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Thinking about the history of road safety research: Past achievements and future challenges ☆

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ABSTRACT

This paper surveys the developments in road safety thinking and road safety research over the last century. It details the general evolution of safety thinking as it applied to road user behaviour, vehicle and road design. More recently, emphasis has shifted towards a system's approach, both in road safety activities and in road safety research. In terms of the future, more likely scenarios for the near future, a few decades from now, are explored and the implications for future road safety research are discussed. In particular, increasing urban density forces changes in travel modes, with a shift to public transport, more cycling and walking, and, thus, imposes new challenges for road safety research. In terms of vehicle technology, more automation and driver assistance systems are envisaged with an accompanying emphasis on evaluation and research, including the issue of behaviour adaptation. Speeding and population ageing will remain major research areas. Increased interest in techniques for exploring large databases, behaviour indicators and randomised experimentation is expected.

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1. Introduction

Over the last decades, a remarkable decrease in road traffic fatalities was observed in many motorised countries, particularly during the 2000s (COWI, 2010; OECD & ITF, 2011). Substantial progress in reducing road safety tolls was attained in the old developed countries (Western Europe, US, Japan, Australia and New Zealand) but also in other countries that passed through a phase of rapid motorisation since the 1990s (e.g. Eastern European countries). Progress in road safety is usually attributed to the implementation of countermeasures related to infrastructure, vehicle and road user behaviours and examples of those are summarised in best practice manuals (e.g. OECD, 2008; Peden et al., 2004). More rigorous analyses carried out in selected countries demonstrated statistical relations between casualty reductions and road safety engineering measures, improved crashworthiness in cars, compulsory seat-belt wearing, drink-driving interventions, speed enforcement, etc. (e.g. Broughton & Knowles, 2010; Chapelon & Lassarre, 2010; Weijermars & Wegman, 2011). Similarly, the evaluation studies of road safety measures and their systematic reviews (e.g. Elvik, Hoya, Vaa, & Sorensen, 2009a) establish a sound background for future applications of various road injury prevention measures as well as for knowledge transfer to other countries.

In spite of the progress achieved, the road safety problem is far from being solved. Traffic accidents[2] still represent a serious public health problem. According to global estimations, by the year 2030, road accidents will reach fifth place among

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[2] "Accident" and "crash" terms are applied interchangeably in this paper as both terms are common in the road safety literature.

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the leading death causes in the world (WHO, 2013). Recent data show that over 1.2 million people die annually as a result of injuries from traffic accidents, while another 20–50 million people sustain non-fatal injuries (OECD & ITF, 2011; WHO, 2013). In Europe, an ambitious target of halving the number of road fatalities by 2020 was set (EC, 2010), whilst throughout the world road safety was recognized as one of the urgent issues needing international collaboration (WHO, 2013).

According to recent estimates (OECD, 2008), in spite of a substantial increase in motorisation level over the period of 1970–2005, a more than 50% decrease was observed in the fatality rates of the best performing countries. Concerning the possible contribution of road safety research to that progress, it was demonstrated by Elvik, Kolbenstvedt, Elvebakk, Hervik, and Braein (2009b) that road safety measures based on the findings of research projects have made major contributions to reducing the number of road accident fatalities in Sweden. Among the accident reducing factors that were substantially based on research, were mentioned, for example, the installation of median guard-rails on undivided roads, increased use of child restraints in cars, enhanced neck injury and side impact protection in cars. Schulze and Kossmann (2010), demonstrated the role of road safety research in Germany, by means of establishing road safety management tools that serve for explaining reasons for safety deficits, fitting evidence-based measures, assessing safety impacts of selected interventions and continuously controlling for progress of the national road safety plan. It seems that road safety research played an essential role in the road safety progress attained so far.

The changing environment of the road transport system imposes new challenges on road safety research. As the effect of traditional road safety measures is exhausted, to a certain extent, at least in the developed countries, it can be argued that new approaches are required to reduce the number of road accidents and injuries further. In this context, for example, Johnston (2010), Navestad and Bjornskau (2012), suggest to explore the potential of the "road safety culture" concept coming from the neighbouring fields of public health and occupational safety. In general, more system-based approaches and theories are promoted today concerning road infrastructure improvement, e.g. safety impact assessment (EC, 2010), road safety management (e.g. ISO, 2012) or road safety policy, in general, such as Sweden's Vision Zero (e.g. Belin, Tillgren, & Vedung, 2012).

Moreover, following the rapid development of in-vehicle electronic devices and intelligent transportation systems, further efforts are needed for systematic evaluation of benefits and dis-benefits of those, with further acceleration of the deployment of systems with proven safety potential (EC, 2010). On the other hand, among urgent safety problems drawing more attention from authorities and researchers, today, can be mentioned, for example, vulnerable road users – pedestrians, motorcyclists and bicyclists, young drivers' involvement in road accidents, the elderly's needs (EC, 2010; Wegman, Zhang, & Dijkstra, 2012; Zegeer & Bushell, 2012).

The motor vehicle and motorised transport have been with us for more than a century and during this period major developments have occurred both in vehicle technology and in changes to the transport system. Road safety research started more than eighty years ago, due to the practical needs of dealing with increasing numbers of road traffic casualties. One of the early documented research studies on accident proneness was carried out in 1929 (Farmer & Chambers, 1929). Over the decades, essential changes took place in the road transport systems of the developed countries, including population and motorisation growth, expanding and improving the quality of the transport network and significant improvements in car crashworthiness. The paper will follow some of these changes and the accompanying evolution in road safety research that went along with it, where it is mostly focused on the highly motorised world, i.e. North America, Europe and Australia. Based on a longstanding acquaintance with both road safety thinking and road safety research over a period of about sixty years, this paper presents an attempt to foresee certain directions in future road safety research.

