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A SAFE ROAD TRANSPORT SYSTEM – FACTORS INFLUENCING INJURY OUTCOME FOR CAR OCCUPANTS

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ABSTRACT

Given that over a million people are fatally injured in road accidents each year, the need for a systematic proactive approach is undeniable. The Swedish Road Administration (SRA) has developed a model for a safe road transport system based on the *Vision Zero* philosophy, to identify and prevent deviations from a safe system approach with regard to crashes. The overall objective of this thesis was: to study road crashes using this system approach, to identify whether the SRA model could be used to classify fatal crashes, and to identify system weaknesses as well as important factors that need to be addressed to further develop a safe road transport system.

The thesis comprises four studies based on real-world crashes in Sweden. Three kinds of data were used in the studies: in-depth fatal crash data, in-depth car crashes involving cars fitted with an on-board crash pulse recorder, and observational data. In two studies, the aim was to investigate the interactions between a few safety performance indicators (SPIs), and how these indicators could be used to identify the most important factors in road crashes. The other two studies focused on SPIs of the vehicle and the road, to evaluate whether the SPIs used reflect the most important factors in the system. The aims of these two studies were also to present average crash severity, depending on collision partner as well as road safety standard.

Most road traffic injuries are related to an interaction between the three components: the road, the vehicle and the road user. Therefore a system approach is needed to analyse crashes and to find preventive interventions. The SRA model was found to be useful for classifying in-depth fatal crashes. However, to identify weaknesses in the road traffic system, a more sophisticated model is needed. Based on crashes involving cars fitted with an on-board crash pulse recorder, crash severity was found to differ depending on collision partner. Frontal two-vehicle crashes and single-vehicle crashes with rigid roadside objects were shown to generate the highest crash severity. The least harmful crash type was single-vehicle crashes into deformable objects. Furthermore, crash severity was lower in crashes occurring on roads with a good safety rating than in those that occurred on roads with a poor safety rating. While it was found that a higher speed limit resulted in higher crash severity on roads with a poor safety rating, the opposite was found on roads with a good safety rating. The main reason for this was that lanes for traffic travelling in opposite directions were more often separated at higher speeds on roads with a good safety rating. On divided roads, no crashes resulted in a crash severity above the level corresponding to a 10% risk of sustaining serious or fatal injury. Simultaneous 100% fulfilment of a set of SPIs (sober driver, non-excessive speed, seat belt use and divided roads) also supports this finding, since only 5% of all fatalities on rural roads in Sweden occurred under these circumstances. Divided roads are therefore one of the most important SPIs for car occupants. The overall the results of the thesis indicates that it is necessary to establish a system approach, where the road infrastructure is based on the capabilities and limitations of human beings through good road and vehicle design.

Key words: crash pulse recorder, crash severity, injury prevention, real-life crashes, road safety, safety performance indicator, holistic

SAMMANFATTNING

Årligen dör över en miljon människor i världen till följd av trafikolyckor. För att reducera antalet allvarligt skadade och dödade i trafiken krävs ett holistiskt synsätt. Vägverket har därför utformat en modell för säker trafik där vägtransportsystemet studeras utifrån tre samverkande komponenter – vägen, fordonet och människan. Modellen används som ett verktyg inom Vägverket för att aktivt föra Sverige närmare Nollvisionens etappmål 2020 (en halvering av antalet dödade från 440 år 2007 till 220 år 2020).

Det övergripande syftet med denna avhandling är att studera trafikolyckor utifrån ett systemperspektiv och att klassa olyckor utifrån Vägverkets modell, för att därigenom identifiera brister och finna vad som krävs för att skapa ett säkrare vägtransportsystem. Vidare var syftet att studera interaktion mellan väg, fordon och människa med utgångspunkt från Vägverkets uppställda kriterier för säker trafik. I två delstudier har kriterierna för en säker väg och en säker bil studerats.

Totalt ligger fyra studier av trafikolyckor i Sverige till grund för denna avhandling. De data som används är Vägverkets djupstudier av dödsolyckor, Folksams djupstudier av krockade bilar utrustade med krockpulsmätare samt resultat från trafikmätningar.

De flesta personskador är relaterade till en interaktion mellan de tre komponenterna – vägen, fordonet och människan. Det är därför viktigt att studera och analysera trafikolyckor utifrån ett systemperspektiv för att kunna förebygga olyckor i framtiden. Vägverkets modell för säker trafik var användbar vid klassning av dödsolyckor. För att identifiera systembrister krävdes en mer djupgående metod vid bedömning av orsaken till en svår personskada.

Krockvåldet, uppmätt i krockar med bilar utrustade med krockpulsmätare, varierade beroende på motpartsobjekt. Det uppmätta krockvåldet var störst i krockar mellan två fordon och i singelolyckor mot fasta objekt, medan krockvåldet var signifikant lägre i kollisioner med deformerbara objekt. I kollisioner på vägar med hög säkerhetsklassning var krockvåldet lägre jämfört med vägar med låg säkerhetsklassning. Kollisioner på vägar med låg säkerhetsklassning genererade högre krockvåld vid högre hastighetsgräns. Det omvända mönstret återfanns på vägar med hög säkerhetsklassning där krockvåldet minskade vid högre hastighetsgräns. Huvudorsaken till detta var att vägar med hög säkerhetsklassning oftare var mittseparerade vid högre hastighetsgräns. Ingen olycka på mittseparerade vägar genererade ett krockvåld högre än gränsen för tio procents risk för svår eller dödande personskada. Endast fem procent av dödsolyckorna inträffade på mittseparerade vägar där trafikanten uppfyllde kraven på att vara bältad och nykter samt att hålla hastighetsbegränsningen. Resultaten i denna avhandling visar att mittseparering är en av de absolut viktigaste säkerhetsparametrarna för att skapa ett säkert vägtransportsystem för bilåkande. Resultat från de fyra ingående studierna visar att ett helhetsperspektiv, där interaktionen mellan de tre ovan nämnda komponenterna studeras, är nödvändigt för att kunna identifiera brister och därmed skapa ett säkert vägtransportsystem.

LIST OF PUBLICATIONS

This thesis is based on the following papers, which will be referred to in the text by their roman numerals.

I. Stigson, H., Krafft, M., Tingvall, C. Use of Fatal Real-Life Crashes to Analyse a Safe Road Transport System Model, Including the Road User, the Vehicle, and the Road. Traffic Injury Prevention, Vol. 9 (5), pp. 463-71, 2008.[1]

II. Stigson, H., Ydenius, A., Kullgren, A. Variation in Crash Severity Depending on Different Vehicle Types and Objects as Collision Partner. International Journal of Crashworthiness, (in press), 2009.[2]

III. Stigson, H. Evaluation of safety ratings of roads based on frontal crashes with known crash pulse and injury outcome. Traffic Injury Prevention, Vol. 10 (3), 2009.

IV. Tingvall, C., Stigson, H., Eriksson, L., Johansson, R., Krafft, M., Lie, A. The role and properties of Safety Performance Indicators in target setting, projections and safety design of the road transport system. Accident Analysis & Prevention, (submitted), 2009.[3]

Authorship of the paper / division of the work between authors

[1] Stigson, H. Krafft, M. Tingvall, C.
Stigson, Krafft, and Tingvall designed this study. Stigson and Krafft performed the data collection. Stigson analysed the results under supervision of Krafft and Tingvall. The paper was written by Stigson and Krafft, and reviewed by Tingvall.

[2] Stigson, H. Ydenius, A. Kullgren, A.
Kullgren, Stigson and Ydenius designed this study. Kullgren, Stigson and Ydenius performed the data collection. Stigson analysed the results and wrote the paper under supervision of Kullgren. The paper was reviewed by Kullgren and Ydenius.

[3] Tingvall, C. Stigson, H., Eriksson L, Johansson R, Krafft M, Lie A.
Tingvall designed this study. Eriksson, Johansson, Lie and Tingvall developed the model used in the study. Stigson and Krafft performed part of the data collection. Stigson analysed the results under supervision of Tingvall. Tingvall made the statistical analysis. The paper was written by Krafft, Stigson and Tingvall, and reviewed by all the authors.

CONTENTS

LIST OF ABBREVIATIONS

AIS	Abbreviated Injury Scale
BAC	Blood Alcohol Concentration
CPR	Crash Pulse Recorder
DAYL	Disability Adjusted Life Year
Euro NCAP	European New Car Assessment Programme
EuroRAP	European Road Assessment Programme
ESC	Electronic Stability Control
ETSC	European Transport Safety Council
GDP	Gross Domestic Product
HGV	Heavy Goods Vehicle (>3.5 tonnes)
KSI	Killed or Seriously Injured
LGV	Light Goods Vehicle (<3.5 tonnes)
MAIS	Maximum Abbreviated Injury Scale
MPV	Multi-Purpose Vehicle
OECD	Organisation for Economic Cooperation and Development
RPS	Road Protection Score
SPI	Safety Performance Indicator
SRA	Swedish Road Administration
SUV	Sports Utility Vehicle
VTI	Statens väg- och transportforskningsinstitut (the Swedish National Road and Transport Research Institute)
WHO	World Health Organization

DEFINITIONS

In this thesis, ***road safety*** is defined as the overall safety of the road transport system consisting of the road, the vehicle and road user.

1 INTRODUCTION

Despite improvements in vehicle safety and occupants' awareness of using safety devices, fatal and severe injuries continue to occur. Road accidents constitute a major public health issue. Almost 1.3 million people are fatally injured in road accidents each year worldwide, and half of the 50 million people who are estimated to be injured are seriously injured and/or disabled (Peden et al., 2004). Traffic accidents are one of the leading causes of disability and reduction of productive years in the population. Road trauma represents between 1-3% of GDP in most countries and causes considerable emotional and financial stress to the affected people (OECD, 2008). The World Health Organization (WHO) has estimated that unless action is taken, global road deaths will double by the year 2030; this will mean that they will advance to the eighth place (no. 10 in 2002) with regard to leading causes of death, and the fourth place (no. 8 in 2002) as regards disability adjusted life years (DALYs) worldwide in 2030 (Mathers and Loncar, 2006). The number of road victims is under-estimated due to the under-reporting of data in most countries. Most severe road accidents occur in low- and middle-income countries. Even if high-income countries have 60% of the total motor vehicle fleet, they only contribute 14% of the total number of deaths in road accidents worldwide (Peden et al., 2004). However, road traffic injuries are the leading cause of death among persons aged 15 to 44 years in high-income countries (Krug et al., 2000). In total, more than 42,000 road users are killed and around 3.5 million are injured each year in the EU (Hobbs et al., 2001). It is gratifying that fatalities have decreased by approximately 50% over the last 35 years (OECD, 2008), and to achieve a further reduction, the European Commission has set up a target for a 50% reduction in road deaths between 2000 and 2010 within the EU member states (European Commission, 2001). It appears unlikely that this target will be met, since the number of road deaths is still too high (OECD, 2008). The Swedish government has set a target (based on 2007 accident data) to reduce the number of fatally injured road users from 440 to 220, and the number of seriously injured from approximately 10,000 to 7,500 by the year 2020 (SRA, 2009b). The road transport system is the most complex and the most dangerous of all systems that people have to deal with on a daily basis today (European Commission, 2001). The WHO and the OECD have therefore pointed out that in the long term a systematic proactive approach is needed (Peden et al., 2004; OECD, 2008). According to Leveson (2004), the most effective way of preventing accidents in a complex system such as the road transport system is to go beyond blaming the road user, and instead study how all the factors involved interact. Road crash causations in this thesis will therefore be viewed as complex processes involving the whole system – the road, the vehicle and the road user – instead of studying the components separately.

2 BACKGROUND

Today the road transport system is not a tolerant man–machine system for its users, in that it has the potential to be one of the most significant public health issues in society. Haddon (1980) described most aspects of road casualty prevention, but the components in the system remain hardly compatible with each other. Different kinds of legislation directed towards vehicle manufacturers, road users and road designers have been developed, but remain independent of each other, with the road user being the unstable link between the vehicle and the road. The Roman philosopher, Cicero, coined the phrase "To err is human". With the knowledge that human error is responsible for 70 to 80% of accidents in general (Rasmussen, 1997), it is obvious that the road transport system must include and respect the limits of human beings in the design of systems to minimise road casualties.

Traditionally, each component of the road transport system has been studied separately by the specific research discipline. In road crash investigations it is typical to find someone or something appropriate to blame in the backward chain of events. The investigation often stops here without further analysis of the reasons why the crash occurred and how the three components (road, vehicle and road user) of the system interact. However, Treat (1980) and Sabey and Taylor (1980) conducted studies where they tried to identify the main contributing factors and their interactions in road crashes. The road user was judged to be the sole contributor in 65% of crashes, and to contribute in combination with vehicle and road factors in 30%. Traditionally, studies like these two have mostly been focused on factors relating to driver error and crash causation (Bedard et al., 2002), rather than finding the reason for injury outcome.

2.1 RISK MANAGEMENT

Research into the human factors of risk has been in progress for a long time in the aviation industry, the nuclear power industry and other industrial process plants, with efforts focused on establishing a total system approach, to avoid or minimise the consequences of human errors (Rasmussen, 1997). A similar system-oriented approach focusing on how the components interact could be successfully adapted to the road transport system. However, the weakness is that the components of the road transport system are often seen as independent, and accidents are consequently judged to be caused by human error (Rasmussen, 1997). Even though most accidents are judged to be caused by human errors, court reports from e.g. Bhopal and Chernobyl confirm that these accidents were linked to system control problems rather than human error alone. The root cause of the accident should be seen as one feasible start of the event. According to Leveson (2004), the accident would have been set off by another cause at another point of time anyway. Looking at accidents in terms of events, acts and errors is therefore not so useful for making improvements in the system. Rasmussen (1997) asserts that task analysis based on human error should be replaced by a model focusing on control factors aimed to remove deviation from requirements for a safe system. To achieve improvements in the road traffic system, Rasmussen (1997) pointed out that traffic safety research should focus on interactions between the components and how they could be controlled in the road transport system, rather than focusing on risk variables. Human error is part of human conditions, and therefore road user mistakes should be seen and accepted as a normal part of traffic. However, an effective way of eliminating or reducing human errors is to adapt the environment rather than focus on changing human behaviour (Haddon, 1980; Reason, 1990; Wegman, 2003; Peden et al., 2004).

