How to Make Bicycling Safer

How to Make Bicycling Safer

Identification and Prevention of Serious Injuries among Bicyclists

Maria Ohlin

Preface

This thesis project has been conducted as a collaboration between the Department of Food and Nutrition and Sports Science (IKI) at Gothenburg University and the Department of Mechanics and Maritime Sciences at Chalmers University of Technology. The research was funded by the Swedish Transport Administration.

I would like to thank my supervisors, Professor Anders Kullgren, Beatrix Algurén, and also my former supervisor professor Anders Lie. I am very happy and grateful to have had your support and guidance during these years. Also, I would like to thank Professor Per Lövsund at Chalmers and Professor Claes Annerstedt at IKI, and also the Swedish Transport Administration, for their support in making this collaboration possible, and for letting me be a part of the 'Chalmers family' as well.

I would like to give a special thanks to my friends Johan Strandroth and Simon Sternlund at the Swedish Transport Administration, and to Claes Tingvall who believed in me and made my research possible. Especially Johan, I would not be writing these words had our paths never crossed. I also want to thank my fellow colleagues at Karolinska Institutet and Folksam for their collaboration, and my fellow PhD students at IKI. I am also grateful to my family and friends for their support, giving me the boost I need to keep on going. Finally, and very close to my heart, Matteo, you and your support mean the world to me.

To the wonderful things yet to come

Abstract

The overall aim of this thesis was to guide current and future safety improvements that address serious injuries among bicyclists. The thesis is compiled by four studies, of which the first two aimed to identify injuries leading to loss of health from a biopsychosocial perspective, and the two following studies aimed to understand how these injuries occur and how they can be prevented.

Study I investigated health-related quality of life (HRQoL), based on the EQ-5D questionnaire, while Study II investigated sickness absence (SA), following a bicycle crash. On a general level, the injuries associated with problems in HRQoL and long-term SA included mainly fractures of the hip and upper leg, fractures of the lower leg and ankle, fractures of the upper arm, fractures and sprains of the shoulder, traumatic brain injuries, and fractures and strains to the spine.

Study III found that the majority (68%) of such injuries occurred in single bicycle crashes, and further 17% in collisions with motor vehicles. In Study IV it was shown that the current Swedish safety performance indicators related to cycling could address up to 22% of crashes involving injuries associated with problems in HRQoL and long-term SA.

In addition to the current safety performance indicators, the following five actions should be the focus of more rapid implementation: autonomous emergency braking with cyclist detection on passenger cars, extended maintenance to include all urban roads used for cycling, improved design of curbstones, and to separate cyclists from both motor vehicles and pedestrians. Overall, this thesis highlights that additional interventions targeting single bicycle crashes need to be prioritised by road authorities in order to prevent health loss among bicyclists.

Swedish summary

Utifrån hälso- och hållbarhetsperspektiv vill samhället öka andelen resor med cykel. Samtidigt är cyklister en oskyddad trafikantgrupp, vilket gör att man som cyklist är sårbar i händelse av en olycka. Sedan några år tillbaka utgör cyklister majoriteten av de som förväntas få bestående men till följd av personskador i vägtrafiken. 1997 antog Sveriges riksdag Nollvisionen, ett angreppssätt med det långsiktiga målet att ingen ska dö eller skadas allvarligt till följd av trafikolyckor. Det övergripande syftet med denna avhandling har varit att bidra till arbetet med att förbättra trafiksäkerheten för cyklister med fokus på allvarliga skador. De inledande två studierna syftade till att identifiera skador som, från ett biopsykosocialt perspektiv, leder till hälsoförlust bland skadade på cykel. I de efterföljande studierna undersöktes hur dessa skador uppstår och hur de kan förhindras.

I Studie I undersöktes förekomsten av problem i hälsorelaterad livskvalité 1–3 år efter trafikskada, baserat på frågeformuläret EQ-5D, bland 959 personer som skadats i cykel- och bilolyckor. Resultaten visade att det både bland skadade i bil och på cykel oftast var skador på ben och rygg bland de personer som hade problem efter sin trafikskada. Studie II var en populationsbaserad registerstudie som undersökte sjukskrivning bland personer som skadats i en cykelolycka. Inkluderade var personer i åldrarna 16–64 år som under 2009 till 2011 fått specialiserad öppen eller sluten medicinsk vård i samband med cykelolycka (22, 045 personer). Omkring 1% av personerna blev sjukskrivna under minst 180 dagar i samband med olyckan. Bland dessa hade 21% skadats i nedre delen av benet, 17% i axel och överarm, och 15% hade fått en hjärnskada. Skador på ryggraden visade högst risk för sjukskrivningsfall som varade 90 dagar eller längre, följt av svårare hjärnskador och skador på ben.

Vidare undersöktes omständigheter kring olyckor där personer fått skador som oftare leder till hälsoförlust. I Studie III gjordes ett urval från den nationella olycksdatabasen Strada baserat på skadediagnoser från de skadade på cykel som hade problem i hälsorelaterad livskvalité efter sin trafikskada (Studie I) samt bland de personer som blivit sjukskrivna minst 180 dagar (Studie II). Dessa skador inkluderade frakturer på ben och överarm, frakturer och stukningar på axel, skador på ryggraden samt hjärnskador. Informationen från Strada kompletterades med ett frågeformulär i syfte att få mer detaljerad information om olyckan och konsekvenser av skadan. Urvalet begränsades till personer som

var minst 15 år vid olyckstillfället och som skadats i en cykelolycka mellan januari 2013 och april 2017.

Resultat från Studie III visade bland annat att majoriteten (68%) skadats i singelolyckor, 17% hade skadats i kollision med ett motorfordon (oftast en personbil), och 11% hade skadats i kollision med en annan oskyddad trafikant. I 46% av singelolyckorna hade personer av olika anledningar tappat kontrollen över cykeln, exempelvis genom förlust av friktion vid halt underlag. I Studie IV undersöktes i vilken utsträckning olika säkerhetshöjande åtgärder hade potential att adressera olyckorna i Studie III. De åtgärder som idag används som indikatorer för säker cykling i Sverige hade potential att adressera 22% av olyckorna. Av dessa stod förbättrad drift och underhåll på vinterväglag för 8%, säkra personbilar för 5%, och säkra cykelpassager för 4%.

Högsta möjliga potential, med lägst antal åtgärder, skulle uppnås genom att kombinera de åtgärder som idag används som indikatorer för säker cykling med: automatisk nödbroms för cyklister, utökad drift och underhåll inom tätort, förbättrad utformning av trottoarkanter och kantstenar, samt att så långt som möjligt separera cyklister från både motorfordon och fotgängare. Implementering av dessa åtgärder bör därför prioriteras. Vidare bör fokus för fortsatt utveckling av nya åtgärder vara på singelolyckor, eftersom dessa står för en klar majoritet av de cykelolyckor med skador som oftare leder till hälsoförlust.