Furthermore, in view of the major changes that are occurring in the transport system over the last decades, such as trends in urbanisation and population density, a shift from four-wheeled individual motorised transport towards more reliance on public transport, increased use of cycling and walking, the fast-going changes in vehicle technologies up to possibly autonomous vehicles, the idea of this paper was to explore the implications of those developments on future road safety research.

When writing about the future, one is always on unstable ground. First, one has to define what future one has in mind. In our case, it is not the Heinlein and Asimov kind of future, a few millennia from now, where we believe that almost anything is possible, limited only by one's imagination. It is also not the future a hundred years from now. Even then one could think of scientific breakthroughs, natural or human made disasters which could bring about fundamental changes in life, as we know it, and the transportation and communication systems that might go with it. In order to remain somewhat realistic and, hopefully, more accurate, we limit ourselves to the next few decades. Our consideration is not intended to be all encompassing and by its nature presents a somewhat personal view.

2. Road safety thinking in the past

2.1. Periods of road safety thinking

Before going into future directions of road safety research, it is reasonable to explore the development of road safety (RS) research in the past. Considering the history of RS developments, various perspectives can be found in the literature. Fig. 1 provides an overview of the descriptions of RS history that were found in three sources: OECD (1997), Wegman, Johnston, Kroj, and Pain (2007) and OECD (2008), and set on the same time-line. It should be noted that they reflect mostly the progress of the developed countries.

Time line

Perspective of consideration	Early years of motorisation	1950-1960s	1970-1980s	1990s	2000s
Road safety management (OECD, 2008)	n/a	Focus on driver interventions	Focus on system-wide interventions	System-wide interventions, with targeted results and leadership	Safe-system approach
Road safety research paradigms (OECD, 1997)	Vehicle control; descriptive research ("what")	Mastering traffic situation ("why"); research around the classical 3E's Engineering, Education, Enforcement	Managing the traffic system ("how"); mathematical models; cost-benefit analysis	Managing the transport system; multi-dimensional analysis	Cross-disciplinary analysis; theory development
Main road crash causes (Wegman et al., 2007)	Crashes as a chance phenomenon	Crashes are mono-causal; Crashes caused by the crash-prone	A combination of crash causes fitting within a 'system approach'	The road user is the weak link: more behavioural influence	Better implementation of existing policies; Systems' management perspective

Fig. 1. Periods of RS research, according to various perspectives.

OECD (1997) distinguished four phases in the history of RS research, with four main paradigms: a description of *what* is happening; an initial period of systematic research aimed to understand *why* accidents occur; a further development of the system's approach focusing on *how* accidents occur and then, extension of the consideration scope to the transport system *as a whole* aiming at a more fundamental understanding of the RS phenomenon to support more radical and evidence-based interventions. With a successive widening of the views, RS research models became more complex and multidisciplinary.

Wegman et al. (2007) and OECD (2008) suggested another description of RS evolution, focusing on major accident causes as those that were internationally perceived at certain time periods, or on the modes of road safety management thinking, respectively. A common line of both perspectives is that the development passed from an initial stage of blaming a human as the main contributory factor in the majority of traffic accidents, with a consequent focusing of interventions on changing human behaviour, to understanding the complex character of the RS phenomenon and a need for a system-wide approach.

Human action is a contributory factor in over 90% of road crashes as was demonstrated, for example, by Treat et al. (1979). However, when crashes were viewed simplistically as having one primary cause, the principal emphasis of road safety measures was on improving road user behaviour, with a clear tendency to be punitive. Road safety research demonstrated the importance of the interactions between road, traffic and vehicle features and particular types of road user behaviours in generating road accidents and fitting respective countermeasures. Over the last decades, a lot of information has become available about the efficiency of various road safety interventions (e.g. Elvik et al., 2009a), enabling to select solutions using evidence-based or research-based platforms. However, the sentences stating that poor road user behaviour is a main cause of road accidents and, as such, should be modified to create a culture of safe road use, still can be found in policy reports on road safety and while superficially appealing, have held back road safety progress (Wegman et al., 2007). Moreover, according to Johnston (2010) such a perception of the primary role of human errors or mis-behaviour in causing road accidents presents a prevailing community culture around road safety that needs to be changed.

Recently, a new paradigm termed *Safe-system* was introduced representing best practice strategic thinking in road safety (OECD, 2008). It builds upon the Swedish Vision Zero strategy (Tingvall & Haworth, 1999) and the Dutch Sustainable Safety concept (Wegman & Aarts, 2006). This paradigm starts from two observations: (a) the current traffic system is inherently dangerous and (b) intensifying current efforts on implementing road safety interventions could lead to fewer casualties indeed, but not to substantially safer traffic. Thus, a shift in RS thinking is needed aiming to create a road traffic system with inherent safety features, which will be tolerant to human errors and mitigate their consequences.

More examples on the role of human factors, vehicles' and road design in road safety as supported by the history of road safety research, are elaborated below.

2.2. The role of human factors: the early days of motorisation & accident proneness

In the early days of motorisation, the first twenty years of the 20th century, most attention was focused on the driver. Initial focus was on traffic law enforcement and publicity and some activity in the field of vehicle inspection. In terms of research most of the attention was on the accident circumstances and the application of basic statistics to accident analysis (OECD, 1997). This period was mostly characterized by the notion that drivers are to blame for their accidents and the emphases in road safety prevention and research were on enforcement, corrective driving behaviour, identification of "accident-prone" drivers and in the field of highway design on treating hazardous locations and developing design standards.

From the 1920s, in addition to the fields described above, attention shifted to basic statistical models on drivers' involvement in accidents and the term of accident proneness came into being, together with first attempts to devise screening methods for the identification of such drivers.

One of the more authoritative books written on the subject in 1971 (Shaw & Sichel, 1971) provides an extensive review of the field of accident-proneness.