2.1.1 Safe system approach in road transport system

In 1997 the Swedish government decided on a road transport safety strategy called *Vision Zero,* with the long-term vision of no fatal or serious injuries within the road transport system (Tingvall, 1995). From its first presentation, *Vision Zero* was seen to require a paradigm shift in road safety work that moved towards to a safe system approach. It is now more common for the road transport system to be seen as a dynamic system consisting of humans and vehicles on the road (Peden et al., 2004; McMahon and Ward, 2006; OECD, 2008). Responsibility for crash prevention has now moved from the human being, and is shared by all those who have an effect on, or participate in, road traffic. As long as the road user obeys traffic rules, the designers of the system must, according to *Vision Zero,* establish that the system is safe to use. The designers of the system are therefore responsible for the level of safety within the entire system, i.e. the design, operation and use of the road transport system. The designers mentioned above could e.g. be from the road authority, the municipalities, the haulage industry and the vehicle industry. The new priority for sustainable development is that the care of human life and health is considered to be more important than anything else (Tingvall, 1995), and this has already been adopted in the other three transport systems (aviation, shipping and rail) (OECD, 2008). The OECD (2008) has pointed out that a safe system approach is the only way to dramatically reduce the number of road casualties. The Netherlands and Australia have adapted a similar risk management approach known as *Sustainable Safety* and *Safe System* that are based on the belief that any level of serious trauma arising from the road transport system is unacceptable (SWOV, 2006; ATC, 2008). The aim of a safe system approach is not to totally eliminate the number of crashes but to limit crash severity, and thereby minimise the road user's risk of being fatally or seriously injured when a crash occurs. The concepts are based on the philosophy that the road transport system should be adapted to the limitations of the road user, by anticipating and allowing for human error. By adapting the road and vehicle either to be more tolerant of human error in a passive sense (e.g. protective barriers between vehicle and roadside object) or to actively take over if an error is detected (e.g. an advanced safety system such as an autonomous emergency braking system), crashes resulting in fatally and seriously injured car occupants can be avoided (Rechnitzer and Grzebieta, 1999).

2.2 SAFETY PERFORMANCE INDICATORS

Safety Performance Indicators (SPI), a battery of proven measures, can be used to describe road safety conditions. The SPIs mentioned are related to vehicles, infrastructure and road users, and have in general terms been defined as "...measures (indicators), reflecting those operational conditions of the road traffic system that influence the system's safety performance" (Gitelman et al., 2007; SafetyNet, 2008). In an EU project, SafetyNet, seven different road safety areas have been identified as important SPIs: alcohol and drug use, speeds, protective systems, daytime running lights, vehicles, roads and trauma management, but the SPIs used can vary in number, from less than 10 to more than 20 (Gitelman et al., 2007; Elvik, 2008; OECD, 2008). In this context, SPIs are understood to represent certain operational conditions that are related to road safety, often expressed as the proportion of the traffic volume that fulfils the condition. One example could be “the proportion of car occupants using seat belts”; another could be “the proportion of the traffic volume travelling on divided roads”. SPIs therefore both represent a certain safety aspect, as well as a value of how this aspect has penetrated the traffic system. All SPIs should have a proven and well-documented relation to the number of road casualties.

In managing road safety, the use of SPIs is becoming more and more common (Vis and Van Gent, 2007; Elvik, 2008; ISO, 2008; OECD, 2008; SafetyNet, 2008; SRA, 2008b) as a way of linking safety countermeasures with final outcome in terms of fewer casualties. SPIs can act as an intermediate step between action and final outcome in terms of casualties, Figure 1. They can also be used to detect deficiencies in the road transport system, as well as guiding progress to make improvements over a specified period along the way of achieving the long-term vision of eliminating road deaths and serious injuries (OECD, 2008). The SRA (2008b) therefore uses SPIs both to set targets and to predict the outcome of improvements in SPIs in terms of road casualties. For example, seat belt use has been shown to correlate with a lower risk of sustaining fatal or serious injuries. One intermediate step to reduce the number of seriously and fatally injured could therefore be to increase the rate of seat belt wearing. Different actions to increase seat belt use could be carried out during a couple of years (e.g. seat belt legislation, a demerit point system, and intelligent seat belt reminders). During subsequent years, the volume could be measured and a step-by-step improvement of the situation in the system could be followed. Both Elvik (2008) and the SRA (2008b) have calculated the combined safety effects of several SPIs (e.g. alcohol, speed, protection systems, road design), which have all been shown to effectively reduce the number of crashes resulting in serious and fatal injuries. By combining SPIs, it is possible to measure the status of the road transport system and to identify weaknesses before a crash occurs. The current or future status of the road transport system will thereby be represented in terms of the number of fatally and seriously injured road users based on calculations of SPIs (Elvik, 2008). Traditional evaluation of road safety has focused on the number of crashes resulting in injury and the number of casualties per capita, by using black-spot methodology etc (see e.g. Meuleners et al. (2008)). A key advantage of using SPIs is that they can be measured more frequently and during shorter study periods, thus proving more statistically reliable than the results from accident analysis. The fact that SPIs imply a ‘proactive’ approach to traffic safety (i.e. identification of safety problems before they result in accidents) is in line with political traffic safety policies such as the Australian *Safe System* and the Swedish *Vision Zero*, which call for preventive measures to develop a road transport system that is adapted to the needs and limitations of all types of road user (see e.g. Tingvall (1995)).

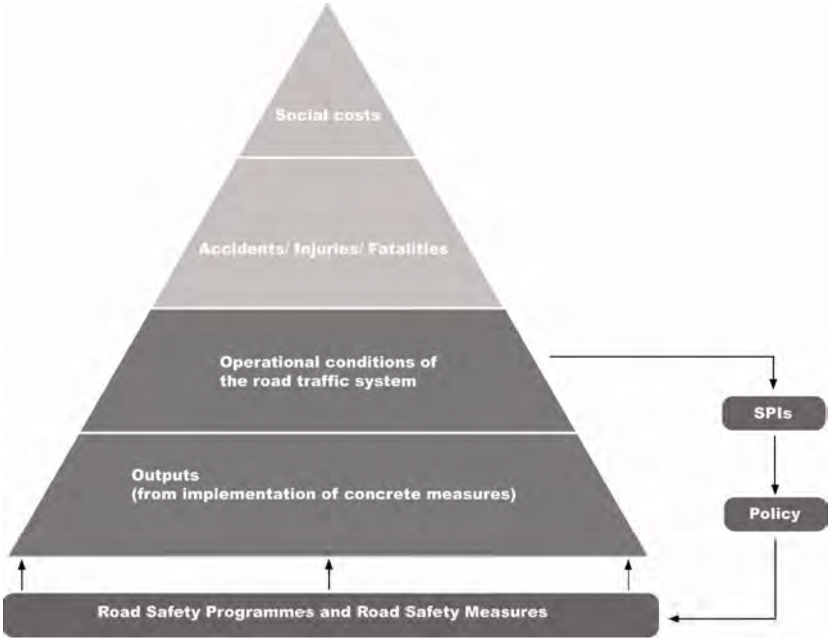


Figure 1. Location of SPIs in the safety management system
Source: (Hakkert and Gitelman, 2007)

SPIs could also be used to benchmark the road safety situation between different countries (Hermans et al., 2009), since there is a logical relationship between input and outcome, e.g. if seat belt use increases, injury outcome will decrease. By using observational measurements for seat belt use, the percentage of road users respecting the legal BAC (blood alcohol concentration) level, the percentage of new vehicles, the density of motorways and the share of gross domestic product spent on healthcare as input, the safety status for a country's road transport system could be estimated.

2.3 THE SRA MODEL FOR A SAFE ROAD TRANSPORT SYSTEM

To identify the most important road safety problems, the Swedish Road Administration (SRA) has introduced a model for a safe road transport system that links the criteria of an inherently safe road transport system through some SPIs (Linnskog, 2007; OECD, 2008; Stigson et al., 2008; WHO, 2008), Figures 2-3. The chosen SPIs are related to the criteria specified in Figure 3. They have been shown to have a potential for reducing the risk of injury and all the SPIs have been linked to each other. The model describes how the three components (road, vehicle and road user) should interact to achieve safe road traffic. Biomechanical limits that the road user can tolerate without sustaining severe injuries, as well as mental and physical conditions of the human being, are the limiting factors in the system. Deficiencies in safety are balanced and controlled by adapting the speed limit to the safety level of the system, based on the *Vision Zero* philosophy (Tingvall, 1995; Tingvall et al., 1996). The procedure will be described further below.

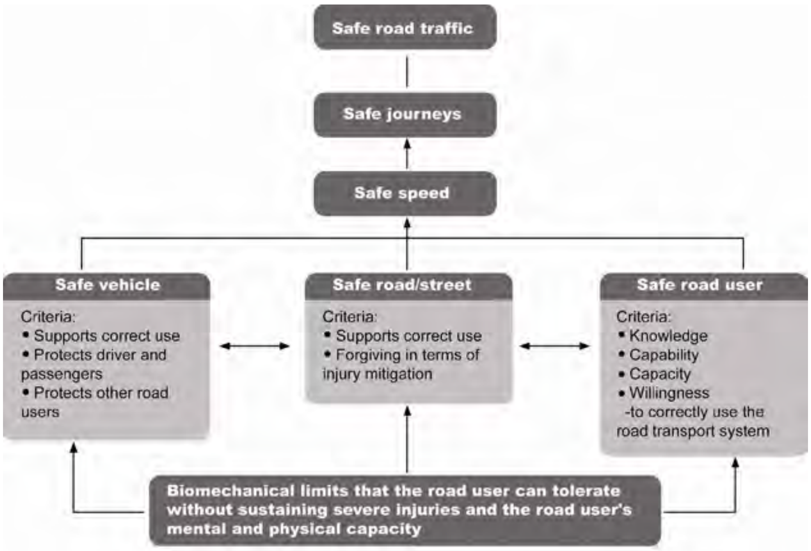


Figure 2. The SRA model for a safe road transport system
Source: (Linnskog, 2007)

2.3.1 Biomechanical limits to be used in the SRA model

Based on the SRA model, the design of a safe road transport system should be based on human injury tolerance, Figure 2. The system should expect and accommodate human errors. Several approaches such as crash tests with volunteers, cadavers, animals, dummies and numerical models, have been used to estimate the human response to impact. However, our knowledge of human injury tolerance is still limited. The risk of human injury is influenced and differs depending on several parameters: road user groups, age, gender, crash type, type of restraint systems etc. Analysis of real-world crashes has increased the understanding of how crash severity correlates with e.g. impact speed, type of striking object and injury outcome (Ydenius and Kullgren, 2001; Krafft et al., 2002; Kullgren, 2008; Stigson, 2009; Stigson et al., 2009). To understand the biomechanical limits and mechanism of injury, it is important to study how crash severity affects the risk of injury.

2.3.1.1 Crash severity

Crash severity is a measure of the violence of a crash and is often expressed as parameters related to the response of the vehicle during the crash, e.g. vehicle acceleration, change of velocity and intrusion to the occupant compartment. The crash severity parameters could be related to the risk of sustaining an injury. The crash severity level to which a human is exposed during a crash depends on several factors, such as relative velocity between the vehicles, the mass and structure of the vehicles, as well as the crash situation, including impact angle, overlap etc.

In most studies, crash severity is described as change of velocity calculated from the exterior deformation of the vehicle and/or by e.g. using the law of conservation of momentum. Nowadays vehicles are often equipped with event data recorders that make it possible to measure the crash pulse during the crash phase. However, the data are often restricted to being used by the manufacturer, and studies from only three databases have been published to the author's knowledge: Volvo, NHTSA and Folksam (see for example (Andersson et al., 1997; Ydenius and Kullgren, 2001; Krafft et al., 2002; Krafft et al., 2005; Gabauer and Gabler, 2006; Gabauer and Gabler, 2008; Kullgren, 2008)). With high quality data of this kind it is possible to improve measurement quality, both regarding validity and reliability compared with calculations from the exterior deformation of the vehicle or use of the law of conservation of momentum. Furthermore, for some crash types with limited exterior deformation such as small overlap and collisions with narrow objects, crash pulse recorders could be one feasible solution for calculating crash severity, compared with conventional methods (Kullgren, 1998; Gabler et al., 2004).

2.3.1.2 Injury risk and distribution of crash severity

The way in which the risk of incapacitating or fatal injury increases with an increase in the posted speed limit has been presented by Gårder (2006), as well as several other authors. Risk curves of this kind are influenced by several parameters: road design, vehicle design, seat belt use etc. In order to draw some conclusions about the underlying factors of the road transport system, more sophisticated data are needed. In crashes involving vehicles fitted with onboard crash pulse recorders it is possible to study how vehicles protect their occupants at a given impact severity (Kullgren, 1998). These crashes could also be used to evaluate design guidelines for road furniture designers.

Injury risk curves based on real-world crashes with measured crash severity are not as common as the risk curves based on laboratory tests mentioned above, but several studies have been presented (Kullgren et al., 2000; Krafft et al., 2005; Gabauer and Gabler, 2008; Kullgren, 2008). Correlation between injury risk in frontal impacts versus crash severity (change of velocity, mean and peak acceleration) recorded by crash pulse recorders, has been presented by Gabauer and Gabler (2008), Kullgren (2008), and Ydenius and Kullgren (2001). Also in rear-end crashes, correlation between injury risk and crash severity, in terms of change of velocity and mean acceleration, has been found (Krafft et al., 2002; Krafft et al., 2005).

Kullgren (1998) as well as Ydenius (2002) have shown that high change of velocity in frontal crashes could be handled as long as the acceleration was kept below critical levels likely to cause an injury. They suggested that the road transport system should be designed with respect to acceleration levels, rather than change of velocity, to more effectively prevent injury outcomes in frontal crashes.

2.3.1.3 Design guidelines

Vision Zero states that the long-term target is that no one should be fatally or seriously injured within the road transport system. However, in Sweden approximately 400 road users are fatally injured and 10,000 are seriously injured each year (SRA, 2009b). To reduce the number of fatally and seriously injured, the SRA use the model today as a tool to systematically identify system deficiencies in severe crashes according to best practices. The model illustrated in Figure 3 has therefore been adapted to the best practices of the present-day road transport system. These criteria will be further described below.

