Identification of Knowledge Gaps in Road Safety Research for the Promotion of Smart Transportation (*October 2020*)

Table of content

1. Introduction: basic notions and the examination framework

Since the early years of their development, transportation systems caused road traffic injury. Evaluations showed that during the twenties' century, 30 million people were killed in road accidents throughout the world (PIARC, 2003). Today, the annual "road toll" is estimated to be 1.35 million deaths and up to 50 million injuries worldwide (WHO, 2018). By 2030, road accidents will become the seventh leading cause of death and disability for all ages, while already now it is the leading cause of death among young people (below the age of 30). The economic burden of road injury accounts for 2-5% of the gross national products in various countries (ITF, 2016; WHO, 2018). The tremendous consequences of road accidents have been explicitly recognized during the last two decades that led to a focused promotion of road safety interventions, initially in Europe (EC, 2003, 2010, 2019) and other developed countries, and later on, throughout the world; the latter was stimulated by the United Nations' Decade of Action in Road Safety[1] (WHO, 2011).

The need for effective road safety interventions draws the attention to road safety research, in particular road safety evaluation research, which is intended to determine whether various measures applied in the transportation system contribute to improving road safety (Elvik et al., 2009). In general, road safety research is supposed to provide objective knowledge on safety impacts of various system's components and their changes (due to countermeasures applied) and, ideally, based on empirical data of the system's performance.

In this context, a distinction can be made between the 'risk factors' and 'safety measures' (Martensen et al., 2019). 'A risk factor' may refer to any factor that contributes to the occurrence or the consequence of road accidents. Risk factors can have a direct influence on the risk of an accident occurring, on the consequences of the accident (severity), or more indirectly by influencing safety performance indicators of the system (i.e. systems' characteristics which have a causal link to accident occurrences or severity, for example, unsafe road user behaviours). 'A measure' may refer to any intervention that is taken to reduce the risk, the frequency or the consequences of road accidents. Measures can have a direct influence on the risk or the frequency of an accident occurring, on the consequences of the accident (e.g. severity), or more indirectly by influencing safety performance indicators. Thus, a high degree of duality between risks and measures is possible, while the absence of a specific measure often poses a risk in the

[1] UN General Assembly Resolution A/RES/64/255, 2 March 2010

system. Road safety research explores both the risk factors of the transportation system and the safety-related impacts of various measures (or interventions) implemented in the system.

It is widely recognized that road safety is a complex phenomenon depending on many factors that act in the transportation system. A taxonomy of the main factors can be described by Figure 1 (based on Elvik et al., 2009). On the one hand, it reflects the basic relationship between traffic exposure, the probability of accident occurrence given the exposure and the probability of accident outcomes (road injuries). On the other hand, it shows the main system domains – infrastructure (and traffic environment in general), vehicles and road users - which may impact both the accident occurrences and their consequences. In addition, concerning the exposure, the amount of travel, the types of road users or traffic modes, and their composition in traffic, may affect the accident numbers and their severity. For example, given the same amount of travel, the injury rates of motorcycle riders, cyclists and pedestrians are substantially higher than those of car drivers or passengers, and this finding is common for many countries (Elvik at el., 2009). Road safety research generally explores the interactions of factors presented in Fig.1, while specific studies focus on selected features of the system's domains (infrastructure, vehicles, road users) and their combinations.

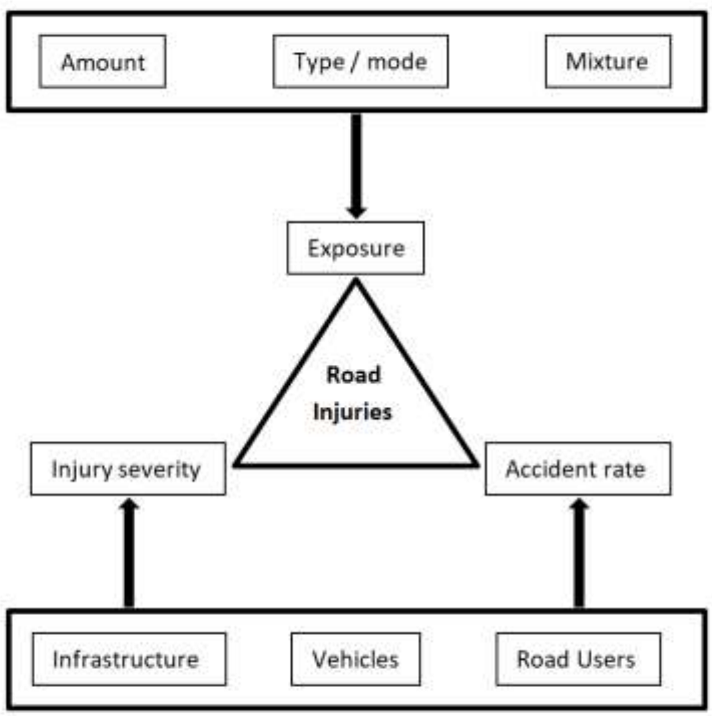

Figure 1. A taxonomy of factors affecting road safety (Elvik et al., 2009).

'Smart transportation' refers to the integrated application of modern technologies and management strategies in transportation systems[2]. These technologies aim to provide innovative services relating to different modes of transport and traffic management and enable users to be

[2] https://enterpriseiotinsights.com/20170626/transportation/20170625transportationwhat-smart-transportation-tag23-tag99

better informed and make safer and ‘smarter’ use of transport networks. A ‘safer’ transportation system implies lower accident and injury risk. Smart transportation is expected to impose changes on traffic exposure (type of mode, the amount of travel, traffic composition), and possibly – road user behaviors, vehicle performance, road infrastructure features. Changes in these factors may impact the transportation system's safety. However, the links between the innovative services and the system’s safety are not obvious and should be examined by empirical research. Some impacts can be explored by using ‘substitutes’ to accident occurrences (or surrogate indicators) such as behaviour indicators, near-crash events, etc.

This paper is intended to explore the knowledge gaps in road safety research related to smart transportation, aiming to identify preferable research directions which would contribute to the benefits of both fields. Matching between the two research fields is not obvious in the current state of research. For example, formal searches in *Scopus* using the combinations of "smart transportation" and "road safety", or similar words, were not very successful, and did not discover studies which would overview recent developments in both fields with their mutual impacts. Similarly, formal searches in the road safety domain (by means of *TRID* and *Scopus* databases) were not useful in finding studies which would discuss "lessons learnt" or "future directions" in road safety research, having considered recent developments in smart transportation. However, papers with more narrow scopes were found, for example, those which examined safety implications of recent trends in urban mobility, or discussed potential safety impacts of vehicle automation.