Table of Contents

List of tables and figures

List of papers

This thesis is based on the following original papers, which will be referred to in the text by their Roman numerals:

I   Ohlin, M., Berg, H.Y., Lie, A., Algurén, B. (2017). Long-term problems influencing health-related quality of life after road traffic injury – Differences between bicyclists and car occupants. *Journal of Transport & Health*, 4:180-190. doi:10.1016/j.jth.2016.08.007

II   Ohlin, M., Kjeldgård, L., Elrud, R., Friberg, E., Stigson, H., Alexanderson, K. (2018). Duration of sickness absence following a bicycle crash, by injury type and injured body region; a population-based study. *Journal of Transport & Health*, 9:275-281.

III   Ohlin, M., Algurén, B., Lie, A. (2019). Analysis of Bicycle Crashes in Sweden Involving Injuries with High Risk of Health-Loss. *Traffic Injury Prevention*, 20(6):613-618. doi: 10.1080/15389588.2019.1614567

IV   Ohlin, M., Rizzi, M., Algurén, B., Kullgren, A., The Potential of Different Countermeasures to Prevent Injuries with High Risk of Health Loss among Bicyclists in Sweden. Manuscript submitted.

Abbreviations

AIS   Abbreviated Injury Scale

EQ-5D   EuroQol five dimensions questionnaire, standardised instrument
           for use as a measure of health status

HRQoL   Health Related Quality of Life

ICD-10   International Classification of Diseases and Related Health
           Problems, Tenth Revision.

ICF   International Classification of Functioning, Disability and Health

MAIS   Maximum Abbreviated Injury Scale

MV   Motor vehicle

PMI   Permanent medical impairment

RPMI   Risk of Permanent Medical Impairment

SA   Sickness absence

SPI   Safety Performance Indicator

Strada   Swedish Traffic Accident Data Acquisition System

WHO   World Health Organization

Background

Traffic injuries in a global context

Traffic injuries are a global safety issue. The World Health Organization (WHO) estimates that 1.35 million people are killed and 50 million are injured annually in road crashes around the world, and millions more suffer injuries with long-term consequences (WHO, 2018; WHO, 2015). Traffic injuries are the leading cause of death in the age group 15 to 29 years, and the 8th leading cause of death for people of all ages (WHO, 2018). While 90% of road traffic fatalities occur in low- and middle-income countries, these countries only account for 54% of all registered vehicles, meaning that they have a disproportionate number of fatalities in relation to their level of motorization (WHO, 2015). In the last five years, there has been no reduction of road traffic fatalities in low-income countries, although a decrease have been observed in some middle- and high-income countries (WHO, 2018).

More than half of the road traffic deaths worldwide involve vulnerable road users: pedestrians (23%), bicyclists (3%) and powered two wheelers (28%) (WHO, 2018). In the European Union (EU), bicyclists represent 8.1% of road traffic fatalities, with more than 2100 people killed in bicycle crashes in 2014 (ERSO, 2016). Sweden, like many other countries in Western Europe, has a history of declining numbers of road fatalities since the 1970s (International Traffic Safety Data and Analysis Group [IRTAD], 2012). In Sweden, the number of fatalities per 100,000 inhabitants has declined from 8.7 to 2.7 between 1991 and 2015 (European Commission, 2016), which is among the lowest fatality rates in the world.

However, bicyclists and other vulnerable road users have a higher risk of being injured or fatally injured in a crash compared with car occupants. In Sweden, the number of bicyclists killed per passenger kilometre has been reported to be five times higher than for passenger car occupants, although motorcyclists have an even higher risk (25-30 times higher compared with car occupants) (Björketun & Nilson, 2006). In a recent study, it was found that the risk of fatal

injury was 10 times higher, and the risk of (hospital-reported) non-fatal injury was 20 times higher for bicyclists compared with car occupants (Nilsson et al., 2017). In recent years, the number of injured bicyclists has increased as the number of injured car occupants has decreased, and bicyclists now account for a higher proportion of hospital-reported crashes and injuries than any other road user category in Sweden. In 2017, bicyclists represented 47% of all those who were prognosticated to be seriously injured, but only accounted for around 10% of all road fatalities in Sweden (Swedish Transport Administration, 2018). The focus of the present thesis will be to investigate serious injuries among bicyclists, and how they can be prevented.

Promoting cycling for increased health

This thesis is written within the subject of sports science, which as an academic research field is rather recent, although the study of sport as subject has been studied since ancient times (Lindroth, 2010). Until the 1970´s, sports science was mainly characterised by physiological and medical sciences (Wirén Åkesson, 2014). During the 1970´s, sports science in Sweden developed within humanities and social sciences to include other scientific disciplines, such as sport pedagogy (Wirén Åkesson, 2014) and the scope broadened to also include areas such as health promotion (Annerstedt, 2007). At the Department of Food and Nutrition, and Sports Science at University of Gothenburg, physical activity is an important aspect of sports science (University of Gothenburg, 2018).

The level of physical activity among the Swedish population has decreased over the last century, and today only a small percentage of the population achieves the minimum levels of physical activity (Schantz, 2015). A pronounced decline in cardiorespiratory fitness, which is a predictor of health and risk for non-communicable diseases (Blair et al., 1996), was observed among Swedish adults between 1995 and 2017 (Ekblom-Bak et al., 2019). Worldwide, physical inactivity is recognized as a major public health problem while the positive effects of physical activity on health are well-known (Ainsworth & Macera, 2012). According to a British report by Cavill and Buckland (2012), increased physical activity delivers the greatest health benefits for those who are physically inactive or sedentary. They found that within this group, a 32% reduction in the risk of premature death could occur if they become moderately active (0.5-1 hour of physical activity per day).

Bicycling has been widely recognized as an important contributor to help increase the level of physical activity (Oja et al., 1998; Sahlqvist et al., 2013) and hence reduce the risk of several diseases related to physical inactivity (Lindström, 2008; Oja et al., 2011) and all-cause mortality (Matthews et al., 2007; Kelly et al., 2014). A Danish study found that among 28,000 people living in Copenhagen, all-cause mortality was 28% lower amongst those who regularly bicycled to work compared with those who commuted by car (Andersen et al., 2000). In the report Cycling, Health and Safety, the International Transport Forum at the OECD (2013) states that "…*cycling, as a form of moderate exercise, can greatly reduce clinical health risks linked to cardiovascular disease, obesity, Type-2 diabetes, certain forms of cancer, osteoporosis and depression*". Stigell and Schantz (2015) showed that active commuting behaviours (walking and bicycling to work) meet the requirements of daily physical activity levels overall, but that seasonal effects impacted on the level of physical activity among bicyclists, who achieved recommended levels of physical activity only during spring to mid-autumn.