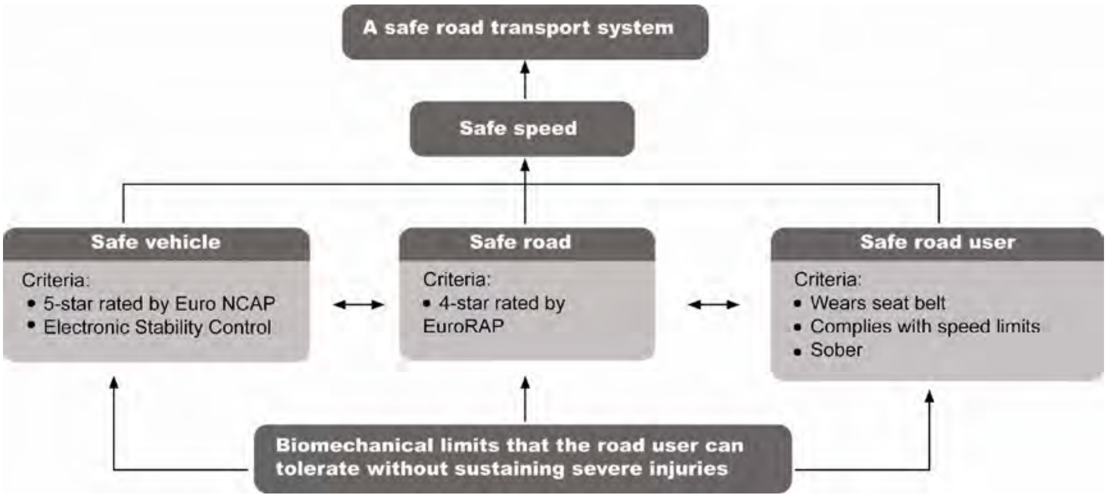


Figure 3. The criteria for the model that reflect best practices in the present-day road transport system

2.3.2 Safe road user according to the SRA model

In the SRA model it is assumed that a safe road user complies with the rules of the road and is therefore defined in the model by the following criteria: wearing a seat belt, complying with the speed limit, and not driving under the influence of alcohol/drugs. These three aspects of driver behaviour have been identified as key factors for fatality and injury risk (Farmer and Lund, 2006; OECD, 2008; WHO, 2008; Hermans et al., 2009). However, there are other behaviour and road-user characteristics that increase driver fatality risk, but the effects of these three factors on injury risk are huge and well-documented, as further described below.

2.3.2.1 Seat belt use and risk of injury

The use of seat belts is fundamental in creating a safe road transport system. All other vehicle-related systems, speed limits, road design, etc, are mainly designed for a restrained occupant. Not using seat belts is therefore a behaviour that takes the occupant outside the encompassing design of the road transport system. Seat belt use has been shown to dramatically reduce fatal outcome (see for example (Kullgren et al., 2005)). The risk of being fatally injured is reduced by 40-50% for drivers and front-seat passengers (Elvik and Vaa, 2004). Based on observational data in traffic, smart seat belt reminders have been shown to increase the rate of seat belt wearing to nearly 98% in Europe (Lie et al., 2008). In cars without smart seat belt reminders, the wearing rate was 86%. General wearing rate is much higher than among those involved in serious crashes (Farmer and Lund, 2006). In fatal car crashes, seat belt use was as low as 40–50% (Kamrén et al., 1994; SRA, 2008a; Stigson et al., 2008). Approximately 15,200 unbelted occupants are killed every year in the EU. If the belt use could be increased to 100%, approximately 7,600 lives could be saved every year in the EU (ETSC, 1996).

2.3.2.2 *Alcohol and risk of crash involvement/severity*

Another high-risk behaviour is alcohol-impaired driving. Several studies have shown that fatality risk increases rapidly with BAC (Evans, 1991; Zador et al., 2000; Bedard et al., 2002; Preusser, 2002; Peden et al., 2004). Drivers with a Blood Alcohol Concentration, BAC, somewhat below 0.1% have been shown to expose both themselves and other road users to a very high risk, Figure 4 (Zador et al., 2000). In only 0.2% of the traffic flow are drivers under the influence of alcohol (legal limit 0.02%), while one quarter of all fatal car crashes in Sweden had a drunk driver (SRA, 2009a).

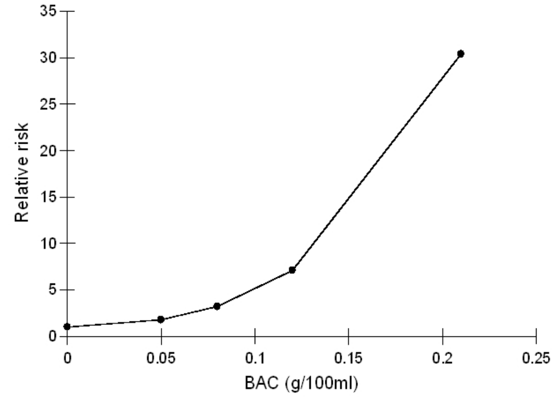


Figure 4. Relative risk of drunk drivers being involved in all passenger vehicle crashes.
Source: (Zador et al., 2000)

2.3.2.3 *Speed and risk of crash involvement/severity*

Speed has been identified as a key risk factor that has a powerful impact on the risk of sustaining a serious injury (Farmer and Lund, 2006; WHO, 2008). The biggest road safety problem in many countries is that road users exceed the speed limit (WHO, 2008). The correlation between speed and crashes/crashes with injuries has been described by power functions, Figure 5 (Elvik et al., 2004; Nilsson, 2004). Even small changes in average speed have a great effect on crash severity and thereby on risk of injury. An average increase in speed of 1km/h is associated with a 3% higher risk of a crash involving an injury and a 5% higher risk of sustaining a serious or fatal injury.

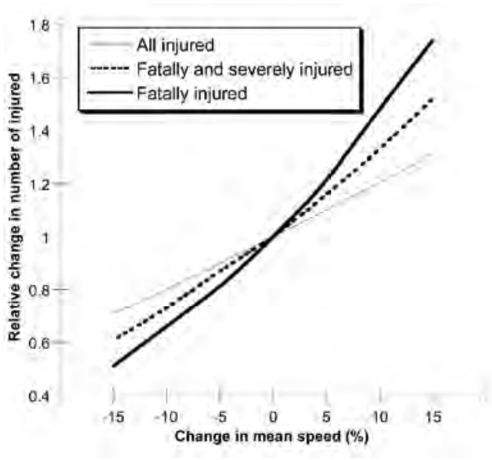


Figure 5. Illustration of the power model and the relationship between percentage change in speed and percentage change in crashes
Source: (Nilsson, 2004)

2.3.3 Safe vehicle according to the SRA model

According to the SRA model, the vehicle must protect its occupants as well as road users outside the vehicle, and it should support correct usage of the system (Linnskog, 2007). The main definition of a safe vehicle in the SRA model is that the vehicle should have been awarded a 5-star rating in a European New Car Assessment Programme (Euro NCAP) crash test (Euro NCAP, 2008), and should be fitted with Electronic Stability Control (ESC). The reason for this is that ESC has been shown to effectively reduce the risk of crash involvement (Farmer, 2006) as well as crashes with personal injuries, especially serious and fatal injuries (Lie et al., 2006; Ferguson, 2007; Erke, 2008). Investigators have established that standardised consumer crash tests such as Euro NCAP have led to significant improvements in vehicle crashworthiness (Kullgren et al., 2002; Lie and Tingvall, 2002; Farmer and Lund, 2006).

During the last 20 years, vehicle safety systems have become much more sophisticated and risk of injury is much lower in a modern car compared with an old one (Farmer and Lund, 2006; Kullgren et al., 2009). Results from Kullgren et al. (2009) indicate a dramatic reduction (up to 75%) in the risk of sustaining a fatal injury in a new passenger car compared with a car from the 1980s, Figure 6. If every car owner upgraded their vehicle overnight to the safest within its class, the fatalities on Europe's roads would drop by approximately 40–50% (WHO, 2008). Based on the studies mentioned above, the level of vehicle safety is an important key factor if a road user is fatally or seriously injured in a crash.

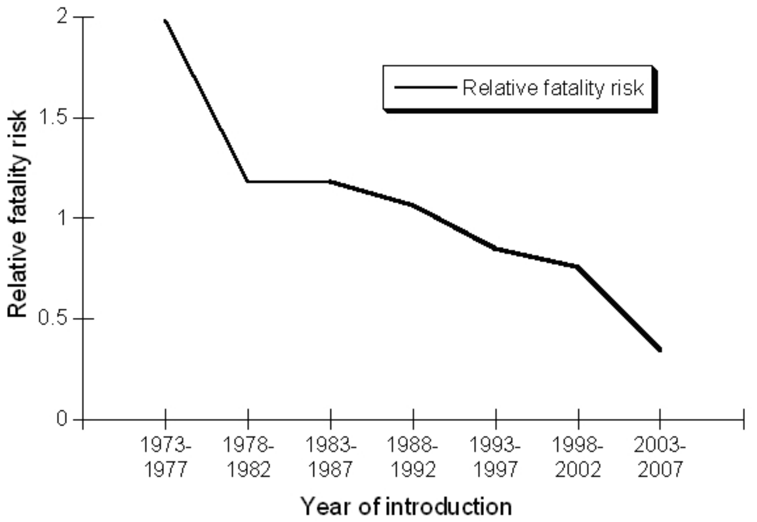
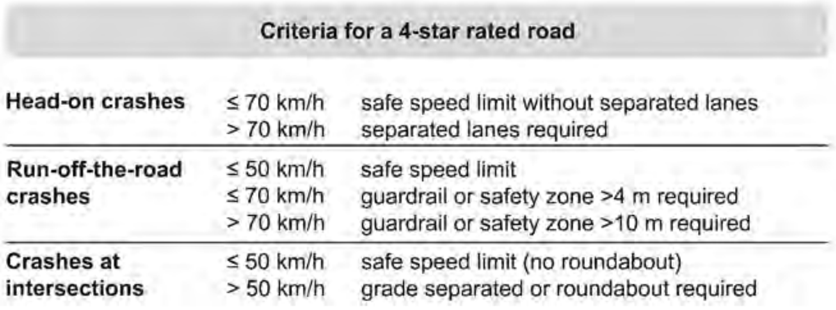


Figure 6. Relative risk of fatal injury with respect to year of introduction for car model (in 5-year intervals)
Source: (Kullgren et al., 2009)

2.3.4 Safe road according to the SRA model

In the SRA model, the European Road Assessment Programme (EuroRAP) has been used to reflect the safety standard of roads. EuroRAP, a complementary activity to the Euro NCAP, provides independent safety ratings of roads in Europe (Lynam et al., 2003). Just as the Euro NCAP rates new cars according to the protection given in crash tests, EuroRAP rates European roads, to reflect how they should be designed to optimise the combined effect of road and vehicle safety. EuroRAP consists of two test protocols, both designed to evaluate road standard: road protection score (RPS) and so-called risk mapping based on accident outcome and traffic flow data. The risk mapping can be used to track, year by year, which high-risk roads are being improved and thereby identify the measures that result in the greatest improvement. The RPS takes into consideration how well a road protects the road user from fatal or serious injuries. The rating score is based on data gathered from real-world crashes and crash tests correlated with survivable limits. The rating focuses on three different crash types: head-on crashes, run-off-the-road crashes and crashes at intersections. The posted speed limit is included as an explicit factor to reflect the interaction between road and vehicle in minimising the risk of severe injury to car occupants when foreseeable crash scenarios arise. Based on best practice, a safe speed and thereby a safe road has been defined for each of the three crash types, Table 1. Crash severity could be limited when foreseeable crash scenarios arise, by e.g. removing trees and other objects close to the road or installing a protective barrier between the vehicle and roadside object, to fulfil the criteria of safe road according to EuroRAP and thereby the SRA model (Johansson, 2008). Furthermore, two-way single carriageways with traffic travelling in opposite directions could be allowed with a speed limit of up to 70km/h, based on vehicle safety system limits (Linnskog, 2007; Johansson, 2008; WHO, 2008). To prevent interaction of vehicles with other vehicles and objects at higher speeds, the road should have physical barriers to prevent crossing over, and guardrails to protect loss of control into objects in the roadside area (trees, poles, rocks or rollover tripping mechanisms) (Rechnitzer and Grzebieta, 1999).

Table 1. Basic criteria for the 4-star EuroRAP rating



Criteria for a 4-star rated road		
Head-on crashes	≤ 70 km/h	safe speed limit without separated lanes
	> 70 km/h	separated lanes required
Run-off-the-road crashes	≤ 50 km/h	safe speed limit
	≤ 70 km/h	guardrail or safety zone >4 m required
	> 70 km/h	guardrail or safety zone >10 m required
Crashes at intersections	≤ 50 km/h	safe speed limit (no roundabout)
	> 50 km/h	grade separated or roundabout required

The RPS has been validated by studying real-world crashes, and the star rating corresponds well with the killed or seriously injured (KSI) rate: the higher the star rating, the fewer the car crashes with serious and fatal injuries (Brüde and Björketun, 2006; Castle et al., 2007). However, irrespective of the RPS rating, road type was found to be the dominating factor for the KSI rate rather than the star rating. In both studies, divided roads were found to have half the KSI rate compared with single carriageways. Several studies have shown that the risk of injury is lower for divided roads than for single carriageways (Wegman, 2003; Elvik and Vaa, 2004; Carlsson and Brüde, 2005). Vis and Van Gent (2007) have pointed out that EuroRAP is a good SPI for comparing road design within the European countries.

2.3.5 Safe interaction of road, vehicle and road user

Despite improvements in vehicle safety and the vehicle occupants' awareness of benefits associated with safety devices, fatal and serious injuries continue to occur. Crash tests like Euro NCAP are mainly focused on how passive vehicle safety systems protect occupants in vehicle-to-vehicle crashes. For instance, no crash test is included in Euro NCAP to evaluate the capacity of the vehicle to protect the occupant in a frontal single-vehicle crash into a guardrail or a rigid object. However, road safety features such as guardrails are tested to fulfil standards. Ydenius et al. (2001) show that the characteristics of different types of barriers (concrete, semi-rigid W-beam and flexible wire-rope barriers) vary considerably as regards transferred crash severity and physical behaviour.