We can assume in this context that the development of smart transportation solutions should account for the previous knowledge in road safety research, e.g. concerning the risk factors and safety-improving measures, safety-related design principles, etc. as well as should refer to current road safety needs (which require innovative solutions). Conversely, the new developments of the transportation system (‘smart’ solutions) should be examined in terms of their impacts on road safety, both direct and indirect.

Thus, to identify the knowledge gaps in road safety research related to smart transportation (in this paper), the following research strategy was applied. First, we provide an overview of recent developments in road safety in terms of the conceptual approach, current needs and emerging social and mobility trends which may have safety implications. Second, we suggest a brief overview of the recent directions in road safety research which may be relevant to smart transportation. Third, we discuss a number of studies which examined safety impacts of recent transportation developments. Finally, based on the previous findings, we suggest future directions of road safety research, to promote smart transportation.

2. Recent developments in road safety

2.1. The Safe-System approach

In road safety analysis and crash studies, two approaches are possible (Hauer, 2016; 2020). The traditional approach takes a backward-looking perspective. Standard crash causation analysis strives to understand all the factors involved in a crash that happened in order to suggest ways how such a crash could have been prevented. Alternatively, a forward-looking view will consider what crashes might potentially happen in the future and identify all possible ways how such crashes can be prevented. This proactive approach is the basis of a Safe System.

The Safe System approach is the leading concept today of road safety policy making at all levels (ITF, 2016; PIARC, 2019; EC, 2019). Its starting point is an ethically inspired perspective that there is no acceptable level of road deaths and serious injuries, and that road users respecting the rules of their road networks have a right to expect that they should be safe. A Safe System encourages a 'forgiving' strategy for road injury prevention, which accepts that, while human error on the road is inevitable, fatalities and serious injury as result of a crash are not. It recognizes the shared responsibility of system designers and road users to ensure that crash energy remain at all times below levels that will cause fatal or serious injury, and promotes a holistic, multi-sectoral approach which can reframe the way in which road safety is perceived and managed.

Four principles underpin a Safe System in road traffic (ITF, 2016):

1. People make mistakes that can lead to road crashes.

2. The human body has a limited physical ability to tolerate crash forces before harm occurs.

3. A shared responsibility exists amongst those who design, build, manage and use roads and vehicles and provide post-crash care to prevent crashes resulting in serious injury or death.

4. All parts of the system must be strengthened to multiply their effects; and if one part fails, road users are still protected.

The term Safe System refers to (ITF, 2016):

- The vision that zero fatalities and serious injuries from road crashes are ultimately possible;
- The four (aforementioned) principles to guide the design, operation and use of a road system;
- The implementation of practices, tools and their interactions that will deliver on the principles.

In particular, a proactive approach of Safe System entails understanding where the risk is inherent in the road network, whether transport infrastructure satisfies the Safe System design principles and if not, priority interventions are to be identified and applied before accidents begin to occur. All stages of this process should be based on road safety research. In addition, as indicated by PIARC (2019), promoting innovation and the adoption of new technologies should be based on well-established principles of a Safe System (that is directly relevant to the topic of this paper).

It should be noted that "Vision Zero", "Sustainable Safety" and "Safe System" are different names for similar policies that fundamentally do not accept death and serious injury as an acceptable product of mobility (ITF, 2016).

Figure 2 illustrates a conceptual framework of the Safe System. It shows that the most vulnerable road users – pedestrians, cyclists, two-wheelers, children and elderly - are placed at the center of the transport system design. The second and third circles of the model capture the relationships between speed, roads and roadsides and road users, applying the principle that the human body has a limited physical ability to tolerate crash forces and thus the system's design should be adopted respectively. The Safe System emphasizes the major role of speed management in reducing traffic fatalities and injuries. The fourth circle shows the importance of post-crash medical care in reducing the severity of outcomes once an accident occurs. The fifth circle reflects the principle of shared responsibility of all those who design, build, manage and use roads and vehicles to prevent crashes resulting in serious injury or death.

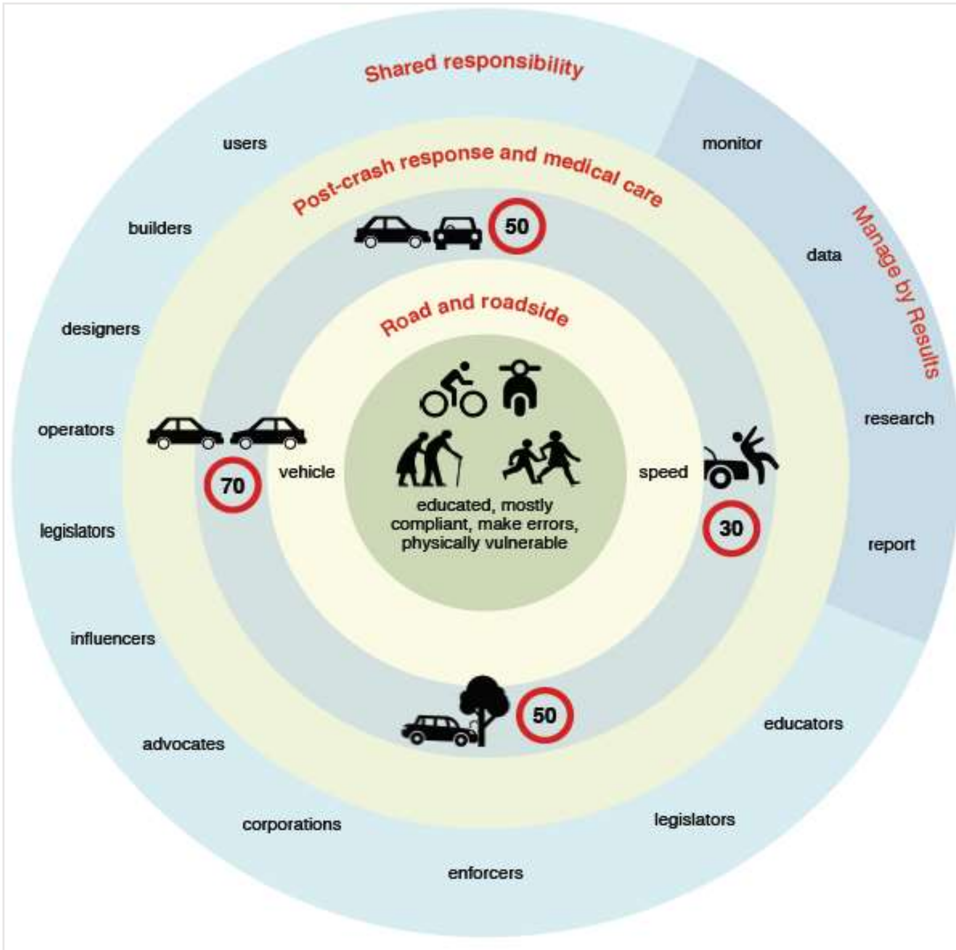

Figure 2. A conceptual framework of the Safe System approach (ITF, 2016).