Several studies have highlighted the positive impacts of increased bicycling regarding both health and the environment (Hartog et al., 2011; Rojas-Rueda et al., 2013, Holm, Glumer, & Diderichsen, 2012; Oja et al., 2011). Summarizing the literature for air pollution, traffic accidents and physical activity, Hartog et al. (2011) found that health benefits associated with bicycling, from a mortality perspective, were larger than the risks of a population shifting their mode of transport from car to bicycle. Other health impact assessment studies for cycling found similar results (Rojas-Rueda et al., 2013; Holm, Glumer, & Diderichsen, 2012). However, bicyclists now account for a higher proportion of hospital-reported crashes and injuries than any other road user category in Sweden (Swedish Transport Administration, 2015), and health impact assessment studies mainly include police reported injuries which do not adequately describe the total number of bicycle injuries (Tingvall et al., 2013; Veisten et al., 2007; Juhra et al., 2012).

There is incontrovertible evidence that regular physical activity contributes to the primary and secondary prevention of several chronic diseases and is associated with a reduced risk of pre-mature death (Warburton, Nicol, &, Bredin, 2006). Active transportation, including bicycling, has become a key focus in the promotion of physical activity (Bull et al., 2010; Chapman et al., 2014; Kohl et al., 2012). Today, different stakeholders in society are recognizing

increased bicycling as an important contribution to improving health among the population, as a way to make cities more sustainable by reducing emissions from motorized traffic and as a more energy efficient mode of transport. To promote increased bicycling, it is relevant to investigate aspects of safety as safety is one important determinant for people choosing to bicycle (Wahlgren & Schantz, 2012; Winters et al., 2013). Safety is related both to the perceived safety and to actual (un)safety with regard to crashes and injuries. Therefore, different stakeholders in society are interested in knowledge about how bicycling can become safer, as a way to promote health.

How we define the problem of safety

The safety level of the transport system and the countermeasures we apply to increase safety are functions of how we define our outcome. Let us therefore start by describing the outcome that guides today's traffic safety work in Sweden and how this outcome relates to concepts of health.

Vision Zero

In 1997, Sweden adopted Vision Zero, a road transport safety strategy with the long-term vision of no fatal or serious injuries in the road transport system (Swedish Government, 1997a, 1997b; Swedish Parliament, 1997). Vision Zero takes a holistic approach to road safety, which is based on the idea of designing the road transport system around the failing human, and that it is not acceptable that the need for mobility and transportation is associated with a risk of fatality or serious injuries. Designing the system around the failing human also means designing a system that, based on the human tolerance for biomechanical forces, does not exceed this tolerance. Vision Zero emphasizes shared responsibility, but also that the designers of the system are ultimately responsible for the level of safety within the transport system (Johansson, 2009).

According to Vision Zero, no one should die or suffer injuries that lead to non-acceptable loss of health in the road transport system (Tingvall, 1997). Elaborating on how loss of health could be defined, Tingvall (1997) states that: "*The first step in the zero vision is therefore to define and quantify a non-acceptable loss of health. It may, for example, be defined and quantified as a degree of medical disability in time after the injury was sustained. A reasonable starting point could be that an injury which has*

healed after, for example, three weeks, may be defined as an acceptable loss of health – but not death or long- term invalidity."

In Vision Zero, the problem of safety is not defined as road traffic crashes, but rather as unacceptable health loss. In other words, crashes are acceptable as long as they do not result in unacceptable outcomes.

Common approaches to assessing road traffic injuries

As it is mainly fatalities and severe injuries that are reported by the police, bicyclist injuries are highly underreported in many countries (Rizzi, Stigson, & Krafft, 2013; Tingvall et al., 2013; Veisten et al., 2007; Juhra et al., 2012). For example, Rizzi, Stigson, and Krafft (2013) found that in Sweden, only 7% of bicycle crashes in hospital records were known to the police. A German study found that 68% of hospital casualties from bicycle crashes lacked a police record (Juhra et al., 2012). Therefore, in crashes involving vulnerable road users, hospital data are more suitable for describing and analysing injuries among bicyclists (Amoros, Martin, & Laumon, 2006; Tingvall et al., 2013).

In hospital data, the international classification of diseases and health problems (ICD) is most commonly used to describe injury (and other) diagnoses (WHO, 1993). In road crash-related hospital data, injuries are sometimes classified according to the AIS. The AIS is a globally used severity scoring system that classifies injuries by body region according to its relative importance on a 1-6 point ordinal scale, where 1=minor injury and 6=maximal and currently untreatable injury. Injury severity classification of 3 is regarded a serious injury, and AIS 4 is regarded a severe injury This classification system mainly captures the injury severity in terms of risk of fatality. Similar to the ICD, the AIS has a description of each injury, together with the severity score. In order to get an overall injury severity score, related to the individual and not each injury, the Maximum Abbreviated Injury Scale (MAIS) is used. The MAIS represents the highest injury severity classification given to the individual and hence shows an overall injury severity classification (AAAM, 2005). Recently, MAIS 3+ was adopted as a common definition for seriously injured in the EU (European Commission, 2015). Also based on the AIS, the Injury Severity Score (ISS) assess fatality risk in relation to multiple injuries by using the sum of the squares of the highest AIS classification in the three most severely injured body regions (Baker et al., 1974). Both the AIS and the ICD are mainly intended to describe

the nature of injuries, and also (in the case of the AIS) grade the severity of the injury based on a threat-to-life approach which does not include the long-term impact.

In Sweden, a distinction is made between the terms '*severely* injured' and '*seriously* injured', which is not comparable to the globally used AIS scale. In Sweden, the term 'seriously injured', that is also the basis for national statistics, refers to injured with a permanent medical impairment of at least one percent. A severely injured is defined as having sustained a fracture, crushing injury, tearing injury, severe cutting injury, concussion, internal injury, or other injury expected to result in hospitalisation (Transport Analysis, 2015). The former term is based on hospital reports, while the latter is reported by the police.

Risk of Permanent Medical Impairment (RPMI)

RPMI was developed to estimate the risk of a patient suffering from a certain level of permanent medical impairment (PMI) based on the diagnosed injury location and the criteria of the Swedish insurance companies (Malm et al., 2008). RPMI is based on and further developed from the Rating system for serious consequences (RSC) (Gustafsson, Nygren & Tingvall., 1985). The principles for grading medical impairment have been developed since the beginning of the 20th century in Sweden and have been established in consensus with physicians. The degree of impairment is based on the functional reduction caused by the injury, and is independent of cause and without regard to the injured person's occupation, hobbies or other special circumstances (Malm et al., 2008; Insurance Sweden, 2004).