By the 1970s the road safety research field seemed to have split into two distinct groups. The first group, mainly coming from the United States and with a strong statistical background, felt that, on statistical grounds, the notion of accident proneness had not been proven beyond reasonable doubt. Their interest shifted away from an attempt to mostly blame the drivers for their accidents and to search for certain groups of drivers that could, through a series of tests, be isolated and blamed for a higher than expected number of accidents. Attention of researchers from the US initially shifted towards the vehicle industry and resulted in the first safety legislation to make vehicles safer. In this respect, the book by Haddon, Suchman, and Klein (1964) was very influential. On the other side, groups of researchers, many of them psychologists and many from Europe continued to hold onto the notion of accident-proneness.

In practice, it has proven to be very difficult to isolate individual drivers or groups of drivers having a ''higher than expected'' number of accidents. Whereas it seems likely that certain individuals, or groups of individuals, have a higher than average likelihood of being involved in an accident, one first has to establish reliable statistical tests to identify these groups, having corrected for various possible intervening variables, such as distance travelled, driving environment, type of vehicle driven and type of occupation. Assuming that these groups or individuals can be reliably detected, one could then think of training programs to improve behaviour. The notion that such groups or individuals can be removed from the driving population is not a notion that can easily be supported in a democratic society.

To give an indication of how limited the scope of this issue is, Table 1 is presented which comes from a recent study on the issue of interaction between accident involvement and social background (Factor, 2008). It can be seen that the large majority of drivers involved in injury accidents in Israel (82.6%), have one injury accident (reported to the police) over a twenty-year period. A certain amount, another 13.6% of drivers have two injury accidents. Drivers with three or more injury accidents constitute only about 5% of the population. These data do not account yet for a variety of confounding factors. Even, unfairly, removing all these drivers with three or more injury accidents in twenty years of driving, would still leave us with 95% of the problem.

It is a different situation when it comes to select professional drivers for a commercial company. Assuming that supply exceeds demand, it is, in principle, possible to devise tests which screen out drivers with a possible tendency to be over-involved in crashes. Such tests normally have a low validity and would also screen out a fair number of perfectly acceptable drivers. It would however be acceptable for such a company to select such drivers for exclusion.

Much more recently, new theories have been introduced into the field of driver behaviour. In 1982, Wilde introduced his theory of risk homeostasis (Wilde, 1982). This was later expanded on and modified to become the field of behavioural adaptation (Rudin-Brown & Jamson, 2013). These topics will be dealt with in some detail in Section 3.7

2.3. Road design and safety

From the early days of motorisation, highway design standards evolved and design manuals were introduced. Elements with a strong safety background, central to highway design, include driver reaction time, sight distance needed to avoid

Table 1
Distribution of the number of injury accidents per driver, in Israel, during the years 1983–2004 (Factor, 2008).

No of accidents per driver	No of drivers	% of drivers
1	452,519	82.6
2	74,770	13.6
3	15,156	2.8
4	3,814	0.7
5	1,075	0.2
6	380	0.1
7	168	0.0
8	75	0.0
9	38	0.0
10	19	0.0
11	9	0.0
12	4	0.0
13	2	0.0
14	2	0.0
15	1	0.0
16	1	0.0
17	3	0.0
Total	548,036	100.0

obstacles, assumptions on travel speed and braking distances. The underlying assumption, held by many highway engineers and officials, was that, according to Hauer (1999):

a. Roads designed to meet current standards are as safe as they can be, or
b. Roads designed to meet current standards are as safe as they should be

Hauer makes a strong case refuting these arguments and illustrates this, amongst other examples, by a detailed description on the evolvement of vertical crest curve design. On such curves, the sight distance is limited by the shape of the curve. Design standards calculate the distance required for a safe stop (the ''stopping sight distance''), assuming the height of an obstacle, vehicle speed, the grade of the road, driver reaction time and the friction coefficient between the tires and the road. Obstacle height was initially set at 4 in (as early as 1940), rumoured to correspond to the height of a ''dead dog''. When, in the 1950s it became apparent that in newer vehicle models the driver's eye height was much lower than a few decades earlier, the implication was that vertical crest curves had to be built with larger radii with all associated costs that such a move incurred. Another serious implication was that most crest curves designed to the earlier eye height, had now become ''substandard''. In the AASHTO design manual of 1965, the obstacle height was conveniently changed to 6 in.

At no stage was there any documented evidence on research conducted between crest curve radii and accidents to come to evidence-based conclusions on the desired obstacle height for planning. Recent literature reviews on the subject have not been able to establish links between the risk of collisions with small objects and available sight distance (Hauer, 1999).

Similar logic was also applied at the time to set design standards for other road elements. In addition, many road design aspects, such as side slopes, obstacles near the shoulders, road lighting were not generally part of the road design standards, but had a significant effect on the accident rates.

It is now known that many roads, although designed according to standards, are not as safe as they could be and procedures such as safety audits and road safety inspections have been introduced to improve the safety of roads, even those designed according to standards (e.g. Belcher, Proctor, & Cook, 2008). Moreover, following the European Directive on promoting management tools supporting safer road infrastructure (EC, 2008), a system-wide and more pro-active approach for managing road infrastructure becomes more common today. Further research is being conducted aiming at the development of tools which would satisfy various field demands (e.g. Laurinavičius et al., 2012).

Over the last decade substantial efforts were undertaken both in the US and in Europe in order to enable more explicit consideration of road safety implications while certain design elements are selected for new or existing roads. Summaries of empirical findings and tools on the topic were given, for example, by the Highway Safety Manual (HSM, 2010) in the US and by the Road Safety Manual (PIARC, 2003), prepared by World Road Association. Elvik et al. (2009a) remains a major international source of knowledge concerning safety effects of various road infrastructure improvements.