2.2. Leading road safety needs

Leading safety problems, in a country or a region, can be identified based on the analysis of road injury data in the context of transportation, economic and social background data. A basic method is an identification of high-risk groups, for which the risk of accident/injury occurrence related to exposure, or injury severity, is significantly higher than that for the entire population or for another (low-risk) group (e.g. Elvik et al., 2009). Such comparisons are applied by the National Road Safety Authority (NRSA) in the annual analyses of the national road accident statistics (e.g. NRSA, 2019). In line with the Safe System approach, the main focus in the identification of leading safety problems should refer to severe (fatal and serious) injuries (EC, 2019). Additional insights can be received based on international comparisons (e.g. ETSC, 2018), where the country of interest (e.g. Israel) was ranked low compared to the advanced countries. Furthermore, emerging safety problems are recognized when the amount of accidents/ injuries of a certain group of road users demonstrates a rapid increase over-time (e.g. Siman-Tov et al., 2017).

Based on the analyses of road injury in Israel, recent research studies and international comparisons (e.g. ETSC, 2019; OECD/ITF, 2018), some current road safety problems can be indicated as follows:

- **Pedestrian injury**

Walking is a basic mode of urban transport in most societies, with well-established health and environmental benefits stemming from increased physical activity and reduced air pollution (e.g. WHO, 2013). However, pedestrian injury is still one of the major safety problems throughout the world, where pedestrians account for 23% of the total fatalities in road crashes in the world (WHO, 2018), and represent 40% of total fatalities and 25% of serious injuries on urban roads in Europe (ETSC, 2019).

In Israel, pedestrian injury is one of the leading road safety problems over the last decades, as pedestrians usually present about a third of the annual fatalities and serious injuries in the country (Gitelman et al., 2012; Sharon, 2017). Most pedestrians are killed or seriously injured on urban roads (e.g. 87%, in Sharon, 2017). The scope and constancy of the pedestrian safety problem, in Israel, strengthen the need for solutions to improve pedestrian safety. Moreover, the plans of sustainable urban development that discourage private car use and encourage walking (as well as public transport use and cycling) raise additional safety concerns since the existing urban environment is not ready for safe walking (Stoker et al., 2015; ETSC, 2019).

International experience emphasizes the role of infrastructure and, particularly, traffic calming measures for reducing pedestrian injury (WHO, 2013; Mead et al., 2014). However, the ways for a balanced application of traffic calming in city centers and other urban areas with a complex mix of various road users still need to be developed.

Signalized crosswalks, including those at signalized intersections, are supposed to serve as a safe place for pedestrians to cross. However, signalized intersections appear to be among urban locations with a high frequency of pedestrian injury (Gitelman et al., 2012; Sharon, 2017). The reasons for that lie in insufficient priority to pedestrian movement at busy intersections but also in non-compliance with red lights by crossing pedestrians. New solutions are needed to increase pedestrian safety at urban intersections (without increased harm to vehicle traffic).

- **Children**

Children are more vulnerable road users due to their cognitive, physical and behavioral traits. The share of children in Israeli population is substantial (e.g. 28% of aged below 14, in 2018) and thus, cannot be ignored in future developments of the transportation system. International comparisons showed (ETSC, 2018) that the child mortality rate in road accidents (per million inhabitants) is higher in Israel than the average value in the European countries while the progress in reducing traffic fatalities is slower. Furthermore, the share of children killed in urban areas is substantially higher in Israel than in other countries, where the majority of them were pedestrians. Hence, further exploration of children's behaviors as various types of road users and the development of innovative measures for reducing children road injury would be useful in the future.

For example, young children's training in virtual reality can serve as an additional form for enhancing hazard perception skills (e.g. Meir et al., 2015). Further development of urban traffic settings, which are focused on safer child pedestrian crossing conditions, can also be promising (e.g. Leden et al., 2018).

- **The elderly**

Older people suffer more road trauma due to the deterioration in their physical and mental ability that leads to higher involvement in road accidents and to more severe consequences of such (e.g. Whelan et al., 2006). In Israel, the relative risk of being killed or seriously injured in road accidents is high for the elderly population: the share of elderly (people aged 65+) among road traffic injuries is substantially higher than that in the population (e.g. 20%-25% vs 12%, in 2018). The majority of elderly people are killed as pedestrians (NRSA, 2019).

Population ageing is one of the growing issues in developed countries with the expected effect of an increased involvement of older road users in accidents, thus, requiring attention from the decision-making, technical and research viewpoints (e.g. Hakkert and Gitelman, 2014). Transport infrastructure conditions have to be adapted to the limitations of older road users. However, such solutions are not readily available and should be developed based on research.

- **Motorcyclists**

In many countries, riders of motorcycles of various kinds or powered two-wheelers (PTWs) are one of the most vulnerable types of road users. In Israel, motorcycles present only 2% of the total vehicle fleet and 4% of the traffic exposure (annual vehicle-km traveled) while the share of PTWs' injuries is substantially higher – they present 9% of the total injuries, 13% of fatalities and 22% of serious injuries, in the country (Hakkert et al., 2019). At the same time, over recent decades, an increasing use of motorcycles is observed throughout the world, since they provide mobility benefits in densely populated areas. Thus, there is an urgent need for effective solutions, in all domains - infrastructure, vehicle safety and road user behaviors, to attain a decrease in the risk of PTWs' road injury, particularly in urban areas.

- **Cyclists and e-cyclists**

Cycling is a transport mode which is highly promoted by the sustainable urban development since a shift from car travel to cycling contributes to reduced traffic congestion, lower energy consumption, improved accessibility and positive health effects (OECD/ITF, 2013). At the same time, cyclists are unprotected compared to car occupants and hence, are exposed to higher risk of severe injury, especially when they move in mixed vehicle traffic. In Israel, cyclists currently present a few percent of the total traffic fatalities (NRSA, 2019), however, the problem may grow in the future due to increasing exposure.

In addition, in the last decade, there has been a sharp increase in the use of electric bicycles, throughout the world (e.g. Fishman and Cherry, 2016) and in Israel. The electric assistance to the rider reduces the physical efforts required for cycling; e-cycling becomes accessible for more road users and for various trips thus providing a potential to expand the role of cycling in urban transport. However, there is a growing concern of e-cyclists' injury, resulting from the increasing exposure and, perhaps, riskier e-riders' behaviors (e.g. Siman-Tov et al., 2017).