RPMI is based on approximately 35,000 diagnoses from 20,000 injured car occupants who reported an injury to an insurance company (Malm et al., 2008). The injured car occupants were monitored for at least five years to assess the risk of permanent medical impairment for different body regions and AIS severity levels. The risk is derived from risk matrices based on the location and severity of the injury for 1%+, 5%+ and 10%+ medical impairment. The risk matrices for 1% and 10% levels of impairment are shown in Table 1.

Table 1. Risk of Permanent Medical Impairment of at least 1% (left side of table) and at least 10% (right side of table). Source: Malm et al. (2008).

RPMI 1+						RPMI 10+					
Body region	AIS 1	AIS 2	AIS 3	AIS 4	AIS 5	Body region	AIS 1	AIS 2	AIS 3	AIS 4	AIS 5
Head	8.0%	15%	50%	80%	100%	Head	2.5%	8%	35%	75%	100%
Cervical spine	16.7%	61%	80%	100%	100%	Cervical spine	2.5%	10%	30%	100%	100%
Face	5.8%	28%	80%	80%	n/a	Face	0.4%	6%	60%	60%	n/a
Upper extremity	17.4%	35%	85%	100%	n/a	Upper extremity	0.3%	3%	15%	100%	n/a
Lower extremity	17.6%	50%	60%	60%	100%	Lower extremity	0.0%	3%	10%	40%	100%
Thorax	2.6%	4.0%	4%	30%	20%	Thorax	0.0%	0%	0%	15%	15%
Thoracic spine	4.9%	45%	90%	100%	100%	Thoracic spine	0.0%	7%	20%	100%	100%
Abdomen	0%	2.4%	10%	20%	20%	Abdomen	0.0%	0%	5%	5%	5%
Lumbar spine	5.7%	55%	70%	100%	100%	Lumbar spine	0.1%	6%	6%	100%	100%
External (skin)	1.7%	20%	50%	50%	100%	External (skin)	0%	0%	50%	50%	100%

For reference, an AIS 2 injury to the lower extremities gives a 50% risk of at least 1% permanent medical impairment (RPMI 1+) but only a 3% risk of at least 10% permanent medical impairment (RPMI 10+). Risk of Permanent Medical Impairment of at least 1% (RPMI 1+) is currently used in Sweden as the definition of a serious injury.

RPMI can refer to specific injuries (body regions) but can also be calculated for one individual with several injuries (overall RPMI) according to Equation 1, where *n* is the number of injured body regions and *risk* is the risk for each body region according to the risk matrices in Table 1.

$$RPMI = 1 - (1 - risk_1) \times (1 - risk_2) \times \ldots \times (1 - risk_n) \qquad \text{(Eq. 1)}$$

The predicted number of impaired individuals or impairing injuries is the accumulated risk for all persons or each body region, respectively. Accumulating the risk for each body region makes it possible to analyse the distribution of impairing injuries, as seen in Figure 3. This means that such distributions are not based on individuals who are predicted to sustain a certain level of impairment. It is rather the distribution of all impairing injuries, calculated with the accumulated RPMI of all injuries, as described above. When accumulating the risk, the impaired individuals or impairing injuries are referred to as PMI individuals or PMI injuries.

The present thesis agrees with the intention of the current definition of serious injury in Sweden, that (in line with what is formulated in Vision Zero) takes into account long-term consequences. However, as it is the functional reduction of the injury that is assessed, and individual circumstances are not taken into consideration, it might not reflect the individual experience of how the injury affects a person's life. It might also mean that people who are regarded as seriously injured might not regard themselves as seriously injured. In order to increase the understanding of the impact on health from injuries, and how serious injuries among bicyclists can be identified, concepts of health and disability become relevant.

The concepts of health and disability

There are many different perspectives on the concept of health, e.g. health as an absence of disease, health as a resource, health as a behaviour (lifestyle), health as social relationships, as energy and vitality, as harmony, as functioning, or as well-being (Blaxtor, 2001; Hughner & Kleine, 2004; Fagerlind et al., 2010; Seedhouse, 2001). In the western world, the concept of health is mainly illustrated from two perspectives; biomedical or social humanistic. From a biomedical perspective, health is the absence of disease and defined as "… *normal functioning, where the normality is statistical and the functions biological*" (Boorse, 1977). The social humanistic approach views health as a continuum between health and illness, and health is considered the ability to function in relation to different aspects of life, e.g., goals, resources and social context (Nordenfelt, 1995; 1996). Comparing the two approaches, one difference would be that from a biomedical view, a person is either healthy or ill, while in the humanistic approach, a person can be both.

Even in the 1940s, it was questioned whether health could simply be defined as the absence of disease (Fraser, 1946). Brüssow (2013) points out the difference between the classical medical definition of health and how the meaning changes if associated with language, where the focus of health is related to wholeness. Nordenfelt's (1995) view on health also represents a more holistic and humanistic approach to health. His theory suggests that "*a person's health is characterized as his ability to achieve his vital goals*". The WHO definition of health also focuses on a more holistic approach in that health is defined as "… *a state of complete physical, mental and social well-being and not merely the absence of disease and*

infirmity" (WHO, 1948). Today, the concept of health could be said to be moving towards the holistic approach, indicating that health is more than the absence of disease and not strictly seen as normal functioning (Medin & Alexanderson, 2000).

Today, the dominant perspective for a holistic approach to health is the biopsychosocial model. In 1977, Engel was one of the first to address the problems and limitations of the biomedical paradigm while also suggesting a new model of health that regards social and psychological aspects in addition to biological, i.e., a biopsychosocial model for health (Engel, 1977). As these three domains – social, psychological and biological – are integrally involved in physical health, explanations for a health state cannot be found in only one of the domains (Suls et al., 2010). In In recent years, responsibilities in the health care sector have developed toward not only treating but also preventing disease and promoting health, adopting methods in line with this biopsychosocial model (Glanz et al., 2008). Although an ultimate, everlasting definition of health might not exist, the biopsychosocial perspective is the widest possible view that can provide a meeting point for the various professions in the health sector.

The biopsychosocial perspective on health and physical activity is not only important in relation to health-promotion. It is also an important perspective when it comes to understanding the impact on health from injuries. Therefore, an underlying assumption in the present thesis is that a serious injury cannot be defined only considering a biomedical approach to health (represented in medical impairment), but instead require understanding based on different domains of health, in line with the biopsychosocial perspective.

A conceptual framework of health from a biopsychosocial perspective

The International Classification of Functioning, Disability and Health (ICF) is a systematic framework to describe the full range of human functioning that may be affected by a health condition (WHO, 2001). Within this framework, the term 'disability' is used as an umbrella term that covers impairments, activity limitations and participation restrictions as a result of disturbances in human functioning (WHO, 2002). ICF is an internationally recognized model for health and functioning, and has its foundation in the United Nations' (UN)

Universal Declaration of Human Rights. The ICF is based on a biopsychosocial approach, which incorporates biological, individual and social perspectives on health and disability. The ICF enables a holistic view of health, and structures the many factors affecting health in different components, where functioning is the interaction between a health condition, body functions and structures, individuals' activities and participation in their unique life situations and environment (WHO, 2001).