In addition, the topic of self-explaining roads is being promoted over the last decades aiming to diminish a gap between the intentions of road designers who select certain road characteristics and the perception by vehicle drivers who use those roads (Theeuwes, Van Der Horst, & Kuiken, 2012). Following decades of road safety research, it seems that a major switch has occurred in relation to human behaviour where road design characteristics are considered, as the design solutions now account more for the limitations of human beings. This can be seen, for example, in providing forgiving roadsides that became common place in road design guidelines of many countries (e.g. AASHTO, 2011).

2.4. Vehicle design and safety

Until the 1960s it was generally assumed that vehicle designers and manufacturers were designing safe vehicles. Most of the accidents that occurred were blamed on driver errors, mistakes and violations of the traffic laws. The whole legal system and the police investigative system are till this day mostly designed to assign blame to the drivers involved in an accident and to determine the appropriate section of the law. Some attention has always been paid to the mechanical investigation of the vehicles involved in a crash, but more for the establishment of faulty parts, e.g. brakes, lights, the steering mechanism, which can then, in turn, be blamed on the driver.

As late as 1952, Charles Wilson, head of General Motors (GM), uttered the famous quote: ''What is good for the country is good for GM and vice versa''. This was later, on many occasions, misquoted as ''What is good for GM is good for the USA''. In the 1960s two events took place in the USA which altered the balance between industry and government. In 1966 the National Highway Traffic Safety Administration (NHTSA) was established by the US Federal government and was put in charge of vehicle safety regulation. Its first director was Dr. William Haddon, who had previously co-authored the book ''Accident research: Methods and approaches'' (Haddon et al., 1964). Haddon also introduced the famous Haddon matrix which was one of the first attempts of system's thinking applied to road safety, away from single cause analysis and blame apportioning. It was through the legislative efforts of NHTSA that vehicles became much safer. Regulations regarding door closure mechanisms, preventing occupants being ejected during a crash, collapsible steering columns, the elimination of sharp objects inside the vehicle compartment, frontal crash absorption capacity during the crash, side impact resistance are all part of current vehicle safety legislation. This progress is nowadays tested in various parts of the world through the NCAP programs in the US, EuroNCAP in Europe and AusNCAP in Australia.

At about the same time, Ralph Nader published his book ''Unsafe at any speed'' (Nader, 1965), which contained an all-out attack on the motor-vehicle industry, claiming that they knowingly disregarded safety and produced vehicles with safety faults they knew about. The book was very influential in awakening public opinion and, in fact, supported the activities of NHTSA.

A more sinister trend associated with the large vehicle industry in the US was described by Snell (1974). Apparently, through the 1930s till 1950, National City Lines, a company sponsored and funded by GM, bought more than 100 electric surface-traction systems in 45 cities in the US, to be dismantled and replaced with GM buses. In 1949, GM and its partners were convicted in a US court of criminal conspiracy in this matter and were fined.

The use of streetcars in the US (what we would nowadays call trams or light-rail) declined from 72,911 in 1917 to 17,911, in 1948. The annual number of streetcar rides declined from 15.7 billion in 1923 to 8.3 billion in 1940. It has taken over seventy years to reach the current stage with a revival in rail and bus-based urban mass transport systems, to partially overcome the problems of congestion, pollution, lack of parking space and degradation of the inner city.

The history of the demise of public transport in the US in the 1930s, as depicted above, has been contested in a recent book by Mees (2010). According to Mees, the problems of the tramway industry in the 1920s, including increasing competition from the private cars, jitneys and a lack of funds for investment, came about because these transit companies in the US were almost all privately owned and chronically lacked funding.

On the subject of safe vehicle design and legislation, it became quite obvious that safe vehicle design and the introduction of safety devices in vehicles could not be left to the manufacturers. For a long time, seat belt systems were not optimally designed, initially advocating the use of lap-only belts, or lap-belts with detachable shoulder straps (only in the US). Automatic seat belt systems, although they technologically became known around the 1980s were opposed by most of the industry. The airbag was invented in 1951, it was installed in some US vehicles as early as 1973, but it took until the 1990s for them to become standard equipment on many vehicles. Similar opposition occurred more recently with the introduction of centrally high-mounted rear brake lights, which have proven beneficial in reducing rear-end collisions (Somers & Hansen, 1984). Over recent years it has become obvious that improved safety cannot be left to the vehicle industry alone, government intervention is needed and, indeed, widely occurs now in the US, Europe, Japan and Australia. All along this path, road safety research has accompanied vehicle safety legislation and has provided the evidence for new standards and automotive legislation.

2.5. The system's approach

In the 1960s and 1970s many road safety researchers and some of the decision-makers started to realise that the mono-causal approach was not helpful. One of the earliest thinkers along those lines was the above mentioned William Haddon. In addition to his book (Haddon et al., 1964), Haddon also developed his well-known matrix concept, describing the accident as a short sequence of events before, during and after the crash, wherein countermeasures can be sought applying to the human, vehicle and road elements involved in such a crash. The concept turned away from seeking blame towards seeking counter-measures to prevent accidents.

One of Haddon's favourite analogies was to compare the road safety industry to other industrial processes. In industrial safety, when accidents occur, the situation is analysed and counter-measures are sought. It is possible to suggest training courses for employees but these should first be evaluated as to their effectiveness. Similarly, improvements can be sought in the safety of the industrial processes by, for instance, making floors more skid-resistant so that workers do not slip (instead of explaining to them that they should walk carefully), or making machines more fail-safe by introducing safety systems that need, for example, operation by two hands before a press, or cutting knife, is activated, again instead of having employees pass training courses. This line of thinking was the underlying philosophy of the vehicle safety regulations which eventually made cars so much safer. In a way similar to the ideas of industrial safety, Haddon suggested treating crash injury through "packaging" the car occupants and creating a safer environment. Unfortunately, this approach has its limitations. We have not yet found ways to safely "package" vulnerable road-users such as motorcyclists, cyclists and pedestrians. The car industry has progressed in making car fronts somewhat less aggressive towards pedestrians in low speed crashes but many more and different ways should be found to make modern society safer for these road users.