Furthermore, following the introduction of e-scooter sharing systems, a growing use of e-scooters was recently observed, in many cities, raising concerns of associated injuries. Medical studies on the topic showed an increase in the number of e-scooter related injuries when the use is rising (e.g. Trivedi et al., 2019; Bekhit et al., 2020). The safety effects of e-scooter and e-cycle use in mixed traffic are not yet well understood.

- **Injury in accidents with heavy vehicles and public transport**

Heavy trucks and buses are involved in a substantial share of accidents leading to fatalities and severe injuries in Israel (29% and 15%, respectively), while they comprise only 8% of the total vehicle traffic (NRSA, 2019). The involvement of heavy vehicles in fatal accidents is higher in Israel compared to other developed countries thus indicating a need for safety improving solutions.

In addition, the rise in urban density, around the world, leads to a growing use of public transport as a mobility mode (e.g. Paganelli, 2020). Local and national governments frequently address the objective scarcity of space for traffic in urban areas by establishing bus priority systems to improve mobility and promote public transport use. Previous research showed extensively that bus priority systems reduce passenger travel time and improve the attractiveness of public transport (e.g. Ingvardson and Nielsen, 2018). In contrast, assessing the safety impacts of such systems is still limited since analyses were only carried out in a few countries and much more empirical research is required concerning both the general effects of these systems on urban traffic safety and the implications of specific design solutions. Negative safety impacts can be expected in this context, as observed in Israel and some other countries (e.g. Gitelman et al., 2020).

- **Speeding**

Speed was proven to be a crucial factor in accident occurrences and their consequences (e.g. Elvik et al., 2019). Thus, great importance is assigned today to speed management of the road system to improve its safety and mobility, particularly within the paradigm of the Safe System (ITF, 2016). Speed surveys conducted in Israel and in other countries showed that the problem of traveling at excessive speeds is prevalent on various road types (Adminaité-Fodor and Jost, 2019); the problem of speeding is especially urgent in urban areas due to the presence of vulnerable road users.

The strategy of sustainable road safety aims to match the road design characteristics to the target travel speeds, on every road type. Previous research indicated which road infrastructure characteristics may be applicable for attaining targeted travel speeds in urban areas (e.g. Gitelman et al., 2020). Traffic calming measures may provide particular safety benefits for pedestrians and cyclists, while implemented in various urban areas including city centers (ETSC, 2019). However, their implications on traffic in the whole urban network and all road users should be examined by empirical research.

2.3. Emerging social, mobility and technological trends with possible safety implications

A background study for road safety strategy in the European Union (EU) for the next decade (EC, 2018), summarized the main “external” factors – social, mobility and technological trends – that should be accounted for in considering future road safety developments. In this section we provide an overview of these trends, based on EC (2018) and other sources. All these trends can be seen as relevant to future needs in road safety research in the context of smart transportation.

- **An ageing population**

The population statistics in the developed countries indicate a rising share of older people as a greater proportion of the post-war baby-boom generation reaches retirement and has a better and longer life expectancy. The proportion of people aged 65 years and over, who are at a disproportionately high risk of serious and fatal crash injury due to physical vulnerabilities, is about 20% today (in Europe) and is expected to rise in the future. The protective needs of older road users should be taken into account in road safety developments. The road traffic system needs to be adapted to support safe and increased mobility for an ageing society (EC, 2018).

- **New urban mobility patterns**

Active travel by walking and cycling plays a key role in sustainable mobility and is expected to increase alongside the trend in greater urbanization. The need for greater equity in urban transport modal share is being acknowledged and encouraged in urban transport policies, as well as in walking and cycling strategies at the EU, national and city levels.

However, walking and cycling will have an adverse impact on road safety outcomes unless urgent steps are taken to take better account in road traffic system planning and design of the physical vulnerabilities of users of these modes (EC, 2018). This can be addressed by protecting them in mixed traffic by lowering motor vehicle speeds to, at most, 30 km/h as a priority on residential roads and ensuring that speeds do not exceed the protective qualities of roads and vehicles (in line with the Safe System approach - ITF, 2016), or by physically separating these users from motorized traffic on roads which require speeds above 30 km/h. Solutions promoting active travel should be accompanied by road safety research.

- **Continuing popularity of powered two-wheelers**

The popularity of PTWs continues in Europe, evidenced for example by the new vehicle stock of PTWs registered in the EU which has increased by 34% since 2000. However, the risk (in terms of road deaths per distance travelled) for motorcyclists is 40-50 times higher than that for car users. Urgent action is needed to address the exceptionally high risks of this road user group, while a focus should be on implementing evidence-based measures (EC, 2018).

- **Cooperative, connected and automated vehicles**

The advent of cooperative, connected and automated vehicles can be expected to significantly change the face of the automotive sector and vehicle use. Increasing automation and the exchange of data between vehicles (V2V), between vehicles and the traffic infrastructure (V2I) and the connection of vehicles to the internet are developments with far reaching consequences on travel patterns (EC, 2018). Different levels of automation have been defined by the Society of Automotive Engineers (SAE). A recent report for the European Parliament noted that a variety of driving assistance systems of Level 0 (no automation), Level 1 (driver assistance) and a smaller number of Level 2 (partial automation) technologies are currently available on the market. Vehicle manufacturers are investing in research and development of more advanced automation systems up to Level 3 (conditional automation) and research and testing of higher automated systems (level 4 – high automation and level 5 – full automation) is already underway (EC, 2018).

The same study reflected the broad view that increasingly automated systems (Levels 2 to 4) are likely to be introduced in the short (next 5-10 years) and medium term (10-20 years), while full automation is expected to be feasible on a large scale in a farther time horizon (more than 20 years), but not necessarily universally implemented. For example, truck platooning is expected to follow an incremental pathway leading towards progressive reduction of the responsibilities of the drivers. On the other hand, urban mobility and public transport is expected to follow a different path, consisting in the development of highly automated vehicles initially circulating in specific restricted environments. The High-Level Group concluded that till 2030 full automation will likely remain confined to niches and it will be a period of learning rather than transformation (EC, 2018).

Forecasts indicate that there will be a long transition phase to full automation as more, increasingly autonomous vehicles are introduced to the vehicle fleet. For many years there will be a mix of highly automated and non-automated vehicles in traffic. Without large scale trials of autonomous systems, it is not known how this will affect road safety overall. For example, a system that automatically limits speed is likely to produce benefits. On the other hand, pedestrians and other vulnerable road users may have expectations of vehicle functionality that are not there. Furthermore, there is the possibility of technical or design failure, problems with interaction between vehicles with different technical systems, etc. While there is a general expectation that road safety may improve through better connected and autonomous vehicles, effective safety performance of automated systems has yet to be demonstrated. Technical challenges still need to be addressed and little information is available on the potential emergence of new risks (EC, 2018).