Health condition

(disorder or disease)

Body Functions & Structure → Activity ← Participation

Environmental Factors   Personal Factors
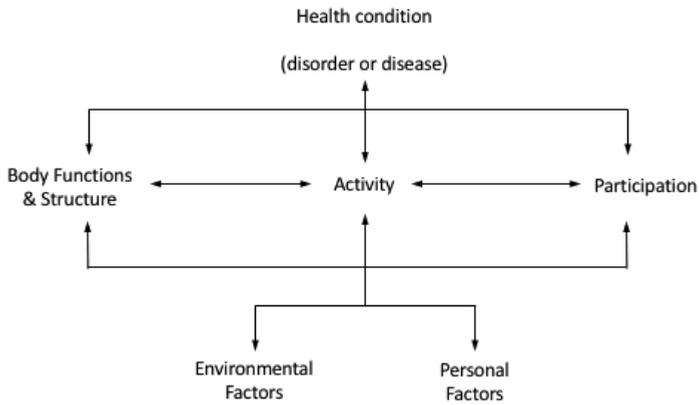
Figure 1. The ICF and the interactions of its components, adapted from WHO (2001).

The model (Figure 1) identifies three levels of human functioning that relate to:
- Body or body part
- The whole person
- The whole person in a social context

Disability is defined by dysfunction in one or more of these levels, and is referred to as impairments, activity limitations and participation restrictions (WHO, 2002). This means that both impairments and functional and social limitations are seen as different aspects of disability (WHO, 2001). In Table 2, all components included in the framework are specified.

Table 2. Definitions of the ICF components, derived from WHO (2002).

Component	Description
Body Functions	Physiological functions of body systems (including psychological functions)
Body Structures	Anatomical parts of the body such as organs, limbs and their components
Impairments	Problems in body function or structure such as a significant deviation or loss
Activity	Execution of a task or action by an individual
Activity Limitations	Difficulties an individual may have in executing activities
Participation	Involvement in a life situation
Participation Restrictions	Problems an individual may experience in involvement in life situations
Environmental Factors	The physical, social and attitudinal environment in which people live and conduct their lives

Apart from the description of injuries (ICD, AIS) the link to and the description of the consequences of injuries need to be made in order to understand the impact from injuries. In other words, it is necessary to also describe the functioning and disability related to injuries, which the ICF provides a framework for (WHO, 2001). Medical impairment is one way to describe the consequences of injuries. It is also the current definition of serious injury in Sweden. PMI relates only to the body functions and structures part of the ICF. To develop an understanding of the consequences of bicycle injuries that go beyond a biomedical perspective toward a biopsychosocial view on health, the present thesis will incorporate two other ways to understand health impacts from road traffic injuries: health-related quality of life (HRQoL) and sickness absence (SA).

Health-related quality of life and sickness absence

Health-related quality of life

The concept of quality of life has been defined by WHO as "individuals' perception of their position in life in the context of the culture and value systems in which they live and in relation to their goals, expectations, standards and concerns". It is a broad ranging concept affected in a complex way by the person's physical health, psychological state, level of independence, social

relationships and their relationship to salient features of their environment'"
(The WHOQOL Group, 1995). HRQoL is a subset of QoL that includes health
and health-related domains that affect an individual's quality of life. The
narrowing of the quality of life concept to HRQoL, including health-related
domains, is of interest for those who want to assess the impact of diseases,
injuries and treatments. Even though there is no single agreed definition of
HRQoL, in general – when operationalized – it takes into account levels of
physical, mental, social and role functioning (Wood-Dauphinee, 1999). These
levels are all associated with the ICF framework that was previously presented.
As implied by the WHO definition of QoL, the individual's perception is the
main focus, which is in line with the shift in health care from a biomedical to a
biopsychosocial view of health, into which the patient's view is incorporated
(Wood-Dauphinee, 1999). The focus on individual perception emphasizes
individual experiences, which makes the concept subjective as this perception
will vary from person to person. The assessment of QoL and HRQoL is
therefore centred on self-reporting, where the respondent reports on their
experience in relation to specific domains of health (Cieza & Stucki, 2005).
There is a wide variety of scales and instruments for assessing HRQoL, both
disease-specific and generic (general) instruments. Generic instruments have
largely been used in studies assessing HRQoL after road traffic injuries
(Polinder et al., 2010).

Previous research on health-related quality of life after road traffic injury

In a study from the United States, Alghnam et al. (2014) carried out a
longitudinal follow-up study among adult participants (≥18 years, n=62,298) in
the Medical Expenditure Panel Survey. The study examined the relationship
between traffic-related injuries and HRQoL using the generic health status
measure Short Form 12 (SF-12), and found that people who suffered non-fatal
motor vehicle injuries (n=993) reported impacts on physical health up to nine
months after injury. Jagnoor et al. (2015) studied HRQoL outcomes among
patients with mild to moderate injuries after a motor vehicle crash in Australia
(n=364). HRQoL was measured with SF-12 and the EuroQol five dimensions
questionnaire (EQ-5D) (The EuroQol Group, 1990). The results showed that
a significant proportion of the patients experienced HRQoL problems,
although the follow-up was limited to only two months. A Swedish study

investigated HRQoL after traffic injury among hospitalized patients and found that among 200 non-fatally injured adults and 30 children, 38% of adults and 13% of children experienced problems in HRQoL one year after injury, and an additional 23% of adults and 10% of children still had problems 3.7 years after the injury (Maraste, Persson, & Berntman, 2003).

In a study from the United Kingdom, Mayou and Bryant (2003) investigated the consequences of traffic crashes for different road users (vehicle occupants, motorcyclists, cyclists and pedestrians) among adults (n=1441) attending an emergency hospital. Outcome measures were all self-reported, including physical health, general health status, post-traumatic stress disorder, mood and travel anxiety. They found that despite differences between the road user groups in terms of injuries, immediate reactions and treatment, there were few longer-term differences. Compared with other road user groups, bicyclists suffered less severe injuries and their injuries were likely to be head, face, arm and leg injuries. Vehicle occupants reported problems related to pain more frequently than the other groups. In a French study, Nhac-Vu et al. (2014) used a self-report questionnaire on health, social, emotional and financial status to investigate consequences one year after a road traffic crash. The sample was adults ≥18 years, and 616 out of 886 respondents completed the questionnaire. The results showed that injury type was related to consequences in terms of quality of life one year after a road traffic crash: among groups with poor outcome at one year, more than two thirds had lower limb injuries associated with restricted leisure activity.

