to the IRTAD-database from International Transport Forum

	All modes	Motorized two-wheelers	Mopeds	Motorcycles	Passenger cars	Heavy goods vehicles
Australia	4.5	87.6			3.0	2.7
Austria	4.9	50.6	22.9	59.8	2.9	0.4
Denmark	3.6			558	2.1	0.9
France	5.3	66			3.4	1.0
Germany	4	43.8	16.2	54.7	2.1	
Great Britain	3.1	70.2			1.6	0.7
Hungary	13	148			8.3	2.4
Ireland	3	140.4			2.3	
Israel	5.6	64.8			2.5	
Poland	7			68.9	6.5	1.1
Slovenia	4.5	142.9			2.5	1.9
Sweden	2.6			50.6	1.5	0.6
Switzerland	2.7	18.9	32	17.5	1.1	0.9
United States	6.9	159.2			5.6	

Note: Motorized two-wheelers encompass moped + motorcycles

be explained by a combination of high speed with the relatively low mass of the vehicle in conflict with other motorized traffic, as well as poor crash protection. On top of these factors, two-wheelers (especially mopeds) are popular among young people. Besides, youngsters have a relatively high risk in traffic because of age-specific characteristics and needs, and the lack of driving experience (Table 11.2 and Figure 11.1).

On the one hand, the car is a fast and weighty collision partner in conflicts with two-wheelers and pedestrians, who also include especially vulnerable road users such as children and the elderly. On the other hand, cars are more severely damaged in crashes with heavy goods vehicles.

Young people are an especially high-risk group of those involved in serious crashes because of their lack of driving or riding experience and age-specific characteristics. Elderly road users (of 75 years old or more; see Figure 11.1) are the next most important risk group because of their physical frailty. In many low- and middle-income countries the majority of the casualties are vulnerable road users such as pedestrians and cyclists, most of the time young people.

Differences of risks for different road types can also, to a large extent, be explained by a combination of the fundamental risk factors introduced earlier. For example, serious crashes outside urban areas, and particularly on rural roads, are dominated by single-vehicle crashes along sections of road, often running off the road. These are usually the result of inappropriate speeds, possibly in combination with other factors which increase risk such as alcohol

Table 11.2 Road user fatalities per 100,000 population by age group (2019) for a selected number of countries that made data available to the IRTAD-database from International Transport Forum

	All	0–14	15–17	18–20	21–24	25–64	65+
Australia	4.7	0.7	3.2	9.2	7.8	4.9	6.8
Austria	4.7	1.3	5.1	6.1	6.5	4.4	7.6
Belgium	5.6	0.6	2.9	8.8	9.8	5.9	7.7
Canada	4.7	0.7	4.6	6.0	7.1	4.8	6.7
Czech Republic	5.8	1.1	3.2	12.2	11.6	6.0	7.4
Denmark	3.4	0.5	3.0	4.7	4.1	3.4	5.5
Finland	3.8	0.6	5.7	8.9	5.8	3.9	4.5
France	5.0	0.6	3.7	10.3	10.7	5.2	6.5
Germany	3.7	0.5	2.9	7.3	4.7	3.4	5.8
Greece	6.4	0.8	4.3	9.1	10.4	6.8	7.7
Hungary	6.2	1.1	3.1	5.4	7.2	6.9	8.2
Iceland	1.7	0.0	7.8	0.0	0.0	2.1	2.0
Ireland	2.9	0.4	1.0	3.7	6.8	2.9	5.1
Israel	3.9	1.3	2.7	8.0	6.8	4.3	6.2
Italy	5.3	0.4	3.9	8.2	8.1	5.2	7.2
Japan	3.1	0.4	1.4	3.7	2.5	2.0	6.3
Korea	6.5	0.5	2.1	3.9	3.7	5.0	19.8
Luxemburg	3.6	0.0	0.0	4.8	16.1	3.9	2.3
Netherlands*	3.5	0.4		4.7		2.8	7.7
New Zealand	7.1	2.8	6.4	8.7	10.6	7.7	8.8
Norway	2.0	0.0	0.5	4.5	3.3	2.1	3.3
Poland	7.7	1.2	4.7	14.7	12.6	8.0	9.9
Portugal	6.0	0.9	1.9	6.2	11.0	5.7	9.8
Slovenia	4.9	0.3	3.6	8.7	3.6	5.4	6.8
Spain	3.7	0.5	2.4	4.4	4.2	4.0	5.4
Sweden	2.2	0.2	1.5	2.1	2.5	2.3	3.7
Switzerland	2.2	0.3	1.2	2.2	2.0	1.9	4.8
United Kingdom	2.7	0.3	1.8	4.2	4.1	2.7	4.5
USA	11.1	1.8	7.1	15.4	17.2	12.9	13.4

Note: Netherlands*: age group 15–25

consumption, distraction and/or fatigue. The fact that many roadsides are not 'forgiving' also results in severe outcomes. On urban roads, transverse conflicts (side impacts) dominate. It is on these streets and roads where most people are killed, and where mass differentials and the vulnerability of road users are the most important factors, combined with comparatively high speeds and the vulnerability of vehicles in transverse conflicts. Motorways are the safest

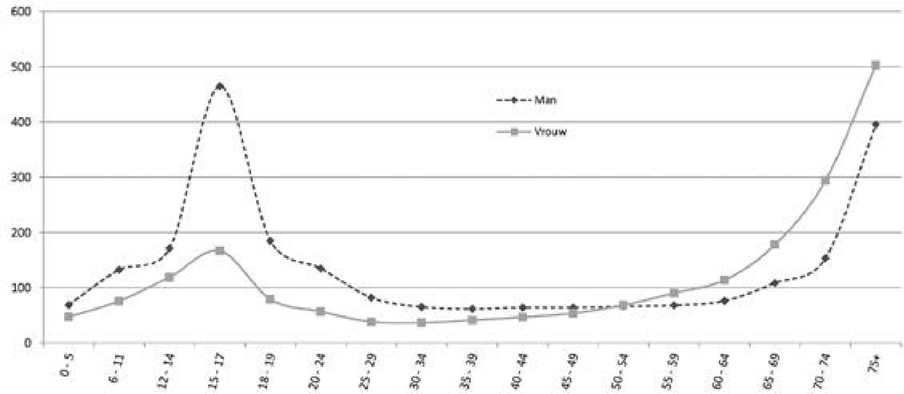


Figure 11.1 Number of severely injured people in traffic per 1 billion kilometres travelled of age group and gender for the Netherlands in the period 1999 to 2009

roads when it comes to crash risk. This is due to a combination of high-quality road design and slow-moving traffic not being allowed on these roads. For high driving speed conditions, as is the case on motorways, good design is extremely important, both physically (separation of driving direction, grade-separated intersections) and psychologically (predictable design). Only then high speeds can be managed safely. In situations where vulnerable road users and motorized traffic share the same physical space, a low risk can only be achieved when travelling speeds are low (see also Section 11.8).