- **Electro-mobility and micro-mobility**

The EU commitment to reduce greenhouse gas emissions from the transport sector stimulated a shift of car manufacturers towards electric mobility (EC, 2018). In addition, new types of small city vehicles are being introduced, including e-bicycles and other light vehicles with electric power which belong to L-categories (according to the EU regulation 168/2013). Furthermore, a growing use of various micro-mobility devices has been recently observed in urban areas, throughout the world (OECD/ITF, 2020).

Safety impacts of the new vehicles are generally yet unclear. Indeed, as we indicated above, the increased use of e-bicycles and e-scooters led to a jump in the related injury. However, the macro-impacts of the new mobility means on urban road safety still need to be evaluated. The potentially higher speeds of powered bicycles and the extended mix of vulnerable road users will probably have negative consequences on urban road safety. On the other hand, the use of light vehicles instead of cars and trucks in city centers may reduce safety risks. Empirical research is required to better understand the needs and behaviors of the new road users, to determine safety regulations which would improve their safety and to suggest infrastructure changes (and other measures) to attain a safer sharing of urban space among various road users.

- **Mobile communication technologies**

Over the last decade, substantial increases have been reported on the availability and use of a range of mobile technologies, including smartphones and tablets as well as handheld or wearable devices for communication and information. The increasing use of in-vehicle internet and email access systems and the mobile phones while driving increases the potential distraction from the driving tasks' performance and, thus, the accident risk (EC, 2018). As indicated, the human-machine interface of in-vehicle systems needs to be designed in a way to allow their safe use by various groups of drivers and to prevent external distractions, for example, by providing an automatic postponement of the connection of incoming calls (or messages) while driving.

3. Recent research directions in road safety

In this section we provide a brief overview of the main directions in road safety research that may be relevant for smart transportation developments.

- **Main forms of safety knowledge**

As indicated in Sec.1, road safety research, in general, aims to provide objective knowledge on safety impacts of the transportation system's components and their changes; the latter may happen due to an external development (e.g. economic, social, environmental) or an internal intervention (countermeasure). Road safety research is usually based on the analysis of accident/injury statistics (yet, substantial research is focused on road user behaviors, see below). Accident data are examined in combination with data on traffic exposure and additional characteristics of the population of interest (e.g. road sites, road user groups) that may be essential for understanding of risk factors and/or safety impacts.

At the initial steps of safety investigation, various forms of **descriptive** analysis can be applied when, for example, accident frequencies or rates are compared between various groups of units. Such comparisons provide an indication of the expected change in road safety associated with the characteristics considered. However, to evaluate a systematic safety impact of a certain feature or intervention, more complex statistical analyses should be undertaken which account for possible confounding factors (e.g. crash randomness, regression-to the-mean, variations in unit characteristics). Road safety manuals, e.g. Elvik et al. (2009), HSM (2010), explain the rules of correct safety evaluations. They also provide many examples of road safety knowledge that was produced by previous road safety research. Such knowledge can be found in two main forms:

* **Crash modification factors** (CMFs) which reflect a relative change in crash numbers or severity associated with a change in road infrastructure/vehicle/road user characteristics. CMFs should preferably be evaluated using before-after analyses;

* **Accident prediction models** which reflect quantitative relationships between road infrastructure/ vehicle/ road user characteristics and accident occurrences. Models fitted for crash occurrences on selected road types or sites are known as 'safety performance functions' (SPFs).

The European project SafetyCube provided an updated summary of recent research knowledge in road safety, with quantification of the effects of risk factors and measures related to infrastructure, vehicles and road user behaviors. The results were integrated in an innovative road safety Decision Support System[3]. For example, the infrastructure-related risk factors were structured in a hierarchical taxonomy of ten areas (covering 59 specific risk factors in total), which include: alignment features (e.g. horizontal-vertical alignment deficiencies), cross-section characteristics (e.g. super-elevation, lanes, median and shoulder deficiencies), road surface deficiencies, work-zones, junction deficiencies (interchange and at-grade), etc. (Papadimitriou et al., 2019). For that, 243 recent and high quality studies were selected and analyzed; synthesis of results was made through 39 'Synopses' on individual risk factors or groups of risk factors.

SPFs can be used for identifying high crash risk locations, evaluating road safety before and after countermeasure deployment or comparing the safety of alternative road designs. The traditional method of modeling crash counts is negative binomial (NB) regression (HSM, 2010). Recent road safety literature is rich with a **variety of modeling techniques**. For example, Farid et al. (2019) developed rural highway SPFs for a number of US states using a range of models such as: NB, zero-inflated NB, Poisson lognormal, regression tree, random forest, boosting and Tobit models. According to the transferability results, there was no single superior model type. The Tobit, random forest, tree, NB and hybrid models demonstrated better predictive performances in a considerably large proportion of transferred SPFs.

With the increasing emergence of connected vehicles (CVs) technology, there is a growing interest in developing **real-time safety models** that can utilize CVs data to evaluate traffic safety in real-time. Real-time safety models differ from traditional SPFs in two main aspects. First,

[3] www.roadsafety-dss.eu

traditional SPFs predict the number of collisions in several years, while real-time safety models can predict the level of safety, such as the crash risk or the number of traffic conflicts, in considerably shorter time periods, e.g. a few minutes. Second, traditional SPFs consider mainly the aggregated traffic flow (e.g. annual average daily traffic), while real-time safety models consider several traffic characteristics and their recurrent variation (e.g. Essa et al., 2019).

- **Surrogate safety measures**

While actual crash occurrences can be seen as the ultimate outcome measure for road safety, **safety performance indicators** (SPIs) have in recent years been taken into consideration to quantify the road safety level (Martensen et al., 2019). SPIs may include driving behavior, like speed choice or lane positioning, or characterize the quality of the road infrastructure and vehicle fleet (Gitelman et al., 2014). The SPI variables included in safety analysis are those for which there is some scientific evidence of an association with increased crash risk or severity.

In a broader sense, surrogate safety measures are applied when crash frequencies are not available because the facility is not yet in service or was in service for a short time, when crash frequencies are low or the facility has unique features (HSM, 2010). The HSM (2010) considers two basic types of surrogate measures: (1) surrogates that presume the existence of a causal link to expected crash frequency or severity (for example, the non-use of safety belts in cars), i.e. a definition similar to that of SPIs (above); and (2) surrogates based on events which are proximate to or usually precede the crash event (for example, at an intersection, the time during which a turning vehicle infringes on the right-of-way of another vehicle).