Farmer and Lund (2006) argue that the reduction of fatality risk is merely caused by improved safety of the vehicle fleet rather than improvements in the road environment. They even state that the road environment in USA has become riskier since the mid-1990s. However, road design solutions such as roundabouts have been shown to dramatically reduce the number of crashes resulting in injuries (by up to 80%) at intersections compared with traditional intersection designs (Persaud et al., 2001; Brüde and Vadeby, 2006). In general, by applying mid- and side barriers on Swedish rural roads, the number of fatalities can be reduced by 85-90% (Johansson, 2008). Furthermore, 2+1-lane roads with wire-rope barriers that were introduced by the SRA in 1998 have been shown to reduce the number of fatally and seriously injured road users on Swedish roads. The 2+1-lane roads were a cost-effective way of increasing road traffic safety on Swedish 2-lane highways with a severe injury pattern record. Follow-up studies have shown that the number of fatally injured road users on these segments has been reduced by approximately 79% compared with the situation earlier (Carlsson, 2009). As mentioned in section 2.3.4. above, the study of Brüde and Björketun (2006) supports this finding, since 2+1-lane roads with wire-rope barriers were shown to have the lowest KSI rate of all road types.

2.3.5.1 Safe speed

Traditionally, speed limits have been chosen to achieve a balance between safety and mobility. Therefore, most road authorities allow higher speed in general on roads without protective barriers between the vehicles travelling in opposite directions, as well as between vehicles and roadside objects, than a modern vehicle is able to control if a crash occurs (WHO, 2008). Rechnitzer and Grzebieta (1999) pointed out that an implementation of crashworthy systems (compatibility of infrastructure design, vehicle design, vehicle speed with human injury tolerance) is needed. In a safe system based on the SRA model, the speed limit of the road will be set to reflect the safety standard of the road in relation to vehicle capacity, to protect the road user when foreseeable crash scenarios arise (Linnskog, 2007; Johansson, 2008; WHO, 2008). The posted speed limit is therefore included as an explicit design parameter in the SRA model (Linnskog, 2007). Based on best practice, some road designs such as 2+1-lane roads, have been considered in a more favourable light than others with regard to casualty reduction and cost benefits (Johansson, 2008). In a crash on these roads, the road and the vehicle design can together reduce crash severity, and thereby succeed in protecting the road user from sustaining a serious or fatal injury. Johansson (2008) uses the SRA model to describe a maximum travel speed related to the infrastructure, given best practice in vehicle design and 100% restraint use:

1) Locations with possible conflicts between pedestrians and cars, maximum posted speed limit 30km/h
2) Intersections with possible side impacts between cars, maximum posted speed limit 50km/h
3) Roads with possible frontal impacts between cars, maximum posted speed limit 70km/h or 50km/h if the oncoming vehicle is of a considerably different weight
4) Roads with no possibility of a side impact or frontal impact, posted speed limit >70km/h is allowed

In order to follow the *Vision Zero* philosophy, these four steps have been defined according to best practices, and the SRA use these as design guidelines and to set relevant speed limits in relation to road design (Johansson, 2008). In the SRA model these speed limits have been described as *safe speed.*

2.4 IMPLEMENTATION OF THE SRA MODEL

The underlying idea of the SRA model is to reflect the long-term target of a road transport system that protects the road user from serious and fatal injuries. The model could be used as a tool to set performance targets and the steps essential to achieve them. The SPIs will act as an intermediate step between action and final outcome in terms of casualties to guide progress towards an inherently safe system.

The SRA initiative to develop a model for a safe road transport system is ambitious and challenging. As the background has pointed out, the road transport system, and therefore road safety, represents complex phenomena where a high number of factors concerning road users, vehicles and roads interact. The course of action for creating an inherently safe system is therefore not entirely straightforward, and the characteristics of the SRA model and SPIs require further study.

3 AIMS

The overall aim of the thesis was to study crashes from a system perspective and to gain knowledge about how the three components (the road user, the vehicle, and the road) interact, and how they influence the risk of injury. This research addresses mainly front seat car occupants and all included crashes occurred on Swedish roads. The aim of Study I was to use a model with a system-oriented approach to classify fatal car crashes and to try to identify system weaknesses. Study II and Study III focused on the safety criteria of the vehicle and the road. In the last study, Study IV, the use of SPIs and the system approach were questioned. In total, four studies are included in this thesis and the specific aims of each individual study are described below.

3.1 STUDY I

The aim of Study I was to evaluate if the SRA model for a safe road transport system, which includes the interaction between the road user, the vehicle, and the road, could be used to classify fatal car crashes according to some Safety Performance Indicators (SPIs). A further aim was to present a development of the SRA model to better identify system weakness.

3.2 STUDY II

The aim of Study II, using data from crashed cars fitted with on-board frontal and rear crash pulse recorders, was to present differences in average crash severity and distribution of crash severity, depending on collision partner.

3.3 STUDY III

The aim of Study III, using data from crashed cars fitted with on-board frontal crash pulse recorders, was to present differences in average crash severity, distribution of crash severity and injury outcomes, based on the EuroRAP RPS (European Road Assessment Programme Road Protection Score), and also taking road type and speed limit into consideration. Furthermore, the objective was to evaluate differences in injury risk, based on the distribution of crash severity.

3.4 STUDY IV

The aim of Study IV was to study the properties of examples of Safety Performance Indicators (SPIs); to evaluate whether SPIs are independent variables in the sense that they can be treated by using simple probability functions, and whether simple probability methods can be used for predicting the result of multiple improvements in SPIs. Further, whether SPIs could be considered to have a linear relationship to final outcome, and whether the combination of SPIs proposed by the SRA model is logical in the sense that it produces a high level of safety.

4 MATERIALS AND METHODS

Several methods have been used to illuminate the aims of the included studies. More detailed descriptions of the methods are found in each respective paper. Three kinds of data were used in the studies: in-depth fatal crash data collected by the SRA; in-depth data on car crashes involving cars fitted with an on-board crash pulse recorder collected by the Folksam Insurance Group; and observational data collected by the SRA and VTI (the Swedish National Road and Transport Research Institute). Comments concerning some materials and methods, including their strengths and limitations, are given below.

4.1 STUDY I

Empirical data was used in Study I to evaluate if the SRA model could be used to classify fatal car crashes. The data consisted of in-depth investigated fatal crashes occurring in Sweden 2004 on the road network where at least one car occupant was fatally injured. In all 248 car occupants were fatally injured in those crashes. The data was collected from the in-depth fatal crash data of the SRA and all crash types were included. All crash spots were classified according to EuroRAP, where the infrastructure safety quality is rated in relation to posted speed limit. The vehicle's safety rating was classified according to the Euro NCAP crash test results as well as the fitting of ESC (Electronic Stability Control). Human behaviour in terms of speeding, seat belt use, and driving under the influence of alcohol were classified.

All crashes were classified according to the SRA model to identify if the crash involved non-compliance with the road, vehicle, and/or road user criteria (Step 1 in the method section in Study I). The criteria for the model were based on best practice, see Figure 3. Crashes where more than one of the three components did not comply with the safety criteria, were reclassified. Based on levels of crash severity that human beings can survive, each of these crashes was analysed to identify if all the components correlated with the fatal outcome (Step 2, a further developed model that is described in the methods section in Study I). From now on, this will be called "the further developed model".

4.2 STUDY II AND STUDY III

The in-depth datasets used in Studies II and III are unique, not only because the data is collected case by case by investigation teams, but also because crash severity is measured by on-board crash pulse recorders, CPR (further described in Kamrén et al. (1991)). The data used in Studies II and III are therefore of high quality. Approximately 250,000 CPRs have been installed in passenger cars in Sweden, comprising 29 different car models of 4 car makes (Honda, Opel, Saab and Toyota), with the aim of measuring frontal and rear-end impacts. The car fleet has been monitored since 1992 and approximately 500 frontal and 200 rear-end impacts with recorded crash pulse are included in the Folksam Insurance Group database.

CPRs measure the time history of acceleration in the impact phase in frontal and rear-end crashes. Only parameters calculated from the vehicle acceleration were used, Figure 7. Intrusion into the occupant compartment was not considered. The crash severity parameters used in these studies were: change of velocity and mean accelerations calculated from the measured crash pulses.

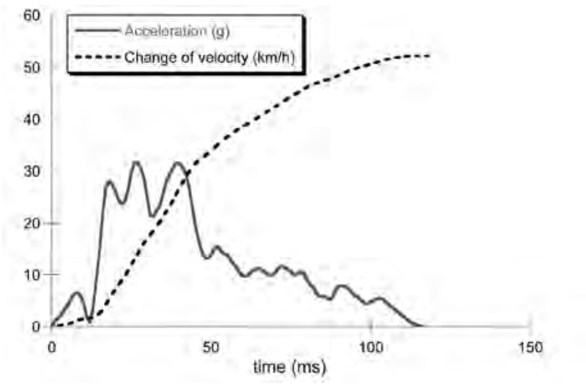


Figure 7. Example of a measured and calculated crash pulse

4.2.1 Inclusion criteria and method used in Study II

The inclusion criteria were: all frontal crashes with a repair cost exceeding 5000 EUR and all rear-end crashes irrespective of repair cost. The crashes occurred between 1992 and 2007. Both two-vehicle crashes and single-vehicle crashes were included. In total, 544 crashes were included in Study II. For all crashes, average mean and peak acceleration, change of velocity and duration of the vehicle acceleration pulse were measured and calculated.

The CPR data were divided into different categories based on the opposite vehicle or object, the so-called collision partner, Table 2. The categories were compared in order to identify differences in crash severity. Frontal two-vehicle crashes were compared with the total number of rear-end crashes, single-vehicle crashes and with the two subcategories: single-vehicle crashes with deformable and rigid roadside objects respectively. Within the groups, crash severity was compared for some categories. In two-vehicle crashes the “passenger car” category was compared with “HGV” (Heavy Goods Vehicle) category, and for single-vehicle crashes the category “deformable object” was compared with “rigid roadside object”.

Table 2. Number of crashes with different collision partners

Size classes of collision partner	Frontal two-vehicle crashes, n	Rear-end two-vehicle crashes, n	Single-vehicle crashes collision partner	n
Passenger car	192	126	Rigid roadside object	74
Supermini	15	7	Trees	23
Small Family Car	42	41	Rock face cutting	6
Large Family Car	50	22	Rocks/boulder	12
Executive Car	73	50	Culvert	4
MPV	4	11	Rigid barrier	9
SUV	5	9	Bridge pier	1
LGV (<3.5 tonnes)	2	3	House wall	6
Bus	8	-	Embankment	13
HGV (>3.5 tonnes)	18	8	Deformable object	51
			Deformable pole	30
			Deformable guardrail	21
			Other	33
Total	**229**	**157**		**158**

To explore the difference in crash severity distribution between categories, the number of crashes above a specific level in crash severity was studied. For frontal two-vehicle crashes and for rear-end crashes, the level was chosen to represent 95% and 90% of the crashes respectively.

4.2.2 Inclusion criteria and method used in Study III

The inclusion criteria in Study III were as follows: every frontal crash that occurred in a rural area, with known crash scene and with a repair cost exceeding 5000 EUR. In total, 209 crashes that occurred during the period 1992 and 2007 were included. Both two-vehicle crashes and single-vehicle crashes were included. For all crashes crash severity, in terms of mean acceleration and change of velocity was used.

All crash spots were classified according to the EuroRAP Road Protection Score (RPS), and the data were categorised based on the safety level of the infrastructure. The injuries were classified according to the 2005 revision of the Abbreviated Injury Scale (AIS) (AAAM, 2005). The categories were compared in order to identify differences in crash severity and injury risk. Risk curves presented in Kullgren (2008) were also used to identify the risk of injury, Figure 8.

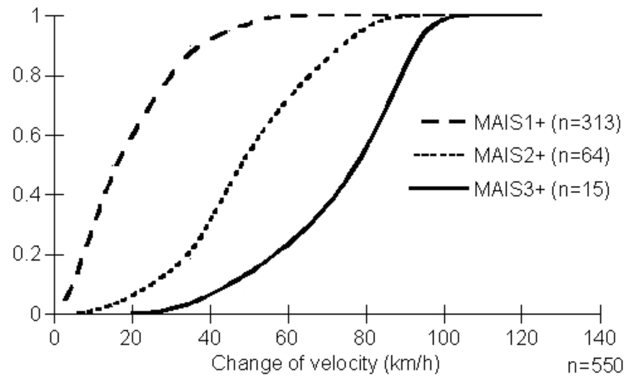


Figure 8. Injury risk, MAIS1+, MAIS2+ and MAIS3+ for front-seat occupants with respect to change of velocity in frontal impacts
Source: (Kullgren, 2008)

4.3 STUDY IV

Both empirical data as well as observational data were used in Study IV and several methods were used to illuminate the aim of the study. The empirical data consisted of all in-depth investigated fatal crashes occurring in Sweden in 2004 on the state road network, where at least one car occupant sustained fatal injuries (almost the same data as in Study I, except for those crashes that were excluded due to the fact that they occurred in urban areas). In all, 217 car occupants were fatally injured in those crashes. The crashes and occupants were classified according to the SPIs used in the SRA model that was presented in Study I, Figure 9. The observations are part of a long series produced by VTI and the SRA (SRA, 2008a).

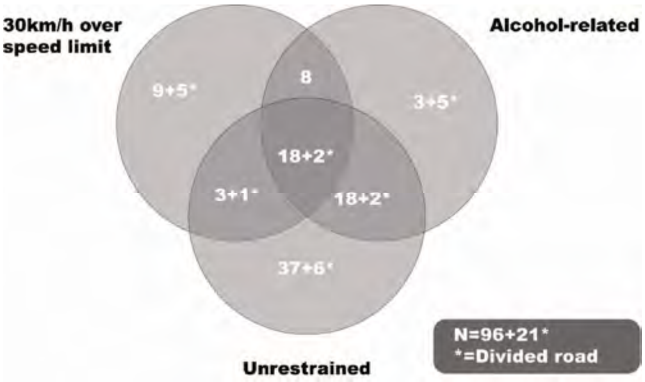


Figure 9. The number of fatalities not fulfilling SPIs for alcohol, restraint use and speeding in the SRA model

4.3.1 Linearity between SPIs

In the analysis of linearity between SPIs and final outcome, seat belt use over time was studied. For this analysis, both in-depth investigated fatal car crashes data from 1997 to 2007 collected by SRA in-depth study teams, and observational data in traffic were used. The data on seat belt use in traffic were collected and analysed by VTI (SRA, 2008a).