One of the more amusing examples of early system thinking in road safety was provided in Haight (1973). Haight describes a fictitious example of a bridge that was built but where, for various cost-cutting reasons, it was decided to build the bridge without bridge railings. This made the bridge much lighter and also saved the costs of the railings. Once opened to traffic, it was not surprising that there were a considerable number of cars driving over the bridge's side and falling into the river below. A permanent 24 h rescue service was established on the site rescuing people who had fallen into the river. An accident investigation team, researching the accidents, concluded that almost 90 percent of the accidents were associated with driving errors, a large percentage was associated with prior alcohol consumption, reckless driving, too high a speed according to conditions, etc. Only a small percentage was associated with roadway conditions and vehicle failure. The authorities together with a large public relations firm developed a publicity program, sponsored by a tyre maker and a large safety foundation, called DRILL: "Driving right is living long". At about the same time a contract was awarded to a small University team who, somewhere in their 237 page long report suggested the erection of safety railings. This solution was rejected, because it turned out that the study was ordered by the Department's Road Safety Division who, as it turned out, did not have jurisdiction over the Bridge Authority, who was responsible for bridge railings.

System's thinking has been the preferred way of thinking since the 1970s and continues till the present days (see Section 2.1). It suggests analysing accidents in a multi-disciplinary manner, looking at the accident circumstances and suggesting cost-effective ways to prevent such accidents in the future. The issue of blame apportionment, although still a major element in road safety work, is regarded more for the sake of maintaining law and order and achieving a normative way of behaviour. However, it is not necessarily associated with developing the most cost-effective countermeasures.

Over the past twenty years the notion is spreading that road accidents cannot be accepted as a necessary unwelcome by-product of motorisation and mobility. This has lead countries to develop national road safety plans, with quantitative targets for reducing the number of fatalities over time (OECD, 2008). Moreover, recognizing that human errors are unavoidable and, therefore, a road traffic system should be created with inherent safety features which would enable to mitigate the consequences of those errors, a new level of system thinking in road safety was introduced. Among the first countries to suggest this approach were the Netherlands (Wegman & Aarts, 2006), where the notion of a sustainably-safe system was developed, and Sweden which suggested the Vision Zero (Belin et al., 2012; Tingvall & Haworth, 1999). Australia followed with the development of the Safe-system approach that is currently a general concept promoted in the developed countries (OECD, 2008).

Under these concepts the State is responsible for providing a basically safe roadway system, industry is responsible for providing safe vehicles and the road user is responsible for behaving in a basically safe manner. To achieve this concept, roads are being built to a safety standard that makes it very difficult to create situations in which the outcome of a crash will be fatal or cause serious injury. The authorities also apply enforcement to achieve "normative" behaviour. In the future, it should be possible to replace a large part of enforcement, by self-enforcing systems, e.g. Intelligent Speed Adaptors, or other kinds of self-enforcing solutions.

3. Future directions in road safety research

Having recalled the developments that have led to the current state of advancement in road safety, one can now ask what future trends can be expected and what the implications are for future road safety research. We would like to consider future needs in road safety research accounting for trends mostly in three fields: urban development, demographic changes and advancements in intelligent transportation systems.[3] Doing this, we focus on the *more likely scenarios* to evolve in the coming few decades, leaving aside the less likely scenarios of revolutionary changes in the transportation system, such as completely autonomous cars being the majority of vehicles (e.g. Fagnant & Kockelman, 2013), or radically different forms of urban design, such as "compact city" described in Dantzig and Saaty (1973).

3.1. Greater reliance on public transport, walking and cycling modes

In the countries with high levels of motorisation, the age of overwhelming fascination with the car seems to be coming to an end. In many countries, the limitations of continued increases in individual motor-vehicle transport and its many unwelcome side-effects are coming into focus. In addition, the growing urbanisation cannot be ignored, where by 2050 the share of the world's population living in cities is expected to have risen to around seventy percent (Franklin & Andrews, 2012). A significant increase in urban density is to be foreseen, associated with a greater reliance on public transport, more cycling and walking.

Although in most countries and cities, those transport modes are not yet seen by the public as an appealing alternative, many examples already exist indicating that this can happen. In cities like Amsterdam, Zurich and metropolises like London, New York and Paris a majority of trips are already undertaken by public transport, certainly during peak travel hours. The town of Hasselt, in Belgium, was one of the first to introduce free public transport in 1997. Although some cycling trips converted to public transport, overall public transport increased tenfold and even cycling increased (Van Coeverden, Rietveld, Koelemeijer, & Peeters, 2006). In some countries, like the Netherlands, Belgium, Germany and Denmark, cycling is a significant transport mode (for example, in the Netherlands, 26 percent of all trips are made by bike – EC, 2011), and walking has always been a significant, albeit neglected, transport mode everywhere.

A shift towards a more sustainable transport system will have to reduce the amount of private car use and rely more on public transport, more cycling and more walking. With regard the road safety implications of these developments, a number of questions can be raised. First, it is not obvious, and has not been researched much, what the net impact on safety will be. On the one hand, fewer cars on the streets would reduce the accident risk due to lower exposure, but on the other hand, more vulnerable road users may increase the injury risk per accident occurrences. Elvik (2009) explored this phenomenon using a non-linear relationship between exposure and injury risks for pedestrians and cyclists, and demonstrated that for very large transfers of trips from motor vehicles to walking or cycling, a reduction of the total number of accidents is possible. Similarly, Wegman et al. (2012) reviewed the means of making cycling safer and concluded that more cycling not necessarily increases the number of fatalities and that proper infrastructure solutions may prevent negative safety implications.