Conflict analysis techniques with measures like “time-to-collision” and “post-encroachment time” have been widely applied for indirect measurement of safety (e.g. Laureshyn et al., 2010). Figure 3 shows a pyramid of the relationship between normal travel conditions, potential conflicts, actual conflicts and accidents, that was suggested at the beginning of development of traffic conflict techniques, in the eighties. The severity score of the interaction observed is defined depending on the relative speeds, masses and space for manoeuvers of the parties involved. Currently, traffic conflict techniques are mostly based on video-recordings and can be combined with automated video-analysis (Laureshyn et al., 2016).

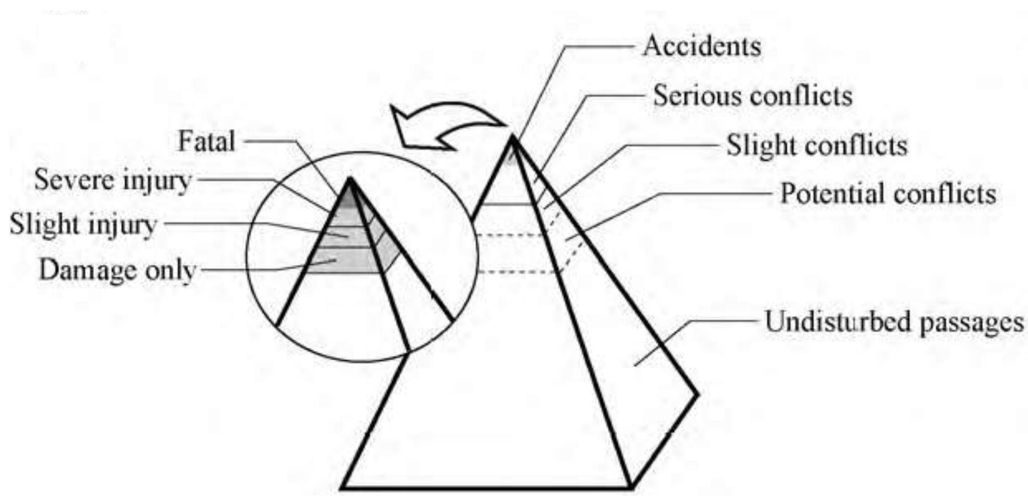

Figure 3. The pyramid of relationship between traffic conflicts and accidents (Laureshyn et al., 2010).

For the analyses of vehicle interactions at intersections, a new framework of using extreme value theory for conflict-based before-after safety evaluation was proposed (e.g. Zheng and Sayed, 2020). Using video footages, traffic conflicts on the treatment and control sites are extracted using an automated traffic conflict analysis system.

Furthermore, given the importance of understanding the driver's interaction with the road, the vehicle and the environment for preventing crashes, **naturalistic driving studies** (NDS) have been conducted over the past decades. Based on a large-scale NDS study conducted in the USA, with 3000 vehicles involved, new estimates were produced on the driver crash risk factors and their prevalence (Dingus et al., 2016).

The huge amounts of data collected by the NDS studies, drew attention to the need for definitions of various types of events. For example, Wu and Jovanis (2013) suggested a distinction between safety-related and surrogate events, while one group includes events that were traditionally examined by road safety behavioral studies and referred to as 'near crashes', 'risky driving' or 'near misses', and another group includes both 'crashes' and 'near crashes' with common etiologies to crashes. In another example, Wang et al. (2015) analyzed data from an NDS experiment in China and developed a method to quantify the driving-risk level of a near-crash scenario by clustering the vehicle braking process characteristics; they also employed a classification and regression tree for unveiling the relationship among driving risk, driver/vehicle characteristics, and road environment using the near-crash database.

In addition, road safety research studies analyze **driving events** which were produced by technology-based solutions installed in cars. For example, in-vehicle data recorders (IVDR) in cars were used to monitor and provide feedback on driver behavior. Studies of the IVDR data in Israel (e.g. Farah et al., 2014) demonstrated the driving events' contribution to the identification and treatment of driver-related risk factors.

- **Road user behavior research**

A substantial part of road safety research is based on examinations of road user behaviors (where such behaviors are assumed to be related to crash occurrence or severity, for example, speeding, crossing on red, non-giving-right-of-way to pedestrians, etc.). Such research can be based on **observations** of real traffic conditions or apply a **simulation** of the traffic environment. The latter can be used to explore the impacts of innovative solutions or those which are not yet common in traffic engineering practice.

For example, Hussain et al. (2020) used a driving simulator to investigate the effect of different innovative countermeasures on red light running and safe stopping behavior at signalized intersections. Five different conditions were tested such as: a default traffic signal setting (control condition), flashing green signal setting, red LED ground lights integrated with a traffic signal (R-LED), yellow interval countdown variable message sign, and red light running detection camera warning gantry. Drivers in each condition were exposed to two different situations based on the distance from the stop line. A series of logistic regression analyses and linear mixed models were conducted to investigate the overall safety effects of the different countermeasures. As found, the probability of red light running was significantly reduced for R-LED, while a clearly inconsistent stopping behavior was observed for the flashing green condition.

Simulation studies may apply a computer simulator (with a virtual reality environment) or a closed area for experimental vehicle running. Simulation studies are common today to explore potential safety impacts of automated vehicles (AV). For example, Jayaraman et al. (2019) conducted a human-subject study in a virtual reality environment to verify a model of pedestrians' trust in AVs based on AV driving behavior (i.e. defensive, normal, or aggressive) and traffic signal presence at a crosswalk (yes or no). Results indicated that pedestrians' trust in AVs was influenced by both factors and the trust in the AV was higher under low aggression behavior of AVs.

- **Safety impacts of vehicle automation**

Many literature sources discuss potential impacts of connected and automated transport systems (CATS). The European project LEVITATE conducted a systematic review of recent studies to develop a comprehensive taxonomy of CATS impacts at different levels of implementation. The proposed taxonomy makes a distinction between direct, systemic and wider impacts of CATS. Direct impacts refer to the operation of CATS by each user. Systemic impacts are system-wide impacts on transport. Wider impacts are societal impacts resulting from changes in the transport system in terms of, for example, accessibility and cost of transport, and impacts like accidents, pollution, changes in land use and employment (Elvik et al., 2019).

Concerning the safety impacts of automated vehicles, unlike earlier publications which promised to solve the road safety problem, the current position reflects more caution. For example, a report published by the International Transport Forum (ITF, 2018) concluded that: "It seems likely that the number of road crashes will decrease with automation, but crashes will not disappear. … Vehicle automation strategies that keep humans involved in the driving task seem risky …, the risk of unintended consequences that would make driving less safe, not more, could increase."