4.3.2 Effect of 100% fulfilment of SPIs

Data from fatal in-depth crash data investigations were used to study the effects of 100% fulfilment of a set of SPIs (divided roads, seat belt use, sober driver and non-excessive speed) combined simultaneously. These data were compared with observational data for travelling on divided roads, seat belt use, BAC over the legal limit and speeding (SRA Konsult, 2005; SRA, 2006); 35% travelled on divided roads outside built-up areas, 96% used seat belts in traffic, the proportion who were under the legal alcohol limit was 99.8%, and the proportion driving no more than 30km/h above the posted speed limit was 99%. The observations are part of a long series produced by VTI and the SRA (SRA, 2008a).

4.3.3 Analysis of independence

In order to study if SPIs can be treated independently, the method used by Elvik (2008) was used, where the effect of two improved SPIs is described as follows:

"If two measures influence the same target group of 100 accidents and one of the measures reduces accidents by 30% and the other by 40%, their combined effect was estimated as"

1- ((100-30)/100) x (100-40)/100), which is 58% instead of 70%, if the effects were simply added. In Study IV this method was used simply to calculate the probability that two factors (seat belt use and influence of alcohol) would be present in the same crash. The chi-square test for equal distributions was used.

5 RESULTS

This section summarises the main findings of the results from Studies I-IV. More information and detailed results can be found in each respective paper.

5.1 STUDY I

The SRA model was applicable to Swedish fatal crash data. It was possible to use the SRA model to classify fatal car crashes according to a few SPIs. The classification based on the criteria of the SRA model provides a picture of the safety standard of the three components (road, vehicle and road user) in fatal car crashes. However, to identify system weaknesses, the further developed model was found to be more useful than the SRA model, since the component/s that correlated with fatal outcome could be identified. Most of the occupants were injured when more than one of the three components did not comply with the safety criteria. The components were often seen to interact, even when the further developed model was used. The criteria for the road and the vehicle did not address rear-end crashes, crashes with animals or hitting stationary/parked vehicles or trailers. The classification could therefore not highlight the system weaknesses in these crashes.

5.1.1 Classification based on the SRA model

It was possible to classify 93% of the fatal car crashes according to the SRA model, Figure 10. No crash occurred where all three components were fulfilled. Most of the occupants (203 of 230) were fatally injured when two or all of the three components did not meet the criteria for a safe road transport system. Few car crashes with fatally injured occupants occurred when only one component did not comply with the criteria for the model.

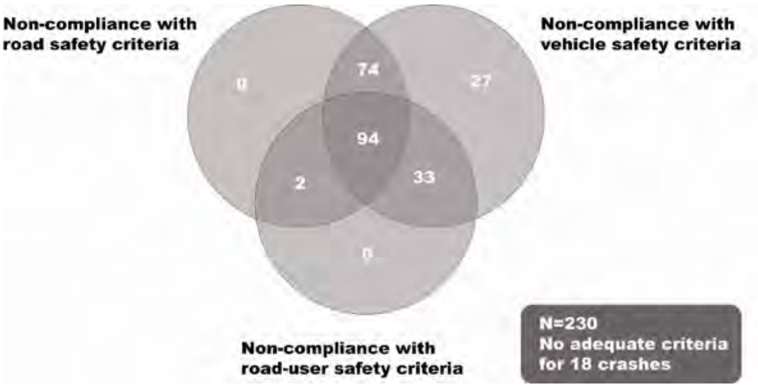


Figure 10. The number of fatalities where the road, vehicle, and/or road user did not comply with the criteria of the SRA model

5.1.1.1 Safe road user according to the SRA model

The road users fulfilled the requirements of the criteria in 101 of the 230 cases. Forty percent of the vehicle occupants who were fatally injured were not wearing seat belts, and more than a quarter of the total number of occupants (66 of 230) was fatally injured in an alcohol-related crash. In 58 of 230 cases it was judged that the driver exceeded the posted speed limit. In most of these cases (43 of 58), the driver/passenger was also not wearing a seat belt and/or was driving under the influence of alcohol.

5.1.1.2 Safe vehicle according to the SRA model

In two of the total number of crashes, the safety standard of the vehicle met the criteria for a five-star rating by Euro NCAP and the vehicle was fitted with ESC. Eighteen percent of the vehicles had a four-star rating, 7% were three-star rated, 2% were two-star rated by Euro NCAP, and the remaining 72% of the vehicles were not crash-tested by Euro NCAP, mostly because they were pre-1996 year models. The potential of ESC could be high, since more than a quarter of the total number of crashes started with loss of control.

5.1.1.3 Safe road according to the SRA model

Even in the case of four-star roads, 60 occupants were fatally injured. Twenty-eight occupants were fatally injured in single-vehicle crashes, 26 in head-on crashes, and 6 in intersection crashes. Collisions with HGVs (Heavy Goods Vehicles) accounted for 53% (17 of 32) of all collisions with another vehicle on four-star roads. All six fatally injured occupants in intersection collisions collided with an HGV or an LGV (Light Goods Vehicle). Only 4 of the 28 fatally injured occupants in single-vehicle collisions fulfilled the occupant requirements.

5.1.2 Classification based on the further developed SRA model

Eighty-eight percent of vehicle occupants were fatally injured when more than one of the three components did not comply with the safety criteria. These cases were reclassified to identify whether all of the components correlated with the injury outcome, by using the further developed model (Step 2, as described in the methods section of Study I), Figure 11. In 85 of the total 230 cases at least two components were still seen to interact. The remaining cases were only related to one of the safety criteria, namely the road user (43), the vehicle (27) and the road (75).

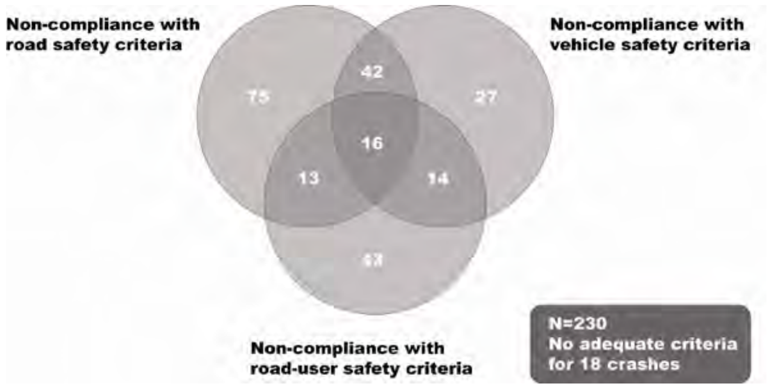


Figure 11. Reasons for fatal outcomes divided into non-compliance with safety criteria for the road, the vehicle, and/or the road user (Step 2, the further developed model)

5.2 STUDY II

Crash severity measured in crashed cars fitted with on-board crash pulse recorders differs depending on the type of opposite vehicle or object involved. Frontal two-vehicle crashes and single-vehicle crashes with rigid roadside objects were shown to generate the highest crash severity. The average crash severity in a frontal two-vehicle crash, in terms of change of velocity and mean acceleration, was 19km/h and 6.4g; in single-vehicle crashes with rigid objects it was 21km/h and 5.8g respectively, Table 3. The least harmful crash type was single-vehicle crashes into deformable objects (15km/h and 4.0g).

Table 3. Average crash severity divided into different collision partners

Collision partner	Change of velocity (km/h)	Mean acc. (g)
Frontal two-vehicle crash	**19**	**6.4**
Passenger car	18	5.5
HGV (>3.5 tonnes)	28	5.2
Single-vehicle crash	17	4.8
Rigid roadside object	**21**	**5.8**
Deformable object	**15**	**4.0**
Rear-end two-vehicle crash	10	3.5
Passenger car	10	3.5
HGV (>3.5 tonnes)	14	3.8

In single-vehicle crashes, the average mean acceleration was 45% higher in collisions with rigid roadside objects than in collisions with deformable objects. No crash with a deformable object occurred with a mean acceleration higher than 9g, Figure 12. Only 8% of crashes with deformable objects had a higher mean acceleration than the average mean acceleration of rigid roadside objects.

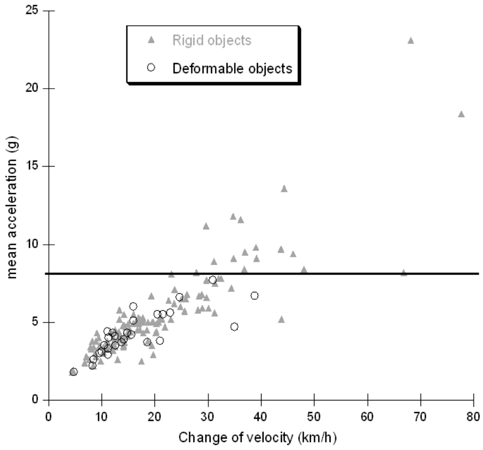


Figure 12. The difference in mean acceleration distribution between crashes with rigid and deformable objects

In frontal two-vehicle crashes, average change of velocity varied in accordance with the mass of the collision partner. The highest average change of velocity was found in crashes with HGVs (Heavy Goods Vehicles), and the lowest in crashes with superminis. Mean acceleration did not appear to follow the same pattern. However, a greater proportion of crashes with high mean acceleration and change of velocity was found in crashes with HGVs compared with passenger cars. For small cars, large cars and HGVs, the percentage of crashes where the change of velocity was higher than 45km/h was 2%, 7% and 22% respectively, Figure 13. These differences indicate the importance of focusing on mass incompatibility.

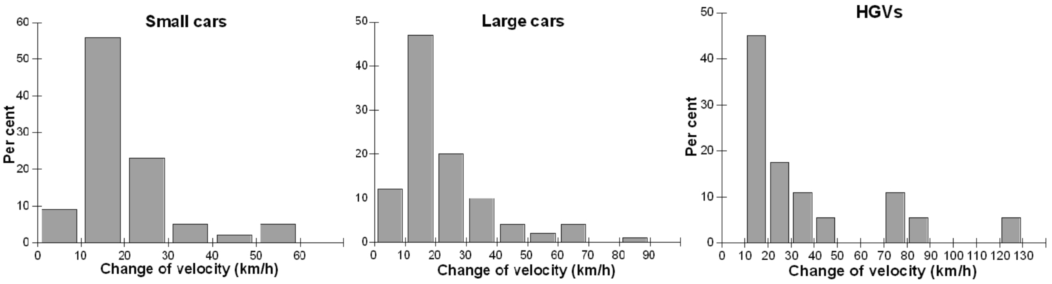


Figure 13. Distribution of crashes with small cars, large cars and HGV

In rear-end crashes, the average change of velocity was similarly influenced by the vehicle mass of the collision partner, see Table 3. Only small differences were found for mean acceleration. For small cars, large cars and HGVs, the percentage of crashes where the mean acceleration was higher than 5g was 13%, 18% and 28% respectively. The average change of velocity for all frontal two-vehicle crashes was almost twice as high as the value of all rear-ends crashes, while the corresponding difference for mean acceleration was 55%. Furthermore, in rear-end crashes, collisions with HGVs generated the highest average change of velocity: 14km/h.

5.3 STUDY III

It was found that crash severity, in terms of change of velocity and mean acceleration, was statistically significantly lower in crashes occurring on roads with a 4-star rating (highest safety rating) than in crashes on roads with a <4-star rating, Figure 14. More notable differences were found when the data were divided into subcategories based on speed limits. Both crash severity, in terms of change of velocity and mean acceleration, and the associated injury risk were lower on 4-star roads with a speed limit of 90km/h or 110km/h, than on <4-star roads, irrespective of speed limit. On the other hand, crash severity was higher on 4-star roads with a speed limit of 70km/h than on <4-star roads with the same speed limit. While it was found that a higher speed limit resulted in higher crash severity on <4-star roads, the opposite was found on 4-star roads.

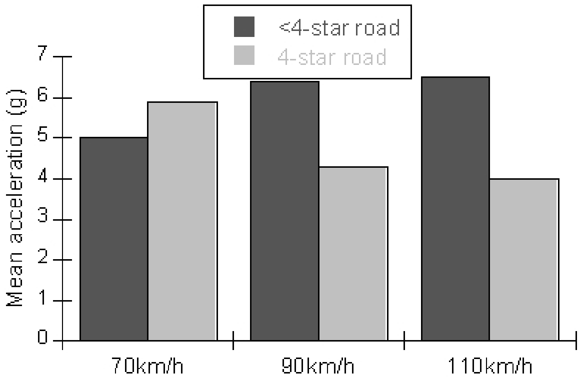


Figure 14. Average crash severity in crashes on 4-star and <4-star roads

Furthermore, statistically significant differences were found within the subcategories of divided and undivided 4-star roads. Both change of velocity and mean acceleration were lower on roads that were divided, compared with those that were not divided (change of velocity of 16km/h compared with 23km/h and mean acceleration of 4.4g compared with 6.3g). When comparing the number of injured drivers on divided and undivided 4-star roads, there was no difference in the proportion of drivers that sustained MAIS1+ injuries. However, there was a higher proportion of MAIS2+ injured drivers on undivided roads compared with divided roads (18% compared with 3%). Furthermore, there were no crashes resulting in a crash severity above the level corresponding to a 10% risk of sustaining serious or fatal injury on divided roads. This indicates that one of the most important road safety measures is divided roads.

5.4 STUDY IV

Safety Performance Indicators (SPIs), at least for seat belt use and alcohol-related crashes, cannot be assumed and treated as statistically independent. The result of the analysis of independence shows a clear indication that these two SPIs are highly associated. The conditional probability of not being restrained is far greater for a drunk driver than for a sober occupant, and the probability that an unrestrained driver is drunk is higher than expected. For Table 4, 217 fatally injured car occupants, divided into restraint use and whether the crash was alcohol-related, were compared with the estimated numbers, on the basis that seat belt use and BAC were not dependent on each other. The difference between estimated and observed outcome, shown in Table 4, is significant.

Table 4. Correlation between seat belt use and alcohol-related crashes in fatal crashes compared with estimations of the proportion (Restraint use 60.4%, alcohol involvement 24.9%)

	Restrained	Unrestrained
Not alcohol-related	114 (97)	47 (65)
Alcohol-related	16 (33)	40 (22)
Total	130	87

N=217
Fatal outcome (estimations)

The results from the analysis of linearity between SPIs and final outcome show that, for at least one of the SPIs, there is a marginal increase in effectiveness. The rate of seat belt wearing in Sweden has increased from 88% to 96% between 1997 and 2007. However, the proportion of the fatally injured drivers who were restrained (40% unbelted) has not changed. Therefore, an increase in an SPI among the general population might not lead to improvement of final outcome.