11.5 MEASURING SAFETY AND DANGER

All countries in the world seem to have the ambition to improve road safety, or at least no country is known to be making public statements that the road toll of today is acceptable. However, measuring road safety is not as simple as measuring a temperature. Researchers or policy-makers cannot read a simple measuring instrument. A simple definition of road safety is complicated and we don't have a simple 'thermometer' to read. Moreover, people can have a discussion on what to include in a definition. The most common measure used to define road safety is the number of road crashes and/or the number of casualties and the associated negative consequences resulting from such crashes. Sometimes subjective feelings related to fears of being involved in a crash are included in the measure as well. In those cases, people's perceptions about (lack of) road safety are taken into account in the measure.

The widely accepted definition of a road traffic crash is a collision or incident on a public road (or private road to which the public has right of access) that results in damage to objects and/or injury to people and that involves at least one vehicle in motion. This means, for example, that a single bicycle crash is included, but not a pedestrian fall. The international definition of a road death, taken from the UNECE Glossary of Transport Statistics 2019, is someone who dies immediately or dies within 30 days as a result of a road crash, excluding suicides. For countries that do not apply the threshold of 30 days, conversion coefficients are estimated for international comparison purposes. The Maximum Abbreviated Injury Scale (MAIS) is a medical classification of the severity of injuries using the coding system created by the Association for the Advancement of Automotive Medicine. MAIS 1–2 are regarded as slight injuries and 3–6 as serious injuries. This system is presently being used in road safety. The European Union and its member states, for example, indicated an ambition not only to reduce the number of road fatalities, but also the number of serious injuries. For that purpose, the EU decided to use MAIS3+ to define serious injuries. Several methods can be applied to arrive at a good estimate of the number of serious injuries: by applying a correction on police data, by using hospital data and by using linked police and hospital data (e.g. Deliverable 7.2 of the SafetyCube project (Weijermars et al., 2016).

Crashes can result in more serious or less serious outcomes: fatal injuries, other injuries or damage only to vehicles involved in a crash. Sometimes, damage-only crashes are not considered serious enough to be included in official crash statistics. Data collection is needed to learn how many crashes occurred in a certain time period and in a certain geographical area. The longer the time period or the larger the area, the more crashes. For that reason, it is a good habit to normalize the number of crashes for time and space, expressing the road safety level. This normalizing can be done in different ways serving different purposes. If we relate the number of fatalities or injuries to the number of inhabitants (the first ratio) we have the mortality rate (fatalities per 100,000 inhabitants; see also Table 11.2, where mortality rates are presented for different countries) or morbidity rate (injuries per 100,000 inhabitants). These rates are public health indicators, allowing us to compare road injuries with other threats or diseases. (See also the link between safety and health in Figure 2.1.) Mortality rates are often used in international comparisons. An important reason is that fatal road crashes have a common definition (dead within 30 days) and are well recorded in many countries, as is the case with the number of inhabitants. This is not the case for injuries.

A second ratio is the so-called fatality rate or injury rate. In this case we relate the number of fatalities or injuries to the degree to which people are exposed to traffic or, more precisely, to risks in traffic. Often, the number of kilometres travelled is used to estimate this 'exposure' or, even more often, the number of motorized kilometres (see Table 11.1). We can also use time in traffic as a measure of exposure.

Unfortunately, the measuring of road crashes, and their consequences, and the measuring of exposure suffer from problems related to the use of different definitions, data quality, data completeness and data availability. In most countries the crash registration is carried out by the police. However, crash statistics are always incomplete as a result of underreporting. Furthermore, data collections suffer from certain biases: crashes involving motorized vehicles are better registered than crashes involving non-motorized transport, such as pedestrians and cyclists (Derriks and Mak, 2007; Shinar et al., 2018). Alcohol-related crashes are also underreported (Vissers et al., 2017). Another bias in data collection is that less severe injuries are more underreported.

An important measure for road crashes is their associated costs. There are two good reasons to estimate road crash costs. Firstly, it allows policy-makers to compare the economic consequences of road crashes with other impacts of traffic and transport, such as environmental impacts and congestion. A second reason is that it allows policy-makers to compare these costs with the costs of other public health issues. For that purpose, public health indicators denoted as 'DALY' (disability adjusted life years) or 'QALY' (quality adjusted life years) are also sometimes used (Wijnen, 2008). These are measures for loss of life years and/or quality of life.

In many countries, a growing interest in estimating the costs of road crashes can be observed. The cost estimation methods have improved considerably. Although an internationally accepted 'standard' method does not exist at the time of writing this chapter (in 2023) and methods differ in including or excluding certain cost categories (Elvik, 1995), there is some convergence on the most important cost categories (Alfaro et al., 1994):

1. medical costs;
2. production loss;
3. human costs;
4. property damage;
5. settlement costs.

Sometimes costs related to congestion as a consequence of a crash are added and/or costs related to replacement of transport (in a sixth category). For the cost categories 1, 4 and 5, a method is used called 'restitution cost method' and for 2 the 'human capital method' (Wijnen and Stipdonk, 2016). Categories 1, 2, 4 and 5 estimate the direct financial costs related to crash injuries, for example, the amount of money hospitals have to spend on injury treatment, vehicle repair costs, lost production hours (e.g. lost wages) and so forth.

Estimating human costs (cost category 3) is based on people's willingness to pay for lower risks (or willingness to accept a reward for higher risks). Human costs for casualties and their relatives and friends are costs in the form of suffering, pain, sorrow and loss of quality of life and joy of life. Cost estimates result in the so-called 'value of a statistical life' (VOSL; e.g. De Blaeij, 2003). A VOSL does not reflect the monetized value of an individual life, which is, naturally, priceless. Instead, the VOSL is based on the relation between changes in risks and willingness to pay for these changes. For example, if someone drives on a road with a risk of 2.5/1,000,000 of death, but is willing to pay 6 minutes by taking a detour to drive on a road with a lower risk of 2/1,000,000, this driver is valuing his or her 'statistical life' at 2 million euros. The reason is that the VOSL is (assuming a value of time of 10 euros/hour, which equals 1 euro/6 minutes; see Chapter 15):

$$\frac{d(travel\ time)}{d(risk)} = \frac{1\ Euro}{\left(\frac{0.5}{1{,}000{,}000}\right)} = 2{,}000{,}000\ Euro \qquad (11.1)$$

In the VALOR project (Schoeters et al., 2021) estimates have been made for four European countries (Belgium, France, Germany and the Netherlands) of the VOSL and the Value of a Statistical Serious Injury (VSSI). The average VOSL was estimated at 6.2 million euros and the VSSI at 950,000 euros. Accordingly, the ratio of values between fatalities and serious injuries is estimated at around 7 to 1. These estimates turned out to be higher than formerly assumed in, for example, the Netherlands.