HRQoL have been investigated among injured road users in Sweden, including cyclists, for example to evaluate the effect of a telephone intervention follow-up (Franzén et al., 2009). However, considering how to target injury prevention, evaluation of injuries effect on HRQoL is crucial. Thereby, a research gap exists of studies that investigate HRQoL after traffic injury with regard to self-reported problems in HRQoL, taking into account injury severity and injured body region.

Sickness absence

In Sweden, sickness absence (SA) is common in the case of illness or injury (Alexanderson & Norlund, 2004). The purpose of the sickness insurance system is to provide financial security if a person has reduced work capacity caused by

disease or injury. Sickness benefit compensates up to 80% of lost income. From a national-economic perspective, sickness absence involves considerable costs for society. In 2014, sickness benefits paid by the Swedish Social Insurance Agency (SIA) totalled 27.7 billion SEK (SIA, 2015). The Swedish sickness insurance system covers all people above the age of 16 years who are living in Sweden and have a minimum annual income from work, those on unemployment benefit, and those on parental leave. The first 2-14 days of sickness absence are compensated by the employer (SIA, 2015), and from day 15 employees can claim compensated sickness benefits from the SIA. Unemployed individuals and individuals on parental leave can be granted sickness benefit from the SIA from the second day, and individuals who are self-employed can be granted sickness benefits from the SIA depending on their insurance coverage. In all cases of sickness absence, a certificate from a physician is required from day eight. In international research, the terms 'work disability', 'compensated time off work' and 'sick-leave' are all used to describe the same concept, namely being unable to work due to an injury and therefore being eligible for monetary compensation, mainly from social insurance. Therefore, in the following section, all terms related to this concept will be referred to as SA, even though the social insurance schemes will differ in the way they are designed, for example regarding the number of payments and the amount paid.

SA is always considered in relation to the individual's work capacity, and it is the functional and activity limitations as a result of the injury or illness, and not the injury or illness itself, that can motivate SA. This means that physicians assessing an individual's work capacity need to be aware of what demands, e.g. physical or cognitive, the individual's work involves. SA can be granted on a part-time or full-time basis, but the work capacity has to be reduced by at least 25%. For the purpose of assessing work capacity, the ICF framework can be used. This means that it is not the bodily functions and structures that are assessed, but instead how the individual functions in relation to his or her work activities (i.e. activity limitations and participation restrictions according to the ICF framework). However, it is the SIA that decides if an individual can be granted SA, and physicians provide the basis for the decision (The National Board of Health and Welfare, 2012). SA is considered an active measure, where the individual's capacity is considered, despite limitations. The starting point is always that the individual is actively involved in the rehabilitation process, in

order to facilitate a return to work (The National Board of Health and Welfare, 2012).

Apart from high costs for employers, insurers and society, there are studies regarding possible negative consequences for individuals on SA, e.g. regarding physical, mental and social circumstances (Vingard, Alexanderson, & Norlund, 2004). Long periods of SA are associated with negative outcomes in terms of one's quality of life, with impacts on leisure activities, sleep and psychological well-being (Floderus et al., 2005), economic and social conditions (Bryngelson, 2009), and morbidity and mortality (Olsson et al., 2015; Karlsson et al., 2008; Björkenstam et al., 2014).

Previous research on sickness absence related to road traffic crashes

In a previous study of people with a musculoskeletal or orthopaedic injury from a road traffic crash, 32% of those injured had subsequent SA ≥6 months. The study was carried out in Australia among 5970 adults ≥18 years who had compensated time off work as a result of the crash (Berecki-Gisolf, Collie, & McClure, 2013). Another study from Sweden investigated SA and disability pension among a smaller sample (n=255) of injured car occupants who visited a hospital after a crash. The results showed that 40% had subsequent SA following the crash, which was mostly related to cervical spine injuries (Bylund & Björnstig, 1998). Based on Swedish hospital admissions in 1970, it was reported that bicyclists, compared with other road users, had the shortest period of SA after a crash, with an average of 29 days (Hansson, 1976). SA as a consequence of non-fatal bicycle crashes among 264 adults in Finland has been studied (Olkkonen et al., 1993). It was found that the mean duration of SA was 82 days for hospitalized patients at two emergency care hospitals. For outpatients, the mean duration of SA was 11 days. They also found that injuries in the upper extremities were most common (33%) and that over half the cases with SA longer than 30 days were due to upper extremity injuries.

No previous nationwide studies on SA following a bicycle crash in Sweden could be found. Knowledge about injuries, especially about those leading to SA of longer durations, is important when considering how to target injury prevention.

Summary of injury outcomes and their relationship to the ICF

Figure 2 illustrates all concepts related to injury outcome included in the thesis in relation to the ICF framework for disability, and also when they are evaluated. The mapping of the EQ-5D instrument into ICF categories was derived from Cieza and Stucki (2005). This means that the present thesis will incorporate all levels of disability according to the ICF framework: impairment, activity limitations and participation restrictions.

Measure	ICF level of functioning	ICF disability level	Time after injury					
			Immediate	14 days	30 days	1-2 years	3-5 years	≧5 years
PMI	Body functions & structures	Impairments						
HRQoL (EQ-5D)	Body functions & structures Activity Participation	Impairments Activity limitations Participation restrictions						
Sickness Absence	Activity Participation	Activity limitations Participation restrictions						

Figure 2. Concepts related to injury outcome and their relationship to the ICF level of functioning and disability level, and when they are evaluated.

Overview of bicyclists' injuries

In a study investigating bicyclist injuries leading to permanent medical impairment in Sweden, it was found that 77% of all bicycle crashes were single bicycle crashes, and that 70% of the injuries leading to medical impairment (PMI 1+) were to the upper (mostly shoulder and wrist) and lower (mostly ankle and knee) extremities. Looking at the more severe level of impairment (PMI 10+), head injuries were most common, accounting for 42% of severe impairing injuries (Rizzi, Stigson, & Krafft, 2013).