The LEVITATE study (Elvik et al., 2019) stated that until automated vehicles become common and make up a sizable share of traffic, it is not possible to evaluate their impacts in terms of final road safety outcomes (accidents/ injury). However, surrogate safety measures can be applied whereas they indicate the loss of safety margins. Table 1 shows a compiled list of surrogate safety measures (indicators) that can be estimated in traffic simulation studies, to assess potential safety impacts of CATS. Their use is unavoidable, as simulating accidents remains impossible (Elvik et al., 2019). However, it relied on the assumption that surrogate measures are a valid indicator of safety.

Using the indicators (Table 1), thresholds are to be set to distinguish between a traffic conflict and an undisturbed situation. For example, for a time-to-collision (TTC) indicator, a value of TTC<1.5 seconds may indicate a conflict.

In general, there is still no clear evidence on the statistical relationship between collisions and conflicts (Elvik et al., 2019). Researchers who found a strong correlation between crashes and conflicts recommend disaggregating both data sources into specific characteristics such as road type, manoeuvers or severity level (e.g. Zheng et al., 2014). It is proposed to use traffic conflicts as an indicator of the safety impacts of CATS, although the generalization of conflict results to overall crash rates requires careful consideration. The LEVITATE study (Elvik et al., 2019) provides an example of applying traffic conflicts estimated by traffic simulation of the effects of CATS-technology to produce a function describing the expected changes in the number of accidents as the market penetration of automated vehicles increases.

Table 1. Surrogate safety measures that are calculable in simulation studies, to assess potential safety impacts of CATS (Elvik et al., 2019).

Surrogate safety measure	Description of measure
Gap Time (GT)	Time lapse between completion of encroachment by turning vehicle and the arrival time of crossing vehicle if they continue with same speed and path.
Encroachment Time (ET)	Time duration during which the turning vehicle infringes upon the right-of-way of through vehicle.
Deceleration Rate (DR)	Rate at which crossing vehicle must decelerate to avoid collision.
Proportion of Stopping Distance (PSD)	Ratio of distance available to manoeuvre to the distance remaining to the projected location of collision.
Post-Encroachment Time (PET)	Time lapse between end of encroachment of turning vehicle and the time that the through vehicle actually arrives at the potential point of collision.
Initially Attempted Post-Encroachment Time (IAPT)	Time lapse between commencement of encroachment by turning vehicle plus the expected time for the through vehicle to reach the point of collision and the completion time of encroachment by turning vehicle.
Time to Collision (TTC)	Expected time for two vehicles to collide if they remain at their present speed and on the same path.
DR distributions	Deceleration rate distributions
Required braking power distributions	Required braking power distribution needed in order to avoid an accident
Distribution of merge points	How merging areas are distributed across a motorway
Merge area encroachments	Merge area layouts
Gap-acceptance distributions	Distribution of the gap acceptance of vehicles
Number of vehicles caught in dilemma zones	Number of vehicles waiting in conflict areas in a simulation environment
Speed differential between crossing movements	Speed differences during crossing movements in intersections
Speed variance	Speed variance across and among lanes
Red- and yellow-light violations by phase	Red and yellow light violations by phase in urban road networks
Time-integrated and time-exposed TTC measures	(TET and TIT— duration of time that the TTC is less than a threshold and the integrated total TTC summation during that time, respectively)

- **Driver safety support systems in vehicles**

A separate research direction can be observed in the development of in-vehicle technologies which are intended to support safe driving task performance. The developments are enveloped by the ADAS (Advanced Driving Assistance Systems) concept, which combines active systems, which may act preemptively to avoid an accident by taking control of the car, and passive systems that provide in-crash protection and notification to the rescue services – Figure 4.

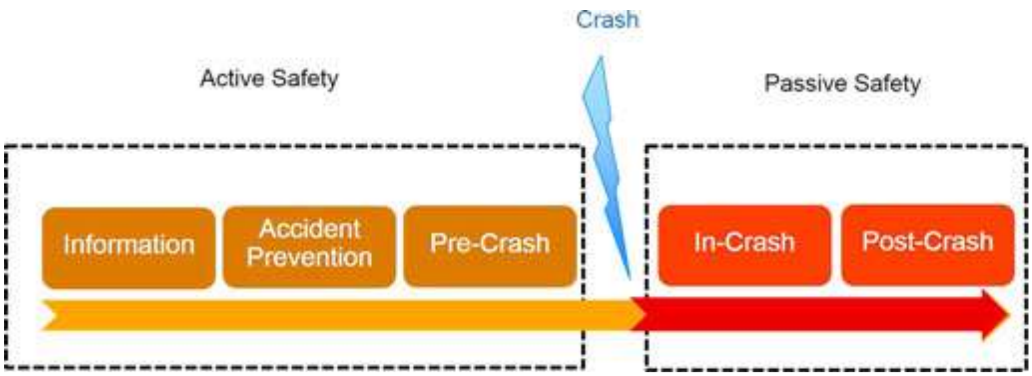

Figure 4. The ADAS concept.

For example, Koesdwiady et al. (2017) provides an overview of recent trends in the development of driver safety monitoring and assisting systems in cars which are aimed to monitor the attention status of the driver and to take the countermeasure (action) required to maintain driver safety. The new generation of driver monitoring systems is presented within the context of "Internet of Cars" - the global framework that provides a basis for "smart mobility". The concept of integrated safety is introduced, where smart cars collect information from the driver, the car, the road, and, most importantly, the surrounding cars to build an efficient environment for the driver. Based on the previous research, a taxonomy of driver sources of inattention is suggested which combines various types of driver **distraction** and **fatigue**. Various data sources can be applied and technologies can be developed to detect driver inattention and to suggest corrective actions for reducing safety risks.

4. Studies on safety impacts of recent transportation developments (examples)

As indicated earlier, research studies with a systematic overview of road safety research in the context of smart transportation developments were not found. However, some studies examined sub-topics which can be related to the field of our interest, e.g. road safety implications of recent trends in urban mobility, the place of safety impacts in sustainable development, potential safety impacts of vehicle automation, etc. Examples of such studies are given below.

- **Road safety in a sustainable urban mobility**

Castro-Nuno et al. (2017) intended to determine factors that explain the different urban road safety outcomes at the provincial level in Spain. The study was motivated by a structural change in mobility in major Spanish cities in recent decades, with a switch from the traditional Mediterranean model, in which economic and leisure activities were more concentrated in the city center, and journeys were predominantly made on foot or on public transport, to a North American city stereotype, with the migration of population to metropolitan residential areas and a higher dependence on private cars. The study developed econometric models using panel data on urban traffic accidents and fatalities in 50 Spanish provinces, while a set of economic, demographic, geographic and urban transport development characteristics served as explanatory variables.