Secondly, in order to encourage these newer transport modes, systems will have to become more integrated and solutions for these integrated systems will have to be safe. Whereas public transport, especially rail-based transport, is a relatively safe

[3] As we pointed out in Section 1 the paper does not pretend to cover all future trends and their possible impacts on safety and safety research. For example, the field of transportation logistics and possible changes in goods transport, are not covered, neither are the possible changes in inter-modality with other transport modes such as rail, aviation and water transport. Similarly, the possible developments in the use and safety of powered two-wheeled vehicles and of alternative personal mobility devices (scooters, e-bikes, quadricycles, etc.) are not considered.

mode, the total safety of a "door-to-door" trip of "walking-public transport-walking", when compared to a car trip, depends on the inter-modality and the safety of various elements of the infrastructure. There is a role here for road safety research in the context of urban and regional planning, evaluation research and risk assessment studies. In many cases the methodologies for such complex research have not been worked out, yet a number of recent studies tried to throw light on the phenomena. For example, Schepers and Heinen (2013) quantified the road safety impact of a modal shift from short car trips to cycling in Dutch municipalities by means of development of accident prediction models. Duduta, Adriazola, Hidalgo, Lindau, and Jaffe (2012) demonstrated a relationship between the design choices made in the planning of a bus rapid transit or busway corridor and the risks of crashes and injuries around the facilities, using accident statistics from a number of big cities throughout the world.

3.2. The introduction of driver assistance systems

In the near future, it is not foreseen, that the world will massively convert to automatic individual travel, yet, in view of the very rapid developments in in-vehicle electronics and V2X systems (Fagnant & Kockelman, 2013), it is likely that more limited-scale implementations of autonomous vehicles will be developed. On the other hand, the widespread introduction of a large variety of driver assistance systems is an almost foregone conclusion. The evaluation and impact of such systems on road safety is becoming a major research issue. Also, the introduction of more and more electronic systems, not directly related to safety, such as navigation systems, smart mobile phones, mobile in-vehicle information systems, all have serious implications on driver behaviour and road safety, not all of them positive. Distracted driving and especially the effects of cell-phone use while driving have become a major cause of concern and have attracted a massive amount of research (NHTSA, 2012). To date, there is only a limited amount of evaluative research on the direct safety impacts of these additional electronic devices.

Some of the new technologies coming on the market these days make it possible to study, in detail, how drivers are behaving under normal driving ("naturalistic driving") and during crashes; these technologies fall under the names of In-Vehicle Driver Recorders (IVDRs), "black boxes" and crash recorders. In the phase of development we are in now, these technologies have to be assessed in the context of research. First, research questions need to be defined for which these technologies can be helpful (e.g. Hallmark et al., 2011). In a second phase, the technologies can be applied in intervention programs and their effectiveness can be assessed. For example, IVDRs can be used to assess driver behaviour, with and without the boxes installed, to examine the effects of various intervention programs of reporting to drivers and/or fleet managers on driver behaviour and so on (e.g. Toledo, Musicant, & Lotan, 2008). Lane-keeping and following distance warning systems can also be evaluated as to their effect, initially on driving behaviour and later on accident involvement.

In addition to the technical and technological questions that arise from the introduction of such technologies, there are many associated ethical and legal issues that arise. The questions of public acceptance, privacy of the data collected, and legal responsibility of the agency operating such a system are all as yet unsolved and need to be addressed.

3.3. Driver behaviour adaptation

A major research issue associated with these developments, but larger in scope, is the issue of behaviour adaptation. The issue was first systematically developed by Wilde (1982, 1994), in his risk homeostasis theory. Whereas the original risk homeostasis thesis, both on the individual and on the societal level was not widely accepted and was never convincingly proven, it did lead to the widespread acceptance of the concept of behaviour adaptation. This applies not only to the introduction of new technologies but also to the application of more conventional road safety measures.

For example, Smiley (2008) recently addressed this issue, where she described the initially unexpected effects of a number of road safety interventions. The effect of post-mounted delineators, providing improved guidance at curves on 80 km/h roads, caused an increase of speeds at night and a significant increase in night-time crashes. Similarly, the installation of raised pavement markers on undivided highways and freeways was associated with a significant increase in crashes when installed on sharp curves. The implication is that the improved guidance is used by drivers to increase their speed and this can lead, in some instances, to increases in accidents.

Other unintended effects can be associated with other kinds of interventions. Camera enforcement of driving through red lights has been proven to have a positive effect on the number of accidents at intersections. It has, however, also been demonstrated that their introduction is generally associated with an increase in rear-end accidents, because of an increase in sudden braking moves. Similarly, the introduction of a two-second blinking green phase, indicating the end of the green phase and thus supposedly providing the drivers with additional useful information, was proven to be associated with an increase in, mostly rear-end, accidents and the measure is considered to have an overall negative effect on safety (Evans, 2004).

Behaviour adaptation is now a widely accepted phenomenon and is being researched in a variety of fields. Rudin-Brown and Jamson (2013) provide a comprehensive overview of the subject as it applies to the areas of vehicle design and, especially, in-vehicle technologies, highway design, the application of road safety measures and even in the field of road safety policy.

3.4. Speed management – the last frontier

One of the most important aspects of behaviour, which has been demonstrated to have a significant impact on safety, is speed, in general, and excessive speed, in particular. In many countries national road safety plans place speed management high on the safety agenda. On the other hand, on many roads, in many countries, drivers are exceeding the speed limit and are driving too fast for the prevailing conditions (e.g. OECD, 2006). How to affect sustainable large-scale reductions in speed is an issue that has not yet been resolved. Whereas with most other behaviours, the large majority of the public is law-abiding and, thus, creates relatively few problems for the police to enforce "normative" behaviour, with speeding, and the large proportions of speeding drivers, it is very difficult to address this issue through enforcement. Although some countries, e.g. the Netherlands, the United Kingdom, France, Scandinavian countries, Australia are having very positive results with increased speed enforcement (Chapelon & Lassarre, 2010; Gains, Heydecker, Shrewsbury, & Robertson, 2004; Stevenson, 2012), this is still far away from realising the potential.