11.6 DEVELOPMENTS IN IMPROVING ROAD SAFETY

Globally, each year more than 1.35 million road users are killed in a road crash, and 20 to 50 million suffer non-fatal injuries worldwide (WHO, 2018). By far the majority of all crashes, deaths and injuries occur in low- and middle-income countries: 93% of road traffic deaths. Moreover, mortality rates are relatively high in these countries (see Table 11.3 for road injury mortality rates per income class worldwide). The majority of these deaths and injuries are vulnerable road users. The social economic costs of road crashes in high-income countries range from 0.5% to 6.0% of the GDP with an average cost of 3.3% of GDP. For low- and middle-income countries the range is from 1.1% to 2.9% (Wijnen and Stipdonk, 2016).

Table 11.3 Road traffic injury mortality rates (per 100,000 population) by WHO regions for 2019

WHO region	Low- and middle-income	High-income
African Region	27.2	12.2
Region of the Americas	17.4	12.1
South-East Asia Region	15.8	-
European Region	10.4	5.1
Eastern Mediterranean Region	17.2	25.4
Western Pacific Region	17.9	5

Source: www.who.int/data/gho/data/indicators/indicator-details/GHO (July 2023)

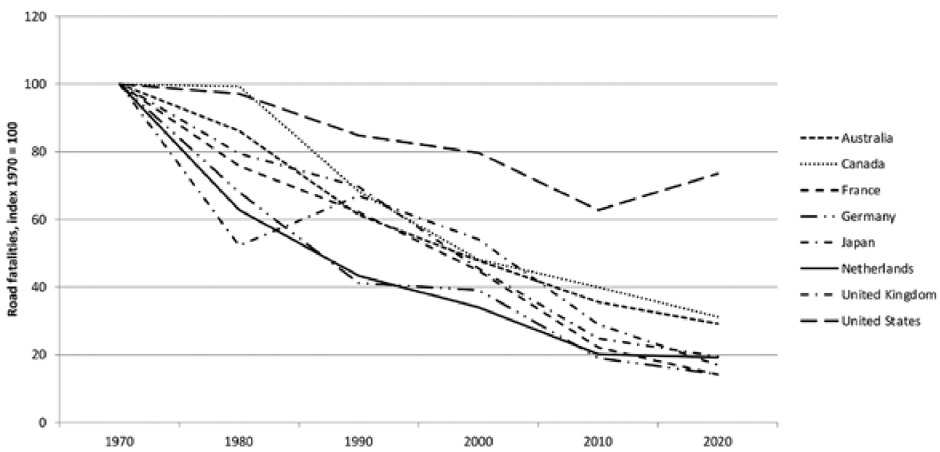


Figure 11.2 Long-term trends in road fatalities 1970–2020 (index 1970 = 100) for a selected number of countries that made data available to the IRTAD-database from International Transport Forum

Since 1970, many high-income countries have made remarkable progress in reducing the number of road fatalities (see Figure 11.2). However, this progress has slowed down during the last decade, with the exception of 2020, due to the COVID-19 pandemic (Wegman and Katrakazas, 2021).

11.6.1 An Example: The Netherlands

To give more detail on the description and explanations for the relatively high rate of improvement in some countries, the Netherlands has been chosen as an example. Details for more countries can be found in *Safety Science*, 'Scientific Research on Road Safety Management' (Wegman and Hagenzieker, 2010). A 50% reduction in the mortality rate occurred in the period 1995–2007 in the Netherlands, whereas Great Britain and Sweden reached a little bit more than 20%. This is partly due to a 'learning society' or an 'investing society', which has adapted itself to motorized, fast-moving traffic and making substantial safety investments at the same time. Infrastructural adaptation has taken place (such as the construction of relatively safe motorways), safety in vehicles has been improved and there is more safety legislation and enforcement which takes account of factors that increase risk and reduce injury (such as alcohol consumption in traffic and mandatory crash helmet and seat belt use, respectively). These measures have all contributed to reductions in the number of traffic fatalities and injuries, despite increased mobility (Koornstra et al., 2002; Elvik and Vaa, 2004). But, as yet, researchers do not have a totally conclusive explanation for the observed trends in road fatalities and to which extent improvements in the road transport system contributed.

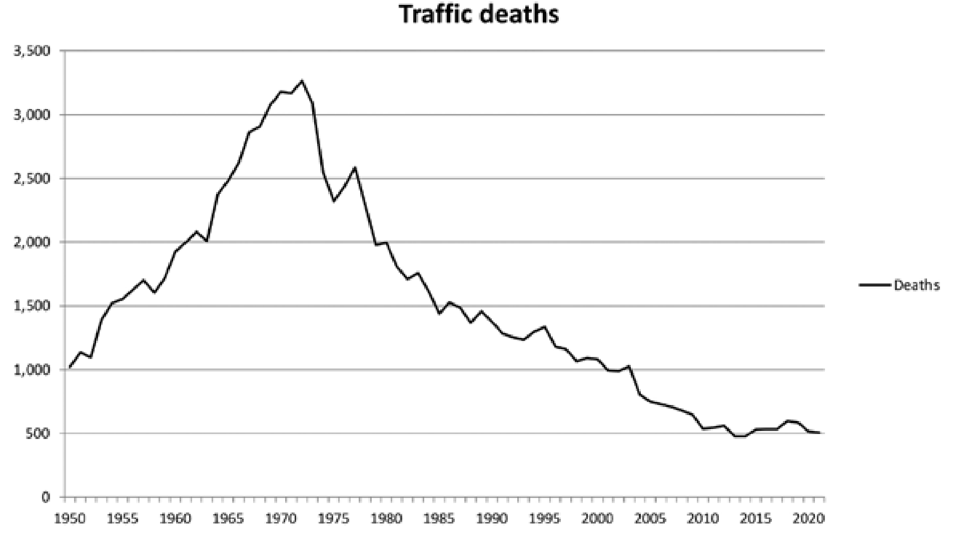


Figure 11.3 The development of the number of traffic deaths in the Netherlands 1950–2020

Between 2010 and 2020 just over 600 traffic deaths were recorded each year in the Netherlands. This amounts to one fifth of the 3264 traffic deaths in the disastrous year 1972.