In a study from Germany, Juhra et al. (2012) conducted a prospective study of bicycle crashes leading to injuries (of any severity). The study included 1767 people who were treated at a hospital and an additional 484 people who were injured but did not go to a hospital. They found that the injury distribution was 37% upper extremities, 30% lower extremities, 26% head injuries, 7% thorax and abdomen, 5% pelvic and 5% spinal injuries.
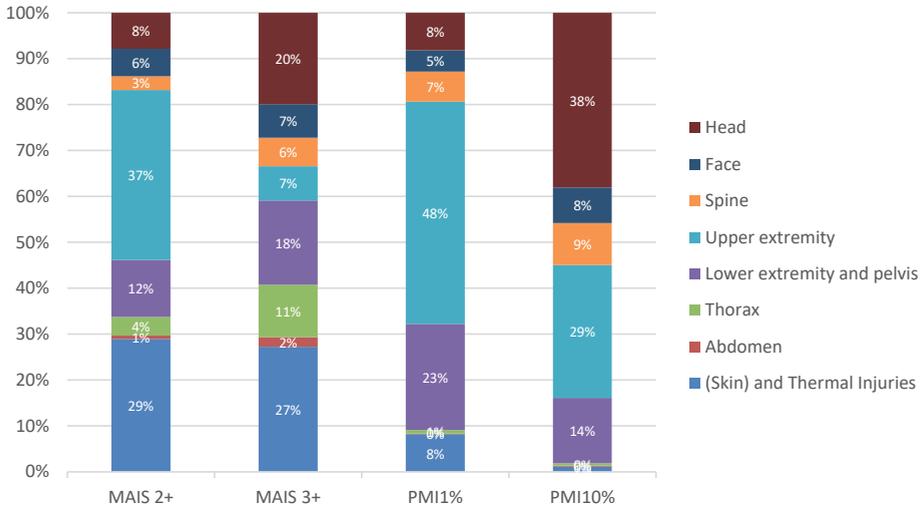
Figure 3. The distribution of bicyclists' hospital-reported Maximum Abbreviated Injury Scale (MAIS) 2+ and 3+ and permanent medical impairment (PMI) 1+ and 10+ injuries between 2007 and 2014. Source: Strada.

Figure 3 shows the injury distribution of bicyclists' hospital-reported injuries between 2007 and 2014 in Sweden. It shows that the distribution of injuries differs when comparing MAIS (overall injury severity classification, threat to life) and long-term (PMI) consequences. Depending on what measure is chosen as the target measure, this will have implications for what injuries stakeholders in society will prioritize to be prevented. For example, thorax injuries, which account for 11% of all injuries among MAIS 3+ injured (high injury severity), are almost non-existent when considering long-term consequences. Basically, this is a life-threatening injury, but if a patient survives, they are not likely to suffer long-term consequences. In other words, if MAIS 3+ were to be considered as a target measure, thoracic injuries could be targeted for injury prevention, whereas they would not be targeted if PMI was considered as a target measure. If medical impairment is considered (PMI 1+ and PMI 10+), injuries to the head and upper extremities are the most common. Upper extremity injuries would, on the other hand, not be considered to the same extent with regard to MAIS 3+.

The injury distribution is also affected by crash type, as shown in Table 3. For example, PMI injuries to the head and cervical spine are more common in bicycle crashes involving motor vehicles compared with single bicycle crashes.

Table 3. Distribution of PMI 1+ and PMI 10+ injuries in single bicycle crashes and in bicycle-motor vehicle crashes. Source: Strada, 2007-2014.

Body region	Single-bicycle crashes		Bicycle-motor vehicle crashes	
	PMI 1+	PMI 10+	PMI 1+	PMI 10+
Head	8%	34%	13%	48%
Cervical spine	3%	5%	11%	12%
Face	5%	9%	4%	5%
Upper extremity	57%	34%	29%	12%
Lower extremity and pelvis	25%	15%	31%	14%
Thorax	1%	0%	2%	1%
Thoracic spine	1%	1%	4%	4%
Abdomen	0%	0%	0%	0%
Lumbar spine	1%	1%	5%	3%
Total	100%	100%	100%	100%
n PMI injuries	12,795	1591	2185	381

Reporting of bicyclists´ injuries in Sweden

In Sweden, injurious road traffic crashes are reported in a national database, the Swedish Traffic Accident Data Acquisition System (Strada). Reports are collected both from the police and from emergency care hospitals. The database is managed by the Swedish Transport Agency. A road traffic crash is defined as a crash involving at least one vehicle in motion and at least one injured person (Swedish Transport Agency, 2016). The Police is obliged by law to report all road crashes according to the definition of a road traffic crash (Swedish Government Offices, 1965). So far, it is voluntary for emergency care hospitals to report to Strada, and the information is only reported with the consent of the injured person (Ds 2016:20). Information about injury diagnoses and severity include the AIS and MAIS, the ISS, as well as ICD-10.

Crashes occurring outside the scope of road traffic (e.g., occurring in a closed industrial area, or on a forest trail) as well as those who do not seek medical attention at an emergency care hospital are not known in national statistics on road traffic crashes. In a comparison between Strada and the National Patient Registry (NPR), a national register that covers all in- and specialized outpatient health care in Sweden, it was shown that almost half of all crashes (both in

Strada and NPR) only were reported in NPR, whereas around 20% were known in Strada but not in NPR (Bengtsson, 2017).

Crash and injury prevention

We have now learned that the definition for a serious injury is currently based on medical impairment, which, according to the ICF model, only represents one aspect of health. Further, we have discussed alternative approaches that also include other aspects of health, i.e. HRQoL and SA, and apply to traffic injuries. However, we have yet to learn about how today's transport system works to improve cycling safety and how these strategies relate to accident and injury prevention theories.

Guiding principles for crash and injury prevention

The aim of Vision Zero is not to totally eliminate crashes, but instead to align the crash severity with the ability to protect road users from fatalities and serious injuries. Thereby, knowledge about the human body´s tolerance to external forces experienced in a crash is crucial. Haddon (1963) was one of the first to formulate the idea that the transfer or various types of energy are the necessary and specific causes of injuries. Around the same time that Haddon formulated his idea, Gibson (1961) had arrived at the same basic understanding; that injury to a living organism can be produced only by some type of physical energy exchange. However, of the two, Haddon has become the best known and his theories on injury prevention are still used today, not only in relation to traffic safety, but also to e.g., sports injuries (Finch, 2006) and public health (Lett, Kobusingye, & Sethi, 2002).

As exemplified by Haddon, injury prevention strategies have been used by humankind since ancient times, where evacuations from floods or volcanic eruptions are examples still being used today. Another example is the very simple and basic strategy of wearing shoes (Haddon, 1980). Haddon is most famous for his matrix, which illustrates a set of injury control tactics, or interventions, in different phases of the injury event. This matrix became common practice within vehicle safety and allowed for injury control to work in multiple dimensions in a new way, but the interventions in different phases (pre-crash, crash, post-crash) were more or less subjected to separate areas of prevention.