In order to study the effects of 100% fulfilment of a set of the SPIs (divided roads, seat belt use, sober driver and non-excessive speed), both observational data and in-depth fatal car crash investigations were used. In Table 5, the traffic flow and associated SPIs are estimated in order, from the smallest to the largest influence on traffic flow. By merely subtracting drivers under the influence of alcohol both from the traffic flow and from the fatally injured, it can be seen that the proportion of the traffic flow decreases by only 0.2% (99,8/100), while the number of fatalities decreases by more than 25% (161/217), Table 5. If the three SPIs for alcohol, speeding and restraint use are subtracted from the traffic flow, 5.2% of the traffic flow equals more than 50% of the fatalities. If only crashes that occurred on divided roads with 100% fulfilment of the SPIs mentioned above were included, one third of the traffic flow equals only 11 fatalities, or 5% of all fatalities on rural roads.

When the same SPIs were applied to divided and undivided roads separately, quite different results were shown. It can be seen in Table 5 that just over 60% of the traffic flow generates almost 90% (185 of 217) of the fatalities; there is a considerable difference between fatalities that do and do not fulfil the SPIs used, although the difference is not as great in the case of divided roads. Almost half of the 185 fatalities among car occupants on undivided roads occurred with 100% fulfilment of the SPIs. The equivalent figure for divided roads was one third of the fatalities.

Table 5. The proportion of traffic flow under certain conditions, and the associated number of fatally injured car occupants, on rural roads

Rural roads	**Percentage of traffic flow**	**No. of fatally injured (%)**
Total on rural roads	100%	217 (100)
Sober driver (99.8% sober)	99.8%	161 (74)
Sober driver + non-speeding* (99% within speed)	98.8%	143 (66)
Sober driver + non-speeding* + restrained (96% restrained)	94.8%	100 (46)
Sober driver + non-speeding* + restrained + divided roads (35% on divided)	33.2%	11 (5)
Divided roads	35%	32 (100)
Sober driver (99.8% sober)	34.9%	23 (72)
Sober driver + non-speeding* (99% within speed)	34.6%	17 (53)
Sober driver + non-speeding* + restrained (96% restrained)	33.2%	11 (34)
Undivided roads	65%	185 (100)
Sober diver (99.8% sober)	64.9%	138 (74)
Sober driver + non-speeding* (99% within speed)	64.2%	126 (68)
Sober driver + non-speeding* + restrained (96% restrained)	61.7%	89 (48)

*Below 30km/h over speed limit

6 GENERAL DISCUSSION

In order to achieve a safe road transport system, a preventive philosophy is necessary, where the road infrastructure is developed through good planning, including road and vehicle design based on the capabilities and limitations of human beings. The Swedish Road Administration's model for a safe road transport system (Linnskog, 2007; OECD, 2008), based on the *Vision Zero* philosophy (Tingvall, 1995) that links the properties of an inherently safe road transport system through SPIs (Study I), is a first attempt to create a new system-oriented approach focused on how the components (road, vehicle and road user) interact to promote safe road traffic. In this thesis, crashes have been analysed, based on this SRA model, to study the interaction between the components and thereby identify criteria and actions that are needed to achieve a safe system in which severe injuries can be avoided.

6.1 A SAFE SYSTEM APPROACH

Road safety is a major public health problem and a wide range of effective interventions are possible. However, this thesis indicates that it is essential to look at the road transport system in a holistic view, and to study the way in which road users, vehicles and the road infrastructure interact, in order to identify and correct the weaknesses that contribute to fatal and severe injury crashes. The SRA model, which links the components through a few SPIs to create and control an inherently safe system, is intended to be a tool to set performance targets and to identify the steps essential to achieve them. Car crashes with fatally or seriously injured occupants were classified according to the model criteria in Study I and in Stigson and Hill (2009). The model criteria seem to be relevant in most of the crashes. However, the results in this thesis indicate that more efforts are needed to create a safe system, and the model should therefore be seen as a first step in this direction. To move towards a safe system, all crash types (e.g. the shortcomings in Figure 15) need to be addressed by the SRA model and therefore more relevant design parameters are needed.

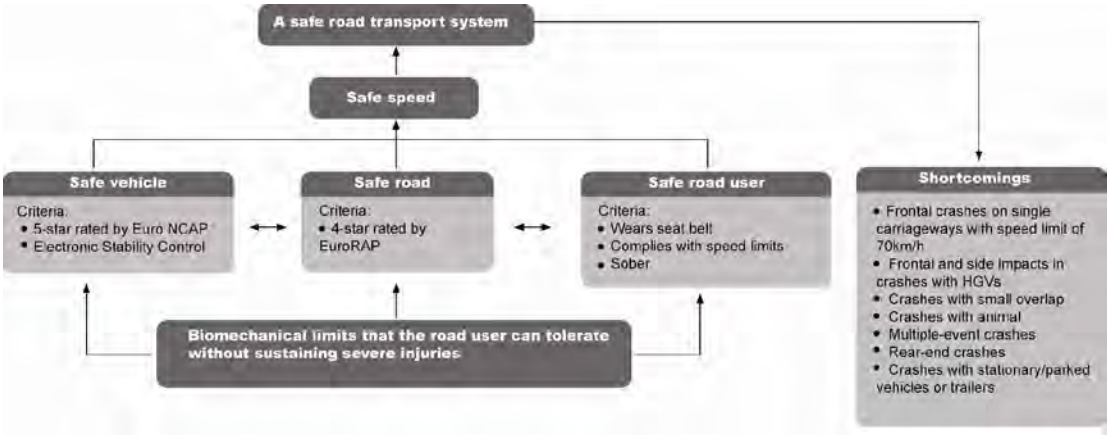


Figure 15. Identified shortcomings in the SRA model

The new safety system approach, for example the SRA model, facilitates discussion and definition of a safe system. In the SRA model it has been defined that in a road transport system, based on the *Vision Zero* philosophy, human tolerance to violence should be the limiting factor. However, in the SRA model this is mainly controlled by a safe speed. Injury risk correlates with speed, but speed is merely a substitute for crash severity and does not totally reflect how crashes resulting in fatal or serious injuries can be avoided. Hence, according to the results in this thesis, based on vehicle acceleration in frontal and rear-end crashes, acceleration has been identified as a relevant parameter for defining design guidelines that could be used in the safe system model. These design guidelines should be based on best practice and can be used to control expected human injury tolerance. The acceleration during the crash phase, measured by a crash pulse recorder, provides important information about how different collision partners or objects influence crash severity, which in a sense can be correlated with injury outcome. Acceleration should therefore be one of the key factors for making the system safe, rather than focusing on safe speed. Speed is an important factor, but should rather be seen as a regulator of the components of the system. The speed limit can be adjusted to fit the safety level of the road environment, and thereby to control the human injury tolerance level.

6.1.1 Terms to limit crash severity

Two-vehicle crashes with an impact speed of 70km/h have been identified as a weakness that contribute to fatal injury crashes in the model, as well as head-on crashes with HGVs, Figure 15. To make the model more stringent it is essential to have a strategy for a crashworthy road transport system that approaches the integration of the vehicle safety and the road design. The potential for improvement in injury prevention can be foreseen if these two components are combined. Some of the data used in this thesis are of high quality, which has made it possible to evaluate the components of the SRA model. The measured crash severity in Studies II and III has/can been correlated with injury outcome. Previous studies have shown that a high change of velocity in frontal crashes is not critical as long as the acceleration is kept below critical levels likely to cause an injury (Kullgren, 1998; Ydenius, 2002). The road transport system should therefore be designed with respect to acceleration levels, rather than change of velocity in order to more effectively prevent injury outcomes in frontal crashes. The least harmful crash type included in this thesis was single-vehicle crashes into a deformable guardrail, where no crash was found with a crash severity higher than 9g, which correlates with a less than 10% risk of sustaining serious injury. Based on the results in this thesis, best practice today could therefore imply setting the design parameter for accepted crash severity in a frontal impact to 9g in the current road transport system. Further verification how this suggestion was drawn will follow in the discussion section below.

6.1.2 SPIs included in model

Based on the result in Study I and Stigson and Hill (2009), it is clear that it is sufficient to use a few SPIs, with a proven potential for reducing injury risk, to classify road crashes and to determine weaknesses in the road transport system. Based on Study IV, the effect of 100% fulfilment of a set of SPIs (divided roads, seat belt use, sober driver and non-excessive speed) combined simultaneously, it is also clear that combining only a few SPIs can lead to a dramatic reduction of fatal injuries. If only crashes that occurred with 100% fulfilment of the SPIs mentioned above were included, one third of the traffic flow equals only 11 fatalities, or 5% of all fatalities on rural roads. While this finding is based on partly weak data (217 crashes occurring during one year), the direction of the results is promising. With this approach, a set of a few SPIs is good enough to count most of the fatalities, and to identify system deficiencies in a systematic way without becoming clouded. Furthermore, results from Studies II, III and IV indicate that the chosen SPIs in the SRA model are good measurements for the three components (road, vehicle and road user), but some of them could be replaced or other SPIs could be added. Furthermore, the road transport system is a dynamic system in which the components continuously change (e.g. the rapid development of new vehicle safety systems). In all the studies included in this thesis, SPIs are used and discussed, and the ones found to be most important are highlighted in the section below.

6.1.2.1 SPIs for the road user

The selected SPIs for the road user (seat belt use, compliance with the speed limit and not driving under the influence of alcohol/drugs) in the SRA model seem relevant, since they correlated to a great extent with fatal crashes. In Study IV, both observational data in traffic and in-depth fatal car crash investigations were used to reflect the differences between road user behaviour. Road user behaviour in fatal car crashes differs from that of road users in general. Approximately 99.8% of the traffic flow is under the legal alcohol limit in Sweden, but alcohol-impaired driving accounted for 25% of the fatally injured occupants included in the study. Furthermore, if all three SPIs for alcohol, speeding and restraint use are subtracted from the traffic flow, 5.2% of the traffic flow equals more than 50% of the fatalities (Table 5). Considering the result in Studies I and IV, it is however clear that a substantial proportion of the occupants that sustained fatal injuries obeyed the road rules. Most of these road users were fatally injured in a head-on crash with high crash severity (see section 6.1.2.3). This finding is supported by a Finnish study (Olkkonen et al., 2007). The opposite pattern was found by studying fatally injured occupants in single-vehicle crashes on a 4-star road, where 86% disobeyed the rules of the road. Furthermore, it was shown in both Study I and in the study by Stigson and Hill (2009) that road users who disobeyed rules often broke several rules at the same time (e.g. driving under the influence of alcohol without wearing a seat belt).

Changing road users' behaviour (e.g. increased seat belt use, reduced alcohol-impaired driving, buying a safer vehicle etc) would reduce the number of fatally and seriously injured people. Earlier studies have shown that information and education have a low impact on road casualties (Peden et al., 2004). A typical example of this is that, although the rate of seat belt wearing is 96% in Sweden, 40% of fatally injured occupants in Studies I and IV were not wearing a seat belt; they thereby represent the remaining 4% of the Swedish population. In the new approach to road safety it is necessary to move closer to 100%, but as the OECD (2008) pointed out, it will clearly be difficult to reach this subcategory of road users through more intensive application of traditional education and enforcement approaches. It is therefore essential to further stimulate design improvements of both vehicles and roads to accommodate improper road user behaviour. The proportion of belted car occupants would probably have been much higher if they had been sitting in a car with a 5-star rating by the Euro NCAP, because these are fitted with seat belt reminders (Lie et al., 2008). In the future, inherent vehicle safety systems should also encourage speed limit compliance and prevent the driver from driving under the influence of alcohol, to minimise injury outcome in road crashes. Concerning the result in Study IV, it is clear that the probability that an unbelted driver is also drunk is high. Therefore, vehicle systems such as seat belt reminders or alcohol interlocks will have an effect on several human behaviours.

6.1.2.2 SPIs for vehicle safety

Advances in car crashworthiness, including advanced seat belts, seat belt reminders, airbags, anti-whiplash systems and stability control systems have undoubtedly done a great deal to make modern vehicles safer. While these safety technologies are relatively widely available in the Swedish fleet, only a low number of the vehicles included in the studies in this thesis fulfil the criteria of 5-star vehicle (according to Euro NCAP test procedure up to autumn 2008). The number of new vehicles was also low in a Finnish study, and no conclusions regarding the effect of vehicle safety could be drawn (Olkkonen et al., 2007). In addition to this, most of the crashes included in Study I would have resulted in fatal outcomes irrespective of the vehicle safety standard according to best practice today, because the crash energy and other factors were far beyond the limits at which vehicle safety systems were able to prevent injury. Olkkonen et al. (2007) found that half of the road users fulfilling the criteria for being a safe road user were fatally injured as a result of crashing into vehicle structures or due to intrusion into the occupant compartment. In nearly one fifth of the cases the road user died because the vehicle was crushed. However, based on the results from Study I, this has more to do with the fact that the speed limit was too high in relation to the road environment, and thereby for the vehicle and the road user. The poor safety standard of the vehicle is also an important factor in these studies. Other studies confirm the benefit of new cars (Kullgren et al., 2009); in Study I, the potential of the vehicle to protect the road user was therefore judged to be high. Based on studies of several investigators (Farmer, 2006; Lie et al., 2006; Ferguson, 2007; Erke, 2008), we judged the potential of ESC to be considerable, since more than a quarter of the crashes included in Study I started with loss of control. Therefore both the proportion of the vehicle fleet that fulfils a 5-star rating in the Euro NCAP and the fitting of ESC are good SPIs with regard to vehicle standard, and should be included as criteria in the model. However, vehicle safety systems such as seat belt reminders and whiplash protection could be included as individual SPIs for the vehicle, both in the model as well as in target settings. In this matter, Euro NCAP ranking is still incomplete, but several improvements have been made in the new rating system that was introduced in spring 2009.