SWOV (2007) describes the major changes that occurred during the period 1950–2005 in a report with the striking title ‘The summit conquered’. To begin with, there is a rise in the number of traffic fatalities, which is followed by a decline. This report illustrates that, for an understanding of why the annual number of fatalities has decreased, one should not look at the total number of traffic deaths; it is preferable to consider separate components (transport modes, age, road type, etc.), because these components develop differently than the totals (as elaborated by Stipdonk, 2013). It becomes clear, for instance, that passenger car mobility in terms of vehicle ownership and vehicle use has been increasing steadily during this period. The sales and use of motorized two-wheelers, however, show a less steady picture: they fluctuate strongly and are sometimes popular, sometimes much less popular. This is clearly reflected in the road safety developments. The number of road deaths among cyclists does not seem to have decreased for years. In recent years more cyclists than car occupants were killed in traffic and about one third of the cyclists killed rode an e-bike.

Stipdonk (2020) argues that the bell-clock shape of the number of annual road deaths in many highly motorized countries, with a peak value in the early 1970s, cannot only be seen as the result of ‘exposure’ (distance travelled by a population) times risk (fatalities per unit of exposure). From this perspective, reduction in the number of road deaths is the result of a higher reduction in the fatality rate (by risk reducing interventions) than the observed increase in exposure. Stipdonk suggests that the average driving experience is an essential factor to understand trends in car crashes.

The quality of roads and vehicles with regard to safety has shown considerable improvement in the past few decades. The structure of the road network in the Netherlands has undergone considerable adaptations to meet the increased mobility. This can be illustrated by the fact that approximately half of all motorized vehicle kilometres are made on relatively safe motorways. The separation of different traffic modes, mainly by the construction of safe bicycle facilities, has taken a considerable step forward. Primary and secondary vehicle safety has been improved considerably. While primary safety systems focus on providing assistance to the driver to prevent crashes (e.g. electronic stability control, anti-lock braking, daytime running lights), secondary safety aims to mitigate the consequences of the crash (e.g. crumple zones, safety belts, airbags and child restraint systems). Today’s conception of vehicle safety has blurred the boundary between primary and secondary safety.

Three important aspects of safety related human behaviour have also improved: drinking and driving has decreased, the safety belt is worn much more frequently and the helmet for motorized two-wheelers is also worn much more often. More specifically, these three unsafe practices are kept by ‘only’ a hard core of offenders. In the Netherlands, the speeds driven have gone down because the speed limits have been lowered on a substantial part of the road network. For driving speeds, it may be observed that, although road users have reduced their speed somewhat, a considerable proportion of road users exceed the limit.

11.7 SHIFTS IN ROAD SAFETY PARADIGMS

Different countries in the world are at a completely different stage of development of road safety and the maturity of policies to reduce crash and injury risks on the roads. At the same time, we see a positive development in many highly motorized and highly developed countries (Figure 11.2). How can these improvements be explained, and which road safety problems still remain? This section focuses on highly motorized countries.

Over the years, there have been very many different ways of tracing crash causes and how they can best be avoided. Table 11.4 presents, by means of a few words, what the dominant thoughts in the OECD countries were in the past century (see also OECD, 1997).

Table 11.4 Road safety 'paradigms' as seen in time

Period	Characteristic
1900–20	Crashes as chance phenomenon
1920–50	Crashes caused by the crash-prone
1940–60	Crashes are mono-causal
1950–80	A combination of crash causes fitting within a 'system approach'
1980–2000	The person is the weak link: more behavioural influence
2000–	Better implementation of existing policies Safe System Approach, e.g., Sustainably Safety (NL) and Vision Zero (S)

Source: Inspired by OECD (1997).

In short, one can notice an increase in sophistication in thinking about road safety. The 'crash-prone theory' (1920–50) dates primarily from the phase in which the legal guilt question was the main one: which road user had broken which law and was, thus, both guilty and liable? This question was answered by the police on the registration form of a crash, finally decided inside or outside the court room, and used by insurance companies to determine how to compensate damages. From 1940 to 1960 the idea shifted to the notion that crashes could be explained using a mono-causal model. In-depth studies showed, however, that there are few mono- or single-cause crashes; accidents are usually caused by, and the result of, a combination of circumstances, which led to the so-called 'multi-causal approach' (1950–80).

This approach, sometimes also called the system approach, was strongly influenced by the so-called Haddon matrix. Haddon (1972) designed a matrix using two axes: on the one hand he distinguishes three phases in the crash process: before a crash, during a crash and after a crash. The other axis is filled with the three components of our traffic system: the road user, the road and the vehicle. Consequently, this 3×3 matrix comprises nine cells. The Haddon matrix was used to classify crash factors and to indicate that more action could be taken than just 'pre-crash – road user related interventions', as was a tradition at the time. As Haddon tried to structure road safety (in nine cells of a matrix), other attempts were made.

One came from Sweden (Rumar, 1999) in which the size of the traffic safety problem is explained as the product of three dimensions:

1. exposure (E);
2. accident risk (A/E: number of accidents per exposure);
3. injury risk (I/A: number of people killed or injured per accident).

The additional 'dimension' given by Rumar (and also by Nilsson, 2004) was the inclusion of exposure as a variable or dimension to be used to improve road safety and to reduce the number of fatalities and injuries.