Eventually, this issue may be solved through technology, with the aid of Intelligent Speed Adaptors, an in-vehicle device that does not allow the driver to exceed the prevailing speed limit. Whereas the technology seems fairly robust, there is, as yet, no public support for the large-scale introduction of this technology (e.g. Carsten, 2012).

Much research is still required on the issue of speed management from a variety of angles. This would include basic and evaluative research on the selection of appropriate speed limits, effective means of enforcement and, through social marketing and other means, affecting general speed reductions in the population. Such societal changes have been achieved, in the developed countries, with regard to other road-user behaviours, e.g. a reduction in alcohol consumption in combination with driving and an increase in the use of seat-belts in cars.

In a more general sense, speed management presents an example of an area associated with difficulties stemming from the need to promote originally unpopular road safety measures. Real challenges are imposed on the research which should reveal the mechanisms of effective interventions through exploring cultural, historical, structural and other perspectives of the country and the society, thorough examinations of full ranges of impacts related to various forms of empirical interventions and learning from adjacent knowledge fields such as public health and social marketing. Further developments of the "road safety culture" concept might be useful in that as well (Navestad & Bjornskau, 2012). On the other hand, it is possible that, in contrast to infrastructure- and vehicle-related measures, the transferability of the results of such socially-oriented research might be limited due to cultural and institutional differences between the countries.

3.5. The ageing of the population

A general evolutional aspect in the motorised countries is the ageing of the population. According to Franklin and Andrews (2012), the world population will grow considerably older. By 2050, worldwide, the segment aged over 65 will more than double, from under 8 percent of the total population in 2010, to over 16 percent in 2050. In the developed world, these percentages will be considerably greater. This has consequences on the accident involvement of the population and requires attention from decision-making, technical and research viewpoints. The main effects of an ageing population will be felt in the increased involvement of older road users in accidents. Thus, infrastructure conditions will likely have to be adapted to the limitations of older drivers, cyclists and pedestrians (e.g. Oxley, Charlton, Corben, & Fildes, 2006). Among others, this may require adaptation of lettering size, junction design, traffic signalization elements, street lighting and roadway infrastructure such as pavements and sidewalks. It may also affect living patterns and transport mode splits. All these changes have to be researched, before appropriate measures can be suggested.

3.6. Joint efforts in health, environment and safety research

Much work still needs to be done in the field of road safety, by safety professionals, decision-makers, politicians and researchers. Those active in the field of road safety watch, with some envy, how other disciplines, especially those associated with the environment and public health, have flourished over the past decades and have managed to capture the public's imagination. In many instances, improvements for the sake of the environment and health will also have positive effects on safety. A joining of forces with the health and environment sectors might, therefore, lead to a positive synergy. For example, reduced speeds are good for safety and are good for the environment (e.g. OECD, 2006). Similarly, a move towards more cycling will have positive health, environmental and possible safety effects, as was demonstrated, e.g., by Schepers and Heinen (2013).

3.7. General research issues

In addition, more general issues related to methodological tools of future road safety research might be addressed. According to our vision, those may concern the needs in techniques for exploring large databases, more focusing on behaviour indicators and a need for high-quality research which brings us to more sophisticated analysis techniques or to randomised experimentation.

a. Techniques for exploring large databases

With ever-increasing computer power and capacity, road accident databases are continually increasing in size. For example, at present, the European database on injury accidents collected by the member states (CARE[4]) contains some 13 million records. Similarly, very large accident databases exist in the US. Other databases have been established by road or safety authorities, some of whom keep information on traffic volumes, vehicle speeds, road characteristics, locations of road-works, etc. for management, monitoring or research purposes (see e.g. PIARC, 2003). Moreover, many modern databases apply GIS-platforms. Even larger databases are becoming available from the naturalistic driving studies being conducted around the world (e.g. Hallmark et al., 2011). A reasonable approach would be to examine what the pertinent research questions we want to answer are and, then, to consider what data are needed and how best to store them.

There are certain straight-forward statistical analyses of such large databases which can be useful for answering certain questions that have implications for road safety work. For instance, looking at the accident involvement of certain segments of the population or certain types of vehicles, looking at developments over-time or comparing countries, understanding the mechanisms of certain accident types, all have their uses, as was demonstrated by various research studies throughout the world. For example, the seminal "100-car naturalistic driving study" in the US (Klauer, Dingus, Neale, Sudweeks, & Ramsey, 2006), explored factors leading to rear-end crashes.

More complex analyses are nowadays attempted using techniques such as data-mining or machine-learning (e.g. Prato, Gitelman, & Bekhor, 2011). There is a general impression that, so far, there has been limited success in this field, but it is likely that these techniques will improve and might lead to more meaningful results.

b. Focus on behaviour indicators

A number of recent studies stated that counting accidents or injuries is often an imperfect indicator of the level of road safety, because they occur as the "worst case" of unsafe operational conditions of the road traffic system. On the other hand, managing road safety needs to take into account many factors influencing safety and especially those that can be affected or controlled. Hence, the notion of safety performance indicators (SPIs) was introduced which are considered as measurements which are causally related to accidents or injuries and are used in addition to those, in order to monitor safety performance of the system or understand the processes that lead to accidents (ETSC, 2001). Simultaneously, a methodological framework of the road safety pyramid was introduced describing the place of SPIs as intermediate outcomes between the layers of safety interventions and final outcomes, i.e. accidents or injuries.