A substantial number of the fatally injured car occupants in Study I were not wearing seat belts. As mentioned above, the proportion of belted car occupants would probably have been much higher if they had been sitting in cars with a 5-star rating according to Euro NCAP, because these are fitted with a seat belt reminder. Lie et al. (2008) showed that seat belt reminders increased the rate of seat belt use from 85.8% to 97.5%. Concerning the result in Study IV, it is clear that there is a high probability that an unbelted driver is also drunk. Therefore vehicle systems such as seat belt reminders or alcohol interlocks will have an effect on several aspects of human behaviour, and should be included in SPIs aimed at measuring vehicle safety.

Gabler et al. (2004) have presented data indicating that 46% of the crashes involved two or more events. Results from Study I and Stigson and Hill (2009) indicate that the vehicle safety systems available are often not sufficiently capable of protecting the occupant in multiple-event crashes; even a 5-star rated vehicle may therefore not protect its occupants. More efforts are needed to solve the problem of multiple-event crashes. Furthermore, the criteria for a safe vehicle are not sufficient in vehicle-to-vehicle crashes involving small overlaps. Even if a vehicle complies with the criteria, it was judged in Study I and in Stigson and Hill (2009) that it would be impossible to protect the occupant in these crashes with today's vehicle safety systems. According to Lindquist et al. (2006) and Lindquist (2007), the injury mechanisms in small overlap crashes differ compared with full frontal crashes, and vehicle safety performance in small overlap crashes needs to be improved. Therefore, more efforts are needed to solve the road traffic problem of small overlap crashes.

Collision avoidance systems such as autonomous emergency braking systems (e.g. Volvo City Safe (Eugensson, 2008)), drowsiness warning systems, intelligent speed adaption, lane-keeping assistance, and alcohol interlock, represent examples of the future of crash and injury reduction. New safety systems added to vehicles to help the driver avoid a crash in the first place, or to prepare for crash protection, will probably be very beneficial (Kullgren, 2008; Krafft et al., 2009). New vehicle safety systems will also support the driver in observance of the rules of the road. Volvo's 2020 vision of an injury-safe passenger car (Volvo, 2009) will force vehicle manufactures to develop more sophisticated safety systems in the future. Volvo estimates that it will be possible to reduce pre-collision speed from 80km/h to a speed where the vehicle safety system will act in such a way that serious or fatal injuries will be avoided (Eugensson, 2008). All these safety systems could somehow make an impact on the number of crashes, and crashes resulting in serious injuries, and will thereby probably be important SPIs in the future road transport system. The new vehicle systems will also to some extent change the course of action for the creation of an inherent safe system, since there will be even more interaction between the three components (road, vehicle and road user). This will affect the relationship between the components in the SRA model. Many new vehicle safety technologies will partly shift the responsibility from the driver to the vehicle (e.g. seat belt reminders, alcohol interlock etc). Furthermore, systems such as autonomous emergency braking systems will reduce a critical speed to a speed where the vehicle safety system can act in such a way that serious or fatal injuries will be avoided. Such systems will thereby to some extent change the structure of the model.

6.1.2.3 SPIs for road design

EuroRAP, which was used in the model, has previously been identified as a good SPI measurement for evaluating the standard of road safety on existing roads (Vis and Van Gent, 2007). Both Studies I and III indicate that a 4-star road is safer than a <4-star road, since both fatal outcome and crash severity were lower. However, 24% of occupants in Study I sustained fatal injuries on 4-star roads. The proportion of fatally injured occupants on 4-star roads was greatest in head-on and single-vehicle crashes, but a few crashes also occurred in an intersection with a 4-star rating. Most of the fatal injuries sustained by occupants in vehicle-to-vehicle crashes were due to huge mass differences between the vehicles. Collisions with heavy goods vehicles (HGVs) accounted for 53% of all fatal crashes with another vehicle on 4-star roads. HGVs were also identified as a safety problem in Study II, since they more often generate higher crash severity than passenger cars. The average crash severity generated by HGVs correlates with an almost fourfold increase in risk of MAIS2+ injury for an occupant in a passenger car compared with the risk in a car-to-car crash. Collisions between cars and HGVs are not so frequent, but they account for a large proportion of fatal injury crashes (DfT, 2005; NHTSA, 2006; SIKA, 2008). By excluding crashes with road users who disobey traffic rules, e.g. alcohol-impaired driving or unbelted road users, Olkkonen et al. (2007) show that 38% of head-on crashes resulting in fatally injured car occupants concerned a collision with an HGV. A similar distribution could be seen in the Swedish national statistics. Collisions between HGVs/buses and passenger cars accounted for 25% of all two-vehicle-crashes resulting in severe injuries and 53% of all fatalities in Sweden (SIKA, 2008). The numbers are very high in comparison with the 10% proportion of HGVs/buses registered in Sweden (SIKA, 2006). This is a complex area that must be addressed to achieve a safe transport system. To prevent head-on crashes, and thereby crashes with HGVs, guardrails as mid-barriers have been shown to be an effective technical solution (Elvik, 1995). But other solutions are also needed to reduce the high acceleration levels in crashes between cars and HGVs. For example, it is necessary to re-design front ends of HGVs or develop autonomous emergency braking systems to reduce vehicle acceleration and thereby reduce the serious consequences of frontal crashes with cars, even on roads with low speed limits. With the exception of divided roads, there is no SPI where this large incompatibility problem is taken into consideration. One feasible SPI used in the target-setting process could be the percentage of HGVs on undivided roads on the national network, and the target could be to force haulage contractors to choose divided roads.

A large number of fatally injured occupants in single-vehicle crashes on 4-star roads in Study I disobeyed the rules of the road. This indicates that it is a special subcategory of road users that are fatally injured in single-vehicle crashes. However, most of these occupants hit a rigid object, and based on the results in Study II it is clear that some of these occupants would have survived if the road had been equipped with guardrails. In general, rigid objects produce 45% higher mean acceleration than deformable objects such as wire-rope guardrails. No crash with deformable objects included in Study II had a mean acceleration above 9g, which corresponds to a lower than 10% risk of an MAIS3+ injury. A previous study presented by Naing et al. (2008) supports this, showing that crashes into trees with impact speeds above 70km/h often resulted in severe or fatal occupant injuries, whereas vehicle occupants have survived after impacting guardrails at speeds above 90km/h. This is a strong indication that the proportion of the roads equipped with guardrails should be seen as an SPI for the safety level of the road. For a road network, the proportion of roads with guardrails could be seen as an SPI. However, it is important to mention that a concrete barrier generates much higher crash severity than a semi-rigid W-beam guardrail or a flexible wire-rope barrier (Ydenius et al., 2001). This was also shown in Study II, where rigid barriers in general generated almost 40% higher mean acceleration than other types of guardrail.

In Study III, crash severity, in terms of change of velocity and mean acceleration, was lower on 4-star roads compared with <4-star roads. However, the average crash severity was higher on 4-star roads with a speed limit of 70km/h than on <4-star roads with the same speed limit. On 4-star roads, average crash severity decreased with an increase in the speed limit. The opposite pattern was found on <4-star roads. The main reason for this was that on 4-star roads the lanes for traffic travelling in opposite directions were more often separated at higher speeds. On divided roads there were no crashes resulting in crash severity above the level corresponding to a 10% risk of sustaining serious or fatal injury. Study IV also supports this, since if only crashes with 100% fulfilment of a few of the SPIs (sober driver, non-excessive speed, seat belt use and divided roads) were included, only 5% of the total number of fatalities occurred under these circumstances. The corresponding percentage for undivided roads was 41. It is notable that 35% of the traffic flow on Swedish roads occurs on divided roads. This fact, together with the findings in the other studies included in this thesis, shows the benefits of divided roads and indicates that one of the most important SPIs for the road is the proportions of divided roads rather than the EuroRAP star rating alone.

In the SRA model, as well as in the EuroRAP RPS, it has been assumed that a modern car can protect its occupants in a head-on crash, on roads where the speed limit is 70km/h. Study III shows that crash severity is too high in vehicle-to-vehicle crashes on roads with a 70km/h speed limit. Furthermore, a fair number of fatal car crashes in Study I occurred on roads with a speed limit of 70km/h (19 of 80). Olkkonen et al. (2007) showed that the probability of death increased rapidly when the change of velocity exceeded 70km/h. A single carriageway with a 70km/h speed limit, without physical separation between opposing flows of traffic, could therefore not be classified as a safe road considering the safety standard of the vehicle fleet in use to date. However, in the future road transport system these single carriageways are becoming safe due to the effects of vehicle safety systems such as autonomous emergency braking, that will limit the impact speed by pre impact braking and thereby reduce the crash severity to survivable levels.

Only a few crashes included in the studies are side impacts, and therefore it is not possible to draw any conclusions regarding which SPI best reflects this crash type. Only six fatally injured occupants in intersections classified as 4-star roads were included in Study I. In all these cashes the opposite vehicle was an HGV or an LGV (light goods vehicle). In Studies II and III no side-impact crashes were included.

6.2 IMPORTANT ACTIONS TO ACHIEVE A SAFE ROAD SYSTEM

The OECD (2008) has strongly recommended that countries should adopt a system approach to achieve road safety targets. Using intermediate outcomes, such as SPIs, has been identified as a suitable solution. The traditional measurements used to identify road safety problems are not powerful enough to model the complexity of the road safety situation. When road traffic authorities seek to prioritise the most effective solution for reducing the number of road traffic victims, measuring road safety in terms of crash and injury rates has limitations. Crash and injury data could be misleading due to random fluctuations and external factors (Elvik, 1997). The possibility of linking safety deficiencies to crashes without knowing the underlying processes that produce the crashes is also limited (Weijermars et al., 2008). Furthermore, the numbers of crashes and seriously injured are proportionally small compared with the exposure risk in daily traffic and it does not provide information about the whole road safety system.

As mentioned in the introduction, the use of SPIs has rapidly increased during recent years (Vis and Van Gent, 2007; Elvik, 2008; ISO, 2008; OECD, 2008; SRA, 2008b; Hermans et al., 2009) and currently safety policies are moving towards defining safety criteria (Peden et al., 2004) rather than identifying risk factors. The use of SPIs is also a more resource-efficient and ethically appealing alternative for fast, reliable and effective safety assessment. SPIs such as seat belt wearing, vehicle fleet standard and observance of speed limits, provide information about underlying causes of crashes.

Traditionally, comparison between countries has often been based on crash data. To some extent, this merely rates the road safety situation in the respective countries and does not identify any aspects of road safety problems that should be focused on. The European Transport Safety Council (ETSC) has introduced a more effective way of benchmarking road safety between countries by using SPIs, so-called PIN (ETSC, 2009). This type of benchmarking could put pressure on countries and help policymakers more effectively prioritise actions needed to further reduce the number of crashes resulting in seriously and fatally injured car occupants.

The safe system approach should also be translated into action in e.g. vehicle-purchasing policies. Although most new vehicle safety systems are first introduced in executive cars, with a stimulation process the most successful technologies could be implemented in mainstream vehicles within a few years. In Sweden, ESC is one example of how systems can effectively be introduced in the fleet by a stimulation process (Krafft et al., 2009). The proportion of new cars registered in Sweden fitted with ESC was 97%, which could be compared with 48% in Europe (FIA Foundation, 2008; Krafft et al., 2009; SRA, 2009a).

6.2.1 Characteristics of SPIs

In some of the analyses included in this thesis, as well as in several other studies and target-setting processes (Elvik, 2008; Hermans et al., 2008; SRA, 2008b; Hermans et al., 2009), calculations of the effect of SPIs are based on the assumption that the SPIs are independent. It is obvious that some SPIs are independent (e.g. rates of helmet wearing and seat belt wearing), in which case the effects of improved SPIs are simply additive. However, if SPIs are to be used in target-setting, the characteristics of the SPIs must be further evaluated. In Study IV, it was shown that seat belt use and high BAC are highly associated, since the probability that a drunk driver was not restrained was far greater than for a sober occupant; furthermore, the probability that an unrestrained driver was drunk was higher than estimated. Similar correlations were found in accident data from Victoria, Australia (VicRoads, 2008). The results from Study IV would imply that when improvements are made with regard to both restraint use and alcohol-related crashes, the benefit is less positive than projected by models (such as those used by Elvik (2008) and the SRA (2008b) where these SPIs are assumed to be independent. On the other hand, increasing seat belt use across all road users would have a major benefit on alcohol-related deaths. Treating the SPIs for sober and restrained drivers as two statistically independent factors as in some target-setting process (Elvik, 2008; SRA, 2008b) could therefore both under- and over-estimate the impact of an improved SPI. The implication is that simple multiplicative treatments of

SPIs to estimate effects of multiple improvements should be treated with some care. Methods to compensate for related SPIs should be developed. This is done by Elvik (2008), but in an instrumental way and not based on actual dependency. In order to derive more accurate estimates of projected improvements of SPI, data on combinations of SPIs should be used. Concerning the results from Study IV (Table 4), it is clear that at least two of the SPIs are highly dependent, and the assumption of statistical independence must be rejected.

SPIs such as seat belt use have been assumed to reflect the number of fatally and seriously injured as if the relationship between SPIs and final outcome is linear. This assumption must partly be rejected based on the analysis of linearity between SPIs and final outcome (Study IV). While the rate of seat belt wearing in traffic increased from 88% to 96% between 1997 and 2007, the proportion of fatally injured car occupants that were restrained did not change. Forty percent of the fatally injured were unbelted. It was quite surprising that a substantial improvement in an SPI, e.g. seat belt use, might not necessarily lead to an improved final outcome. This in no way questions the effectiveness of seat belt use, but merely shows that the risk of a proportion of the non-users being involved in serious crashes increases considerably.

As mentioned above, a few SPIs (divided roads, seat belt use, sober driver and non-excessive speed) can lead to a dramatic reduction of fatal crashes if the SPIs are combined simultaneously. When calculating the amount of traffic under these conditions, the assumption is that the SPIs are independent. In an earlier section this was questioned, but in the present case, the likely consequence when calculating non-compliance with the SPIs in combination, would be smaller. However, for the calculation of the fatalities, it has a major effect, as shown in Figure 7 in the method section. It should also be understood that the number of fatalities shown in Table 5 is not the expected number if all SPIs are fulfilled. As an example, some of the unrestrained would still be fatally injured even if they were restrained. However, the finding that only 5% of the total number of fatal crashes occurred under the circumstances mentioned above is promising, underpinning that the set of a few SPIs included in the SRA model is good enough to count most of the fatalities.