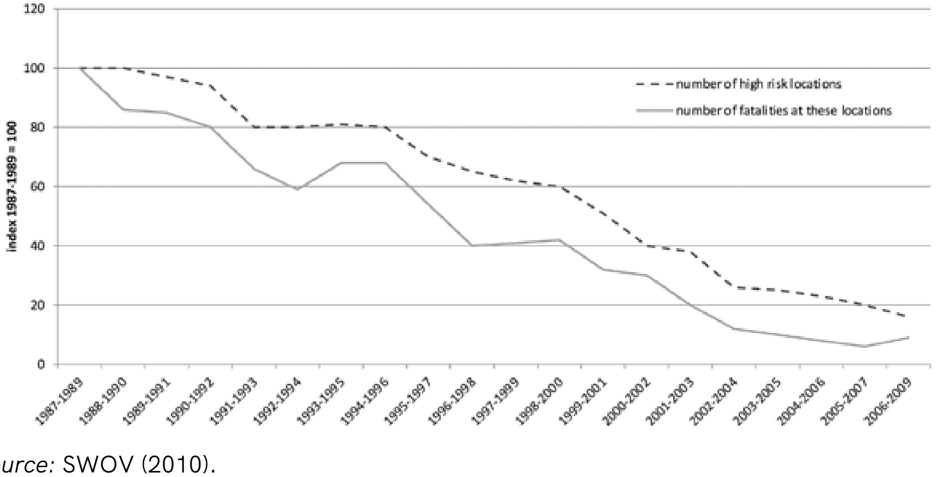
Since around 2000, two new main lines (paradigms) in road safety have appeared. The first one is especially aimed at evidence-based policies implemented in an efficient way. A lot of information has become available about several road safety interventions (see, for example, Elvik et al., 2009), and the idea here is not to develop new policy interventions but to improve the quality of implementing existing ones using evidence-based or research-based information on effects and costs of interventions. An example is to make police enforcement more effective and efficient or to improve roadsides alongside rural roads and motorways in a systematic way. Greater effectiveness is considered to be a matter of scale and quality. Improving road safety in such a way that the number of casualties substantially decreases generally requires a considerable effort, given the relatively low frequency of crashes, their low densities in space and the modest effects of most safety interventions. There has been growing attention given to what is called 'safety culture' and 'cultural change' in the field of decision-making on road safety (Johnston, 2010). In this analysis, road safety progress results from an increased emphasis on strategic planning – comprising the data-driven selection of the major problems to address, the setting of realistic and ambitious targets and a focus on effective implementation of programmes and measures through institutional cooperation and coordination: 'evidence-based policies' are the key words. However, despite overwhelming scientific evidence about certain themes, such as reducing speed limits to reduce speed and risks, both politicians and the public are not always convinced about introducing certain measures, even though the evidence supports this.

The second new line of thinking in traffic safety discipline since 2000 is the Safe System Approach (OECD/ITF, 2008 and 2016; see also Section 11.8). The Safe System approach recognizes that, prevention efforts notwithstanding, road users will remain fallible and crashes will occur. The approach also stresses that those involved in the design of the road transport system need to accept and share responsibility for the safety of the system and those that use the system need to accept responsibility for complying with the rules and constraints of the system. Furthermore, the Safe System Approach aligns safety management decisions with broader transport and planning decisions that meet wider economic, human and environmental goals (Academic Expert Group, 2019), and the approach shapes interventions to meet a long-term goal, rather than relying on 'traditional' interventions to set the limits of any long-term targets. An example is setting a maximum speed limit of 30 km/h in urban areas, unless strong evidence exists that high speeds are safe (for example, by separating vulnerable road users from high speed motorized traffic).

The Safe System Approach paradigm shift is based on two assumptions: (1) the current traffic system is inherently dangerous, and (2) intensifying current efforts could lead to fewer casualties, but not to substantially safer traffic, and the investments are less efficient than in the past and will be even more so in the future. To understand this position, it is useful to analyze the 'remaining' road safety problems in high-income countries.

In very broad terms, two types of problems can be identified in analyzing road safety (Wegman, 2010): generic problems and specific problems. Specific problems are those safety problems that are concentrated on specific locations, specific road user groups, specific behaviour or specific vehicles (they relate, among other things, to the risk-increasing factors, as explained in Section 11.2). Generic problems are caused by the fact that road traffic is inherently unsafe: ordinary people are killed in crashes under normal circumstances. This means that anybody can be involved in a crash at any time and that many people will be involved in a crash at some time in their lifetime because road traffic has not been designed with safety as an important requirement for design and operations.

In road safety policies in many highly motorized countries, for a long time the idea was to identify risk-increasing factors and reduce these specific risks. In public health too, this is a well-known and widely supported approach: cure those who are ill and identify and treat high-risk groups or circumstances *see*, for example, vaccination strategies to protect 'high-risk groups' from viruses, such as the COVID-19 virus. As a matter of fact, much of past road safety policy was based on high risks, high numbers and frequent causes, and on well-identified crash patterns. Crash and casualty rates, for example, were determined and divided into age groups, which showed that the young and the elderly had increased risks. The answer that policy-makers have come up with is the effort to reduce these high risks: smoothing the peaks in distributions. Analysis of road safety was aimed at the detection of peaks, explaining them and finding measures to overcome them.



Source: SWOV (2010).

Figure 11.4 Number of high-risk locations and the number of fatalities at these locations in the Netherlands (1987–2008)

The specific high-risk approach has resulted in successful policies, which can be illustrated by an example from the Netherlands (Figure 11.4). Whereas, in the period 1987–89, 10% of the serious traffic injured were associated with 'high-risk locations', this decreased to 1.8% in the period 2004–06.

Therefore, the least safe locations have successfully been dealt with. However, it is hardly possible for such an approach to have further positive effect in the future. One could say that the approach has come to the end if its life cycle and it will barely make a further contribution to the reduction of the number of road crash casualties in countries with a relatively long history of transport safety policies, such as the Netherlands.

The same case can be used when dealing with crash-prone drivers and for eliminating near wrecks, although the evidence is weaker. In many countries 'peaks in distributions' (e.g. hazardous locations, dangerous road users and defective vehicles) still exist and can still be eliminated. However, this approach will increasingly pose practical problems for high-income countries, such as *how* to identify and eliminate these 'relatively small peaks'.

11.8 SUSTAINABLE SAFETY: THE DUTCH VERSION OF A SAFE SYSTEM APPROACH

The Sustainable Safety vision was developed in the Netherlands because the traditional policies were becoming less effective and less efficient and because the idea was that the Netherlands had not yet found out the core characteristics of its road safety problems (Koornstra et al., 1992). Although, at first glance, the vision seems to be a one-country approach, in this case for the Netherlands, Sustainable Safety is in fact considered to be an appropriate and general vision for the future and not just for highly motorized and relatively safe countries like the Netherlands. Sustainable Safety is one of the examples of a Safe System approach. This has been illustrated in several reports: OECD/ITF (2016), European Commission (2019), Academic Expert Group (2019) and the World Health Organization (2021).

The main lines of this vision will be explained below. For more detailed information about Sustainable Safety, we refer to Koornstra et al. (1992), Wegman and Aarts (2006), SWOV (2018) and Wegman et al. (2023). These publications describe in more detail the three versions of Sustainable Safety. The vision aims for 'inherently safe' traffic (a concept used in rail and air traffic and also in energy production, for example). The Sustainable Safety approach starts with the idea that the present traffic system is inherently hazardous (that serious crashes can happen anywhere and at any time) and that all possible solutions are considered in an integral and rational manner. There is no a priori preference for improving roads or vehicles or changing behaviour. Furthermore, the rationale should not be restricted to road safety only, but wider deliberations are preferable (congestion, environment, scenery, economic development, health care and so on).