Similar to previous research, the study found impacts on safety outcomes of the population age and density, motorization level and the level of health services. The novel findings were in that the variable that captures *Smart City status* was observed to maintain a negative and generally significant correlation in the fatalities' regression; similarly, the variable representing the availability of a well-developed public transit system (in the form of a subway and/or urban light rail system) seemed to reduce the number of fatalities. The study concluded that higher levels of urban development and greater concentrations of activities and population in large cities (as reflected in the variables of population density, hospital density, Smart City status, subway and/or urban rail availability) can result in a lower urban traffic accident rate.

- **The importance of a broad definition of smart transportation**

Anastasiadou and Vougias (2019) provide an overview of various definitions of 'smart city' and 'smart urban mobility' based on previous research, aiming to show that a narrow vision, which is limited to the application of innovative information and communication technologies (ICTs), is insufficient. Instead, smart urban mobility should be considered as a key solution to address the negative impacts of transport.

Advanced technological applications should provide innovative services relating to different modes of transport and traffic control, and enable various road users to be better informed and make safer, more coordinated and 'smarter' use of transport networks. Moreover, intelligent transport systems (ITS) should integrate ICTs with transport engineering in order to plan, design, operate, maintain and manage transport systems, improving environmental performance, energy efficiency, safety and security of road transport. A broad definition of a 'smart' urban network should embody all these characteristics. Previous experience indicated that when a smart city was more seen as a hub of technological innovation, the achievements were limited. A critical analysis of previous findings revealed that a city cannot be 'smart' without being sustainable.

To illustrate the problem of improper implementation of an ITS solution in the urban environment, the most crowded and congested street of Thessaloniki (Greece) was studied. On the street, the ITS ensured high priority of motorized traffic over pedestrians at signalized intersections, thus improving vehicle travel times, but highly extending pedestrian waiting times and minimizing green-man phase duration. This solution resulted in a significant loss of pedestrian man-hours and in an increased safety risk for them.

The researchers underline that the real 'smart' road network should address the needs of all users, including the vulnerable ones, and that the adoption of 'smart' technologies in transport sector should be done in the context of sustainable mobility. The adoption of new technologies is not the end, but the means to upgrade the quality of life in the city.

- **FERSI position paper: Safety through automation?**

Being aware of rapid developments in the area of automated driving (AD) and co-operative intelligent transport services (C-ITS), many research groups and umbrella organizations in Europe pointed to the need for addressing the traffic safety aspects of these developments. The Forum of European Road Safety Research Institutes (FERSI) undertook a study which compiled the road safety concerns raised by a working group of 20 experts on traffic safety and automation, aiming to identify areas where policy making and additional research would be necessary to achieve maintained or improved road traffic safety (Anund et al., 2020).

The experts identified 23 different traffic-safety-related concerns which were grouped into four main categories:

I. How can automated and connected driving and ITS *improve* road safety? What conditions should be met, and which actions taken? More specifically: How to ensure that AD and ITS development incorporates relevant and appropriate safety and human factor considerations? How to adapt and develop in-vehicle technology as well as urban and non-urban infrastructure, so that AD and ITS enhancements lead to substantially increased safety levels?

II. Which road safety issues will likely *not* be solved by AD, connectivity and ITS? In particular, are there groups of road users which *could* benefit from AD and ITS, but are unlikely to do so unless special action is taken? (e.g. vulnerable road users)

III. What road safety issues may be *caused* by AD, connectivity and ITS? What actions can be taken to avoid this? (e.g. maintaining attention, hand-over situations, mode confusion, training needs; transition phase with vehicles' mix)

IV. How should *testing, certification and validation* methods be adapted and how should *"best performing"* AD/connected systems and ITS *best practices* be identified?

Furthermore, a set of ten principles was formulated, intended to guide decision-making, research and, possibly, legislation in the area:

1. **Human Factors at the core** - "Human-Centred Design" shall be put at the core of development to prevent new risks.
2. **All potential user profiles** - Drivers of all types, backgrounds and ages should be catered for by systems designed to experience automation as safe and comfortable.
3. **Safety in mixed traffic** - to adapt infrastructure, vehicles and driving education, to reduce safety risks caused by mixed traffic (automated and non-automated).
4. **Safe communication between automated vehicles and providers of services** - must be established and maintained to ensure safe interaction between all types of road users and the connected road environment.
5. **Safe communication between all road users** - partially and fully automated vehicles, vehicles and other road users.
6. **Safety and automation benefits for vulnerable road users** - specific connectivity or detection-based solutions are to be developed to increase the safety of these groups.
7. **New training & testing** - all drivers are to be well trained, tested, and licensed, in order to cope with driving in modes with different levels of automation.
8. **New tests & tools** - both virtual and physical, are to be set to cover the comprehensive set of scenarios needed to evaluate, validate, and certify automated systems.
9. **Policy mechanisms for incorporating safety considerations** - are to be set to ensure that AD development takes safety and human factor considerations into account.
10. **Impact assessment** - evaluation methods and models are to be established to measure the impact of AD, and information from crashes and vehicles should be available to impartial research for the sake of further improving safety.

5. Suggested directions of road safety research, to promote smart transportation

In general, previous research did not show examples of a direct impact of ICT solutions on road safety. A broad definition of 'smart' transportation is needed to ascertain safety impacts. Various evaluation frameworks are possible in this context.

Accounting for the background developments in the transportation system, current safety needs and research progress, the future directions of road safety research, to promote smart transportation, can be suggested as follows:

- Development and evaluation of smart transportation solutions to enhance the safety of vulnerable road users – pedestrians, cyclists, motorcyclists, elderly, children, etc. (in response to the current needs).
- Assessing safety impacts and promoting safer integration in the transportation system of new transport means, e.g. micro-mobility tools, new types of motorcycles (L-vehicles), etc.
- Development and evaluation of advanced technology solutions to mitigate road user errors, e.g. driver fatigue, road user distraction, etc.
- Development and evaluation of innovative solutions, both single and system-wide, to enhance safety at the points of interaction of various road users, e.g. at signalized intersections.
- Safety impact assessments of macro-changes in the transportation system, e.g. promoting public transport, walking and cycling in cities; infrastructure changes in the road network to increase high-occupancy travel, etc.
- Safety impact assessment of smart transportation developments.
- Exploring the relationships between road user behaviors, critical safety events (e.g. "near accident" situations, traffic conflicts) and accident occurrences, in various transport environments (to enhance the theoretical background for using surrogate indicators in road safety evaluations of smart transportation solutions).
- Studying the safety challenges and technological solutions for human operator (drivers) in their interaction with AV systems, at various stages of transition to automation.
- Studying the safety challenges and technological solutions for AV systems, in their interactions with various transport environments, vulnerable road users, etc.

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