6.2.2 Interactions between components in the system

Instead of focusing on risk factors, some SPIs were used for measuring what could be expected in an inherently safe road transport system in Study I. The classification based on the criteria of the SRA model provides a picture of the safety standard of the three components (road, vehicle and road user) in fatal car crashes. However, to identify weaknesses in the road transport system, the further developed model presented in Study I (Step 2, as described in the methods section of Study I) was needed to give a more adequate picture of the efforts needed to create a safer road transport system. By using the SRA model alone it is difficult to ascertain which failed criteria are important for the fatal outcome. The further developed model is one way of approaching the analysis of correlations between un-survivable crash severity and non-compliance criteria, in order to identify system weaknesses. The model does not propose solutions but rather qualities of a safe road transport system. Based on this analysis, most of the crashes with fatally injured car occupants occurred when more than one of the components did not comply with the safety criteria of the SRA model for a safe road transport system.

The traditional approach to modelling the road transport system has been by decomposition into elements that are modelled separately (Rasmussen, 1997). Most research based on Haddon's matrix (1980) has also been focused on each phase (pre-crash, crash, and post-crash) at one time to examine the causes of traffic crashes and to generate ways of preventing and controlling them. As pointed out by Evans (1991), road crashes are complex, and by just focusing on one component without looking at the interaction, interventions with the aim of preventing crashes or limiting the severity of the crashes are limited. Every crash has its own unique features on the surface but a further analysis will show underlying systematic patterns that lead to increase in risk (Leveson, 2004). Treat (1980) and Sabey and Taylor (1980) conducted studies where they identified that the road user was the sole or a contributory factor in approximately 95% of all crashes. The approach used by Treat (1980) and Sabey and Taylor (1980) fails to consider human errors that could be prevented by adapting the environment. Several researchers assert that this is the most effective way of eliminating human errors rather than focusing on changing human behaviour (Haddon, 1980; Reason, 1990; Tingvall, 1995; Wegman, 2003; Peden et al., 2004). The results from Study I show a totally different view of the problem compared with the two previous studies mentioned above (Sabey and Taylor, 1980; Treat, 1980), Figure 16.

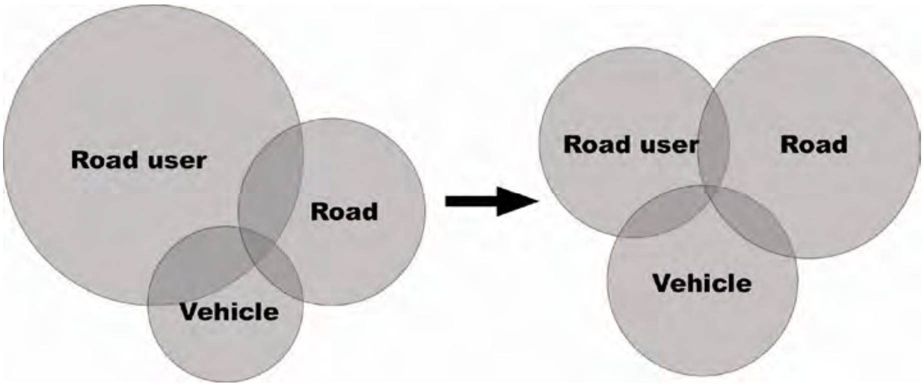


Figure 16. The responsibility has shifted from the road user, to being shared equally by all the components: the road user, the road and the vehicle, (Sabey and Taylor, 1980; Treat, 1980) → (Stigson et al., 2008)

The way of looking at the three components as integrated will certainly be much more common in the future. Many aspects of important road user behaviour will be controlled by vehicle safety systems. Together with successful road design solutions, these systems will probably reduce crash severity. All these solutions combined lead to a safe system. As an example, a vehicle that can automatically brake before impact with a pedestrian is likely to benefit more from a pedestrian-friendly front end as well as from improved urban design including traffic calming. The explanation for such a hypothesis is that the proportion of impacts with pedestrians might take place at speeds where the front of the car can reduce the likelihood of an injury, whereas at high speeds, the envelope of possible protection is more often missed (Yang et al., 2001).

6.3 FUTURE RESEARCH NEEDS

Some improvements must be made in SPIs and/or the SRA model before they can be fully used as a guiding tool towards a safe system. The data selected for the included studies was limited to include only car crashes and car occupants. If the SRA model is to be a fully useful tool in road safety work, it is necessary to include other road users, e.g. motorcyclists, cyclists and pedestrians who do not run the same risk as car occupants. It is also known from previous studies conducted on wider datasets that both age and gender influence the risk of being fatally injured in a car crash (Bedard et al., 2002). In particular, age and fatality risk are strongly correlated with each other (Braver and Trempel, 2004). This has not been taken into consideration in this thesis. The needs of vulnerable car occupants must also be fully taken into account in order to further work with the SRA model. Since road crashes are one of the leading causes of permanent medical impairment and reduction of productive years in the population, it is also important to study how the SRA model can cope with these additional road users and their injuries. Furthermore, the characteristics of SPIs need to be studied in more detail.

6.3.1 Relevant and standardised crash and injury data

The use of SPIs and/or the SRA model as a tool to reduce the number of fatally and seriously injured relies on the fact that data on road crashes and injuries are relevant, valid and standardised. It is especially important to establish standardised data for all the countries to enable comparisons such as those made by Herman et al. (2008) in the use of SPIs. There is currently no systematic collection of SPIs and existing sources of data are limited. It is somewhat strange that while traffic-related data seems to be based on consensus, most databases, as well as in-depth studies, seldom pick up what seems relevant today. Weather conditions, although never proposed as an SPI, seem to be collected all over the world, but this is not the case for seat belt use, car specification or the local quality of the crash protection properties of the infrastructure. This is an issue that needs to be addressed now that SPIs are becoming the most important tool for promoting safety management.

It also is noteworthy, that road user behaviour in fatal car crashes differs from that of road users in general. The finding in this thesis stresses the need to collect and analyse SPIs not only in traffic, but also in real-world crashes. It is important to highlight that the focus should be set not only on fatal crashes, since for each fatally injured road user there are many more who sustain severe or minor injuries (Krug et al., 2000). In many of these cases the injuries result in permanent medical impairment. Malm et al. (2008) have shown that as many as 10% of minor injuries (AIS1) lead to permanent medical impairment. The risk of sustaining a permanent medical impairment was higher in cases of greater injury severity, but due to the frequency of minor injuries, the majority of impairments have been sustained from minor injuries.

6.3.2 Improvement of the model – a continuous process

Based on the results in Study I and Stigson and Hill (2009), it is clear that it is sufficient to just use a few SPIs, with a proven potential for reducing injury risk, to classify road crashes and to determine weaknesses in the road transport system. Studies II, III and IV indicate that the chosen SPIs are good measurements for the three components (road, vehicle and road user). However, a number of shortcomings in the criteria were identified. The criteria of the model are not adequate to classify the safety level of the road and the vehicle in multiple-event crashes, crashes with small overlap, rear-end crashes, vehicle-animal crashes, or hitting stationary/parked vehicles or trailers, and should therefore be further developed. Furthermore, the road transport system is a dynamic system in which the components continuously change (e.g. the rapid development of new vehicle safety systems). SPIs should act as controller to maintain the safety in the system. Hence, it is also important to continuously determine the objectives and performance of the SPIs both by observational data and in real-world crashes. The risk management of the road transport system should have a proactive approach with the prevention of safety problems before a crash occurs instead of being based on responses to previous crashes. Therefore both SPIs and the SRA model could be a useful tool to move towards an inherently safe system. The interaction between the components of the system must be taken into account.

Public education campaigns together with police enforcement could change road user behaviour. Road users may be motivated to change their behaviour over a short period of time, but for a more sustainable system the vehicle and the road design must support the road user in using the system safely. Haddon (1980) described ten possible strategies for injury control. According to these strategies, which are still relevant, the most effective way of preventing injuries is to adapt the environment rather than focus on changing human behaviour (Haddon, 1980; Reason, 1990; Wegman, 2003; Peden et al., 2004). Both road and vehicle design are and will be even more important in the future to create a safe system. In new vehicle safety systems, the distinction between the three components is blurred, and this will to some extent change the structure of the model. As mentioned in the previous section, many new vehicle safety technologies will partly shift the responsibility from the driver to the vehicle and system; for example, autonomous emergency braking system will reduce crash severity. A safe journey in accordance with the SRA model will be achieved either by high road safety standards (e.g. divided roads), or by compensating for poor road safety standards with new vehicle safety systems (e.g. autonomous emergency braking system) that can reduce an unsafe speed, the purpose being to avoid crashes or, in other situations, to limit crash severity. The achievement of expected safety gains from vehicle and road safety improvements will however still depend on setting speed limits that are appropriate to the system design. Figure 17 is one example of how the model could be adapted to the circumstances required to protect the road user in frontal car crashes in the future.

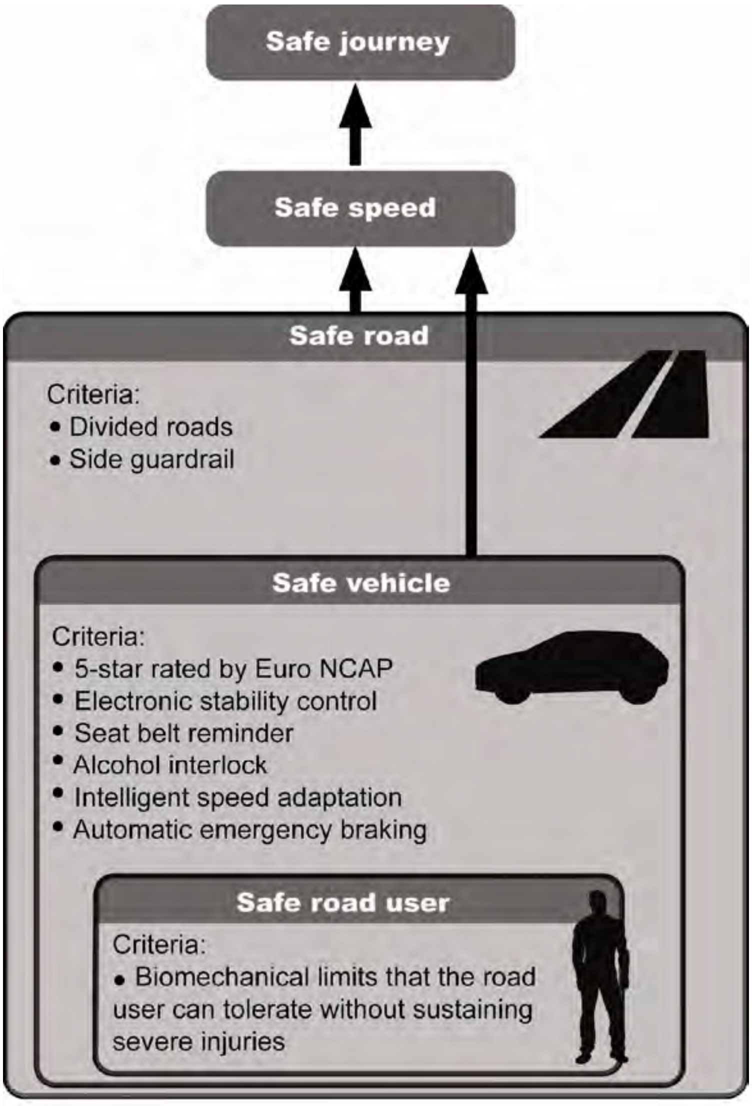


Figure 17. According to the proposed model a safe journey can be achieved in case A or B. *Case A:* the vehicle supports correct use, and different vehicle safety systems reduce an unsafe speed so that crashes can be avoided or, in the case of a crash, so that crash severity is limited. *Case B:* the vehicle and the road together support correct use, and a high standard of road safety (e.g. divided roads) is needed to limit crash severity.

7 CONCLUSIONS

The thesis was carried out with a system approach, to study and identify system weaknesses. The following specific conclusions were drawn.

- Most road traffic casualties are related to an interaction between the three components: the road, the vehicle and the road user. Therefore a system approach is needed to analyse road crashes and to find preventive interventions.

- The SRA model can be used to classify in-depth fatal car crashes. However, to identify weaknesses in the road traffic system, a more sophisticated method is needed as a complement to the SRA model.

- Crash severity differs depending on collision partner. Frontal two-vehicle crashes and single-vehicle crashes with rigid roadside objects were shown to generate the highest crash severity. Crash severity was significantly lower in single-vehicle crashes with deformable objects compared with frontal two-vehicle crashes and single-vehicle crashes with rigid roadside objects.

- A higher proportion of frontal two-vehicle crashes, where change of velocity exceeded 45km/h, occurred in collisions with HGVs than in collisions with small cars (22% as compared with 2%).

- In total, crash severity was statistically significantly lower in crashes occurring on roads with a good safety rating than in crashes occurring on roads with a poor safety rating. Crash severity and injury risk were lower on roads with a good safety rating with a speed limit of 90km/h to 110km/h, compared with roads with a poor safety rating, irrespective of speed limit. On the other hand, crash severity was higher on roads with a good safety rating with a speed limit of 70km/h, than on roads with a poor safety rating with the same speed limit.

- While it was found that a higher speed limit resulted in higher crash severity on roads with a poor safety rating, the opposite was found on roads with a good safety rating. The main reason for this was that lanes for traffic travelling in opposite directions were more often separated at higher speeds on roads with a good safety rating.

- It is possible that a set of SPIs in combination (sober driver, non-excessive speed, seat belt use and divided roads) might lead to very few fatalities. Only 5% of all fatalities on rural roads in Sweden occurred under such circumstances.

- Safety Performance Indicators (SPIs) should not generally be treated as statistically independent, at least not with regard to seat belt use and alcohol-related crashes.

- An increase in an SPI might not lead to an improvement in the final outcome in terms of fatalities or injuries. Therefore, both SPIs and final outcome, classified according to SPIs, should be collected and analysed.

- This thesis indicates that divided roads constitute one of the most important road safety measures for car occupants. On divided roads there were no crashes resulting in crash severity above the level corresponding to a 10% risk of sustaining serious or fatal injury. Furthermore, in no crash with deformable guardrails was the mean acceleration higher than 9g.

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> *"This is not the end. It is not even the beginning of the end. But it is, perhaps, the end of the beginning."*
> Sir Winston Churchill

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