The following key aspects of the Sustainable Safety vision were identified:

1. Ethics:
   a. It is unfair to hand over a traffic system to the next generation with the current casualty levels.

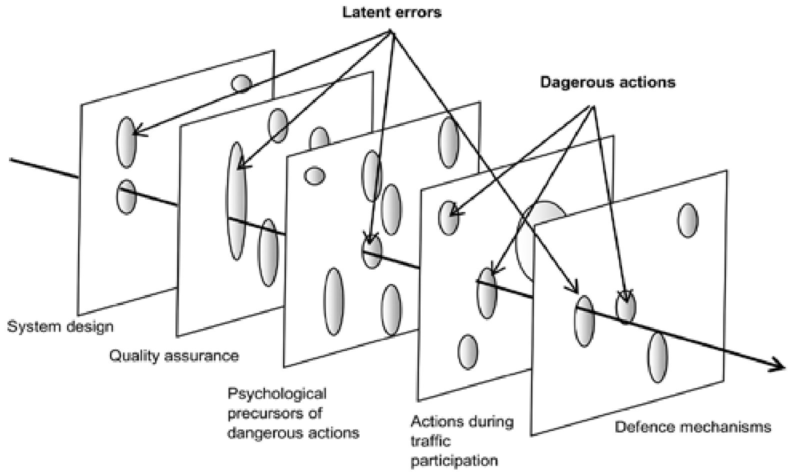
   b. A proactive approach instead of a reactive approach.
2. An integral approach which:
   a. integrates road user, vehicle and road into one safe system.
   b. covers the whole network, all vehicles and all road users.
   c. integrates with other policy areas.
3. Man is the measure of all things:
   a. Human capacities and limitations are the guiding factors.
4. Reduction of latent errors (system gaps) in the system:
   a. In preventing a crash it is better not to be fully dependent on whether or not a road user makes a mistake or error.
5. Use criterion of preventable injuries:
   a. Which interventions are most effective and cost-effective?

As indicated in Section 11.3, intentional or unintentional human errors play a role in nearly every crash. Intentional errors are committed by the 'unwilling' road user; unintentional errors are committed by the 'incapable' road user. No matter how well trained and motivated people are, they commit errors and do not always abide by the rules. Errors originate in many cases from the interaction between the road user and the complex road traffic environment. For avoiding crashes and injuries in crashes, road users now are almost completely dependent on the extent to which they are capable of correcting (and sometimes willing to correct) their own errors. The basic idea of the Safe System approach starts with the insight that human error should no longer be seen as the primary cause of crashes (OECD/ITF, 2016). But, present-day road traffic has not been designed with safety in mind to reduce or even eliminate human errors or to mitigate the consequences when errors are being made. And errors are also made in doing this. Both intentional errors and unintentional errors are made.

Additionally, a crash is rarely caused by one single unsafe action; it is usually preceded by a whole chain of poorly attuned occurrences. This means that it is not only one or a series of unsafe road user actions that cause a crash; hiatuses or weaknesses in the traffic system also contribute to the fact that unsafe road user actions can in certain situations result in a crash. These hiatuses are also called latent errors (Reason, 1990) (Figure 11.5). Road crashes occur when latent errors in the traffic system and unsafe actions during traffic participation coincide in a sequence of time and place.

As unsafe actions can never entirely be prevented, the Sustainable Safety vision aims at banishing the latent errors from traffic. The road traffic system must be forgiving with respect to unsafe actions by road users, so that these unsafe actions cannot result in crashes. The sustainable character of measures mainly lies in the fact that actions during traffic participation are made less dependent on momentary and individual choices. Such choices may be less than optimal and can therefore be risk-increasing.

Adjusting the environment to the abilities and limitations of the human being is derived from cognitive ergonomics, which made its entry in the early 1980s, coming from aviation and the processing industry. In all types of transport other than road traffic, this approach has already resulted in a widespread safety culture. Further incorporation of the Sustainable Safety vision should eventually lead to road traffic that can be considered 'inherently safe' as the result of such an approach.



Source: Wegman and Aarts (2006), adapted from Reason (1990).

Figure 11.5 The development of a crash (bold arrow) as a result of latent errors and dangerous road user actions, also known as the Swiss Cheese model

To make traffic inherently safer is to adjust the environment to the human measure in such a way that people commit fewer errors. Here, environment not only means the physical environment (road and vehicle) but also includes the required 'software' like legislation and the traffic education that is made available. Adjustments can be made along three lines. In the first place, road designers can make potentially dangerous situations less frequent so that road users need to make fewer decisions and therefore can commit fewer errors. An example of this is physical direction separation on secondary roads, which prevents head-on collisions. The second possibility is to design the road user environment in such a way that fewer errors are committed, and it is easier to make correct and safe decisions; this can, for instance, be done by the construction of a roundabout which makes high speeds at an intersection impossible. Thirdly, a traffic environment may be designed in such a way that *if* errors are still being committed, they will not have very serious consequences for the road user. To achieve this, the road user must be presented with an environment which is forgiving of errors that are committed. For example, when a car driver, for whatever reason, is starting to leave the road, road markings (rumble strips) could alert the driver in order to correct and the roadside itself should be (made) safe. In a Safe System approach this should be done in a proactive way because this approach moves beyond a reactive, crash history-based approach.

Five principles are identified as crucial for a sustainably safe traffic system in the second version (see Table 11.5). These are: functionality, homogeneity, forgivingness, predictability and state awareness.

Reduction percentages in traffic deaths in the Netherlands of more than 30% and 40% from 1998 through 2007 compared to business-as-usual levels have been estimated for policy interventions coming from or inspired by the Sustainable Safety vision (Weijermars and van Schagen, 2009; Weijermars and Wegman, 2011). Setting the societal cost of the investments

Table 11.5 The five Sustainable Safety principles

Sustainable Safety Principle	Description
Functionality of roads	Mono functionality of roads as either through roads, distributor roads, or access roads in a hierarchical road network
Homogeneity of mass and/or speed and direction	Equality in speed, direction and mass at moderate and high speeds
Forgivingness of the environment and of road users	Injury limitation through a forgiving road environment and anticipation of road user behaviour
Predictability of road course and road user behaviour by a recognizable road design	Road environment and road user behaviour that support road user expectations through consistency and continuity in road design
State awareness by the road user	Ability to assess one's task capability to handle the driving task

Source: Wegman and Aarts (2006).

alongside the societal benefits of the fatalities, injured and crashes saved shows that these interventions are socially cost-effective. The benefit–cost ratio is highly positive, around 4:1 (Weijermars and van Schagen, 2009).

The moment of the introduction of the third version of this approach (SWOV, 2018) coincided with an increase of the number of road casualties. It tried to respond to developments regarding demography, urbanization and technology and national as well as international discussions on the organization of and responsibility for societal benefits such as road safety. The third edition gave room to these developments by adding organizational principles like 'effective allocation of responsibilities', and the renewal principle of 'learning and innovating' (SWOV, 2018 and Wegman et al., 2021).