SPIs are usually developed for a certain safety domain, e.g. user behaviour, active vehicle safety, road infrastructure, etc., where they should reflect the factors contributing to road accidents/injuries and characterize the scope of the problem identified. Over the last years, rapid development of SPIs concerning safety-related road user behaviours (e.g. seat-belt use, speeding, alcohol-impaired driving) was observed in the developed countries, which are encouraged to apply SPIs for systematic monitoring and comparison of their road safety performance (COWI, 2010; OECD, 2008). However, further theoretical developments are required for a better understanding of the relationship between SPIs and the final safety outcomes as well as between various layers of the road safety pyramid, in general (Bax et al., 2012).

Moreover, introducing SPIs has emphasised the role of behaviour indicators in safety evaluation studies, in general. Thus, more intensive use of behaviour indicators for measuring impacts of road safety interventions, monitoring progress, benchmarking road safety and other purposes can be expected in the future. In addition, rapidly developing fields of "naturalistic driving" studies and vehicle technologies strengthen the need in surrogate safety measures, thus, focusing, again, on various forms of behaviour indicators.

c. Randomised experimentation

In the road safety field, evidence-based decision-making has by now become widely accepted, although not always conducted. At the heart of this approach lies the wish for high-quality research which should control for potentially confounding factors in evaluating the effects of road safety measures (OECD, 2012). Observational before-after studies are mostly common in road safety evaluation, thus, demanding to control, at least, for the regression-to the mean, long term accident trends and exogenous changes in traffic volumes (HSM, 2010). When multivariate accident models are applied, the list of potential confounders is even longer (OECD, 2012). All those cause a need for sophisticated statistical techniques to be applied in the analyses.

An experiment or randomized controlled trial may provide a reasonable alternative to the above difficulties as, in theory, it would control for all confounding factors. However, in the field of road safety randomized experimentation is not widespread. It is often claimed that such experimentation is difficult to conduct, difficult to support from a professional point of view and sometimes said to be unethical. If a countermeasure is considered, applying it randomly to certain sites or individuals and not to others, is seen by some as unethical. At the same time, this type of experimentation is at the heart of medical research, where randomized experiments and summing of evidence from several similar studies by meta-analysis

[4] http://ec.europa.eu/transport/road_safety/specialist/statistics/index_en.htm.

are highly regarded. The strict methodological standards associated with the Cochrane and Campbell Collaborations (Hutchinson, 2005) are not generally applied in road safety research. There are, however, examples where these methods were applied and significant results were achieved. For example, Hutchinson and Meier (2004) listed 18 Cochrane reviews and 18 traffic engineering papers showing the application of either randomization or meta-analysis.

It might be well worth considering the application of these methods, where possible, in future road safety research.

4. Conclusions

The motor vehicle and motorised land transport have been with us for more than a century now, while during this period major developments have occurred both in vehicle technology and in the transport system. Road safety research started more than eighty years ago, due to the practical needs of dealing with increasing numbers of road traffic casualties as the undesired outcome of the growing transportation system. This paper surveyed the developments in road safety thinking and road safety research over the last century, detailing, to some extent, the general evolution of safety thinking as it applied to road user behaviour, vehicle and road design. Yet, the consideration was mostly limited to highly motorised countries, those which led the world in road safety progress over the last decades.

Furthermore, in view of the major changes that are occurring in the transport system over the last decade, such as trends in urbanisation and population density, including a shift from four-wheeled individual motorised transport towards more reliance on public transport, increased use of cycling and walking, as well as population ageing and the fast-going changes in vehicle technologies, the implications on future road safety research were discussed.

From a historical consideration, a major change observed more recently both in road safety research and in road safety activities concerns the emphasis shift from segmented research focused on single areas such as the driver, the vehicle and the road, towards a system's view. Moreover, examining various developments that have occurred over the years regarding road user behaviour, vehicle design and road infrastructure, a close inter-relation between road safety research abilities and road safety interventions applied can be observed. The current state of maturity of road safety research is reflected by the safe-system approach aiming to create a road traffic system with inherent safety features, which will be tolerant to human errors and mitigate their consequences.

In terms of future research, a shift in modality towards more vulnerable road users and their needs, more attention to safety implications of denser cities, greater use of public transport, inter-modality and coordination between the spatial development and the transportation system, can be foreseen. Simultaneously, a growing need in assessing the safety and other impacts of in-vehicle electronic devices and intelligent transportation systems, in general, is expected. In all such research more attention will have to be paid to behavioural adaptation, which was not properly taken into account previously. In addition, speeding remains one of the major safety issues all over the world, where sustainable large-scale changes have not yet been achieved and much research is still required from a variety of angles. Similarly, population ageing presents new challenges to the transportation system that has to be adapted to the limitations of older drivers, cyclists and pedestrians.

The issue of conflicting interests and the relationships among transport, environmental issues, liveability and the economic power of cities cannot be ignored. The least that should be expected is that safety aspects are properly specified, evaluated and researched.

In addition, more general issues related to methodological tools of future road safety research need to be addressed, including the needs for techniques exploring large databases, greater focusing on behaviour indicators and a need for high-quality research where a place of randomised experimentation should probably be reconsidered.

In a more general sense, it appears that the abilities of road safety research have improved considerably over the last decades, due to a dramatic increase in available databases, with both accident and behaviour data, as well as rapid development and a growing number of statistical tools applicable for the analyses, and systematic accumulation of empirical knowledge in the field. The models applied for exploring road safety issues today seem to be more sophisticated, although the findings of such models not always "enlightening". We believe that the current trend of evidence-based research aiming to quantify a relation between a feature or intervention examined and its safety impact should be further supported. However, a relationship between various components of the road safety pyramid as well as the safety impacts of on-going changes in the transportation system still need to be explored, setting major challenges for future road safety research. Based on the current trends, we can assume that future road safety research will provide a more in-depth understanding of the mechanisms of various phenomena, aspiring to fit the transportation systems to the limitations of human road users.

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