As long as individual road users make decisions in traffic and the context of these decisions will be shaped by the many stakeholders involved, the Safe System approach will remain a valid and effective approach. Strong leadership and institutional management remain needed (Wegman et al., 2021). The current paradigm in road safety – the Safe System approach – has a solid basis in scientific knowledge and recognizes that the responsibilities to make road traffic truly safe (without serious injuries) is shared between individuals and a wide range of stakeholders. Integration with other policy goals and expanding stakeholders is introduced in Section 11.10.

Several countries have based their road safety policies on the Safe System approach, including Sweden, Norway, Finland, Canada and Australia, often under the Swedish term Vision Zero. More and more large cities have been following as well. In 2019, the Norwegian capital Oslo became a benchmark for road safety with zero traffic deaths among pedestrians, cyclists and motorcyclists for an entire year. Norway started to implement Vision Zero nationwide in 2002 with national regulations on vehicle safety, speed limits and highway design. In addition, Oslo invested in road infrastructure improvements, bike lanes and public transport funded by tolls from the city's toll roads. The latter and increased car parking charges in the city centre led to a decrease of car traffic. Traffic safety improvements are standard practice in every road project and the city regularly revises speed limits and implements traffic-calming measures (Belin et al., 2022). Finland's capital Helsinki followed a similar road safety strategy and recorded no traffic deaths in 2019. The city has reduced speed limits to 30 km/h on most residential streets and the city centre with speed humps to enforce. Driving lanes were narrowed to provide more space for pedestrians and cyclists and less for car traffic. The city of Helsinki has built dozens of roundabouts since the 1990s (Murray, 2020).

11.9 VULNERABLE ROAD USERS

Pedestrians, cyclists, moped riders, motorcyclists and users of light electric vehicles (LEVs) such as standing e-scooters (e-steps) are vulnerable. A helmet is effective to protect their heads (Olivier and Creighton, 2017), but even wearing a helmet they are less protected than car occupants. These vulnerable road users (VRUs) constitute 54% of all road deaths worldwide (WHO, 2018). Children, youngsters and the elderly are particularly likely to be involved in fatal VRU accidents (Varhelyi et al., 2018). In the remainder of this section, we mainly focus on pedestrians and cyclists as governments encourage these transport modes because of their benefits for society, such as less air pollution and reduced mortality and morbidity due to physical activity (Kelly et al., 2014) – see also the discussion in the chapter on environment (Chapter 10) and health (Chapter 12).

While most fatal VRU crashes are collisions with motor vehicles, most serious injury crashes are single vehicle incidents, such as falls and collisions with obstacles such as kerbs and bollards. An international review of studies based on hospital data showed that between 60% and 95% of cyclists admitted to hospitals or treated at emergency departments are victims of single-bicycle crashes (Schepers et al., 2015). International definitions include single-vehicle crashes on public roads with cyclists, motorized two-wheelers, while pedestrian falls without a vehicle being involved are excluded.

As explained in Section 11.2, pedestrians and cyclists are about five times more likely to sustain fatal injuries in collisions at a 50 km/h impact speed as compared to at 30 km/h. Many measures to promote the safety of vulnerable road users therefore focus on speed management. Area-wide urban traffic-calming schemes in residential areas, sometimes called ‘Zone 30’, reduce the total number of injury crashes, in particular among cyclists and pedestrians (Elvik et al., 2009; Inada et al., 2020). Road safety may therefore be improved by decisions to reduce the general speed limit to 30 km/h in cities (Academic Expert Group, 2019). Road design and roadside environment are important to achieve compliance with the reduced speed limit (Yao et al., 2020). An effective strategy fitting excellently in the Safe System approach along roads with higher driving speeds is separation of VRUs by cycle tracks and sidewalks (Thomas and DeRobertis, 2013; Van Petegem et al., 2021). While a 50 km/h road is safer with cycle tracks than with marked cycle lanes or mixed traffic, Schepers et al. (2013) point out collisions are still much more likely than in traffic calmed areas. At intersections of roads with high-speed limits, cyclists and pedestrians are still exposed to the high-speed motor vehicles and are frequently involved in collisions. Schepers et al. (2013) found that more cycling along low speed access roads corresponds to a higher level of road safety for cyclists. The authors describe this strategy as unbundling vehicular and cycle traffic.

Advanced Driver Support Systems (ADAS) may also play a role in speed management. By 2024 every new car sold in the EU will need to be fitted with systems such as Autonomous Emergency Braking (AEB) and Intelligent Speed Assistance (ISA). AEB intervenes autonomously when (after several warnings) the driver does not apply the brakes. ISA aids the driver in maintaining the appropriate speed. ISA is mandatory on all new vehicles in the EU from 2024 onwards, but drivers are allowed to switch it off.

The majority of non-fatal crashes with classic bicycles and e-bikes are single-bicycle crashes (Hertach et al., 2018; Schepers et al., 2015). A fall is hard to prevent when the front wheel skids or is locked or after hitting an obstacle such as a curb. Infrastructure is an important factor and under winter conditions it is of particular importance to prevent skidding. Other factors in bicycle crashes are a bicycle track being insufficiently wide, the course of the bicycle track or obstacles being insufficiently visible and road surface irregularities such as tram tracks and potholes. To summarize, a forgiving environment is needed. Options that are less related to infrastructure are for instance braking mistakes or sudden braking to avoid another vehicle/cyclist.

In Europe, where e-bikes offer pedal assistance up to 25 km/h, e-bikes on average travel only a few km/h faster than conventional bicycles. This may explain why most studies suggest that crashes with both bicycle types are equally likely and severe (Fyhri et al., 2019; Schepers et al., 2020). Few studies have focused on LEVs (light electric vehicles) such as standing e-scooters as their use has only recently started to grow. The studies that have been conducted show that similar to bicycle crashes, most standing e-scooter crashes are single vehicle crashes. More research is needed to compare risks to other travel modes such as walking and cycling (International Transport Forum, 2020).

11.10 SOME PROMISING OPTIONS FOR FURTHER IMPROVING ROAD SAFETY

Road safety has improved considerably in many (highly motorized) countries, although the absolute numbers of fatalities and serious injuries across the globe are still growing. Improvements are mainly due to risk reducing interventions, improvements in the safety quality of roads and vehicles and better post-crash management. It is reasonable to expect that many of these improvements will bear more fruit in the future: lower travelling speeds in urban areas, more separation of vulnerable road users and motorized traffic, etc. We conclude with presenting two more promising options for further improvements: automation in driving and the contributions by businesses and enterprises.

A promising option for further improvement is the further development and use of Advanced Driver Assistance Systems (ADAS) and in the longer term autonomous driving. While passive safety equipment such as seat belts and air bags greatly reduced crash severity over the past decades, active safety systems are introduced in new cars with the potential to prevent crashes. The development of ADAS began with Anti-lock Braking System (ABS) in the late 1970s for improved braking and expanded to Electronic Stability Control (ESC) to prevent skidding while steering. Other examples of ADAS to improve road safety are Lane

Departure Warning (LDW), Blind Spot Detection (BSD), and the ISA and AEB mentioned in the previous section (Ziebinski et al., 2017). Driver assistance systems are paving the way for autonomous driving. The Society of Automotive Engineers (SAE) defined six different levels of driving automation. While the driver lacks ADAS in level 0, ADAS assist speed and steering in levels 1 and 2 in which the driver still monitors the driving environment. ADAS monitors the driving environment in higher-level (levels 3 to 5) vehicles (Kukkala et al., 2018).

As most crashes result from human errors and violations, it has been claimed that autonomous driving reduces traffic deaths by over 90% (Shinar 2019). These claims are untested. In addition to its great advantages, autonomous driving can also introduce new risks that we must learn to manage. Automated vehicles will be able to respond faster to critical events happening on the road and will not be affected by fatigue, for example. An example of a new challenge in conditional automation in SAE level 3 is that the human driver should be able to intervene in a timely manner if the system requires so, even when the drivers were not paying attention or performing non-driving related tasks (Inagaki and Sheridan, 2019). Furthermore, more complex systems to allow for further automation may rely on vehicle-to-vehicle communication introducing new cybersecurity challenges (Katrakazas et al., 2020). It is not yet possible to predict how much and how quickly road safety can be improved by the introduction of autonomous driving (International Transport Forum, 2018).

We have a better understanding of why crashes occur, and we have gained a lot of knowledge on the effectiveness and sometimes on the efficiency of road safety interventions. The vast majority of these improvements were an initiative from governments, at a federal, national, regional or local level, sometimes as a result of activities by non-governmental organizations (NGOs – organizations representing road crash victims, for example) or from the public. It could be considered to explore how an important, and still rather absent, stakeholder in our society, the private sector, can make a contribution to further improve road safety without being invited (or even forced) by governments.

It is considered to be a responsibility of businesses and enterprises to contribute to the achievement of the Sustainable Development Goals (SDGs) from the United Nations (2015) and to the Agenda 2030 for Sustainable Development more specifically. Improving traffic safety is included in this Agenda. Businesses recognize the opportunities that the SDGs offer them to engage in the Agenda 2030. These go far beyond the corporate social responsibility of businesses, as they deal with the total corporate value chain: inbound logistics, operations, outbound logistics, marketing, sales and service (Porter, 1998). It is from this perspective that it has been proposed to make the private sector an important stakeholder and actor to improve road safety (Academic Expert Group, 2019). Two (of the nine) recommendations of this Group deal with the private sector. One deals with the procurement of fleet vehicles and transport services. This concerns, for example, the specification of vehicle safety levels, training of drivers and scheduling and planning of driving operations. The first recommendation for businesses and enterprises (page 28) says:

> require the highest level of road safety according to Safe System principles in their internal practices, in policies concerning the health and safety of their employees, and in the process

and policies of the full range of suppliers, distributors and partners throughout their value chain or production and distribution system.

For instance, time pressure due to delivery deadlines and payment per delivery in commercial transportation contribute to stress, fatigue and more risky driving or riding (Delhomme and Gheorghiu, 2021) and should be prevented. Workplace road safety risk management and a positive road safety culture help to control these risks (Warmerdam et al., 2017).

Looking back at the history of road safety and how to reduce risks and the number of road casualties, we may conclude that these attempts took place inside the 'road safety silo', that is to say they were attempts with the only or main goal to improve road safety. We can observe developments to include road safety in a more integral approach for improving the human condition and the condition of the planet, as for example being recommended in the report of the Academic Expert Group (2019) and in the policy proposals for the European Union (EC, 2019) and by the World Health Organization in their Action Plan (WHO, 2021). Improving road safety is part of improving health, climate, equity and prosperity. Active transport modes such as walking and cycling are good for health, reduce air and noise pollution, as well as energy use and greenhouse gas emissions (see also Chapters 10 and 12 of this book), but from a road safety perspective this could only be supported if walking and cycling is safe.

11.11 CONCLUSIONS

The most important conclusions from this chapter are:

1. Speed, speed and mass differences, and vulnerability are fundamental risk factors for road crashes and injuries. These fundamental risk factors explain the fact that pedestrians and cyclists are vulnerable road users in collisions with (high-speed) motorized vehicles.
2. Risk-increasing factors from the road users' side are impaired driving (alcohol and drugs), fatigue and distraction.
3. Both human errors and (intentional) violations (and related extreme behaviour) are important contributory factors for road crashes.
4. Measuring road safety is not without its problems, because of non-harmonized definitions, poor data quality, data incompleteness and lack of data availability.
5. Positive development in many highly motorized and highly developed countries can be noted. These highly motorized countries haves made considerable progress by implementing behaviour-, vehicle- and infrastructure-related measures in the last decades.
6. However, the effectiveness of many 'traditional' policies will reduce. The next step is to move from policies targeted at decreasing specific risks to policies aimed at lowering generic or inherent risks: in other words, to a Safe System approach.
7. A Safe System approach starts by using the idea that the present traffic system is inherently hazardous (that serious crashes can happen anywhere and at any time) and that all possible solutions should be considered in an integral and rational manner. Cost–benefit analyses show that such an approach can have positive benefit-to-cost ratios.
8. Vulnerable road users (pedestrians, cyclists, powered two-wheelers) are disproportionally impacted by road crashes and this group accounts for more than 50% of road deaths world-

wide. Risks for this group will be lowered by separating them from high-speed motorized traffic and by speed reduction at locations where they interact with motorized traffic, for example by installing 30 km/h zones. A forgiving environment is needed to prevent severe injuries due to falls.
9. Automated and autonomous driving are very promising for improving road safety, however it is not yet possible to predict how much and how quickly road safety improvements will reduce the number of road fatalities and injuries.
10. Road safety shall be further improved by expanding and intensifying the engagement of stakeholders in the public sector and by engaging new partners especially in the private sector. Improving traffic safety is part of the Sustainable Development Agenda which connects improving road safety with other goals on good health and well-being, green mobility, gender equality, sustainable cities and communities, etc.

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