This separation of intervention areas can, in reference to vehicle safety, be referred to as crash avoidance and injury protection (see for example Page et al., 2009). In this sense, crash avoidance features are responsible for avoiding crashes, for example anti-lock braking systems (ABS) or electronic stability control (ESC). Injury protection features, on the other hand, are safety features that prevent or mitigate injuries in the actual crash, for example airbags, three-point seat belts and bicycle helmets. However, taking a system approach to road safety, this separation of intervention areas can be regarded as a drawback when we want to understand how different safety interventions interact. The integrated safety chain is a further development of the Haddon Matrix (Kanianthra, 2007; Tingvall, 2008). With this approach, the whole chain of events, from normal driving to a crash, can be treated like a process in time where interventions can take place at any stage (Figure 4). This integrated view recognizes the fact that the output from one phase becomes the input for the next, and is useful when different safety interventions are introduced simultaneously, such as improved infrastructure or enforcement and education. This integrated approach may be more difficult to distinguish using the Haddon's matrix, where each phase is more isolated.
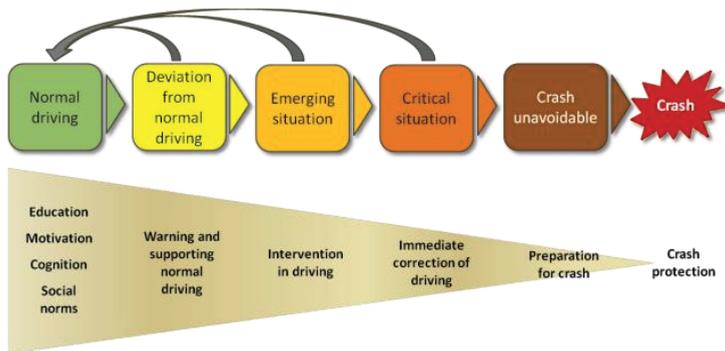
Figure 4. The integrated chain of events. Source: Rizzi (2016).

The underlying principle for developing safety interventions is the human body's tolerance to external energy. When energy build-up and release was found to be the basic injury mechanism, injury thresholds could be defined, resulting in preventive strategies such as Haddon's fifth strategy "… *to separate, in space or time, the energy being released from the susceptible structure, whether living or inanimate…*" (Haddon, 1995). Based on this approach, injury risk functions for

e.g. pedestrians in collisions with motor vehicles have been developed and used to understand what constitutes a 'safe' speed in areas where pedestrians and cars are not physically separated (which today is defined as 30 km/h with regard to fatality risk).

It is easier to find examples of traffic safety features and technologies that relate to passenger cars. Cyclists, on the other hand, are vulnerable road users without a surrounding structure to protect them in the case of a crash, and the list of safety features for cyclists is rather incomplete. However, as illustrated in (Figure 5), a tentative approach to apply the integrated safety chain to cycling can be made. Also, as illustrated by Ohlin et al. (2017), it can be used to visualize the combined effect of vehicle frontal design, autonomous emergency braking (AEB) and helmet use, to reduce serious injuries among cyclists.
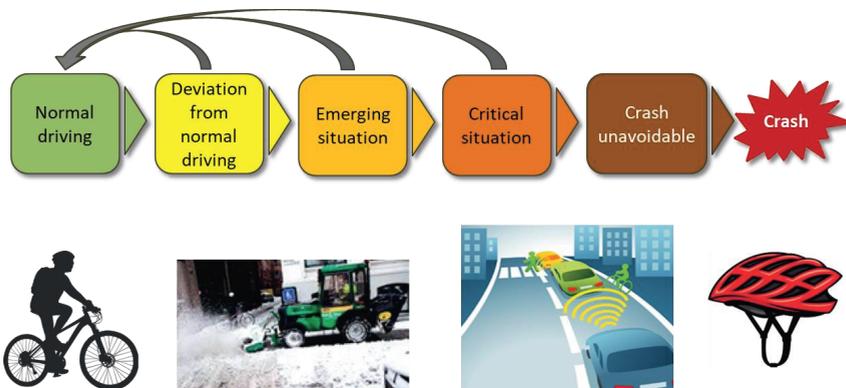
Figure 5. The integrated chain of events applied to bicycle safety.

Previous work on crash and injury prevention related to cycling

Traditionally, the protection for bicyclists has been addressed by speed management of motor vehicles, separating motor vehicles and vulnerable road users, and the use of bicycle helmets.

The correlation between impact speed and fatality risk among pedestrians hit by cars was estimated by Rosén and Sander (2009), who found that the fatality risk at 50 km/h was more than twice as high as the risk at 40 km/h, and more than five times higher than the risk at 30 km/h. In Sweden, lowering speed

limits is most often combined with other traffic-calming countermeasures, such as smaller roundabouts and speed bumps (Swedish Association of Local Authorities and Regions & Swedish Transport Administration, 2013). Separating vulnerable road users from motorized traffic is also a way to make the road environment safer (Pucher, Dill, & Handy, 2010). The use of separate cycling lanes in Sweden is estimated to reduce injuries by 20-30% (Swedish Association of Local Authorities and Regions & Swedish Transport Administration, 2013). Previous studies have shown that crashes involving a motor vehicle more often result in severe injuries compared with other types of crashes, e.g. non-collision crashes (Cripton et al., 2015). Furthermore, crashes involving motor vehicles have been reported to account for 64-92% of fatal bicyclist crashes (Bil et al., 2016; Gaudet et al., 2015; Nicaj et al., 2009). Speed management to protect bicyclists only addresses a small share of bicycle crashes, as only 13% of all bicycle crashes involve a motor vehicle, while 77% are single bicycle crashes (Rizzi, Stigson, & Krafft, 2013).

The use of bicycle helmets has been promoted and regulated in some countries. Helmet use in Sweden is estimated to be 37% but with great variations between different regions. In 2005, helmet use amongst children <15 years was legislated and helmet use amongst this group is now around 65% (Swedish Transport Administration, 2015). Wearing a helmet is an effective way to prevent head injuries (Amoros et al., 2012; Attewell, Glase, & McFadden, 2001). In a recent systematic review including 40 studies, the effectiveness of bicycle helmets was reported to show significant reductions in all head injuries and severe head injuries by 51% and 69% respectively. Facial injuries were also found to be reduced by 33% (Olivier & Creighton, 2016). However, other research has shown that, depending on the injury outcome, head and face injuries account for a relatively small proportion of all bicycle trauma, although head injuries account for a large proportion of more severe injuries (Rizzi, Stigson, & Krafft, 2013).

Swedish safety performance indicators (SPIs) for safe cycling

Providing guidance and direction for increased bicycle safety requires knowledge about the strategies regarding bicycle safety used today. In road safety management, safety performance indicators (SPIs) are frequently used to measure the quality of the road transport system. The SPIs are indicators that

facilitate a link between a safety countermeasure and the outcome on which the target is set. For example, a target can be a reduction in fatalities and serious injuries (European Transport Safety Council, 2001; Hakkert et al., 2007a; Hakkert et al., 2007b). Therefore, the SPIs that are used need to have a proven effect to, in this case, reduce fatalities and serious injuries.

In 2007, interim targets were set in Sweden to reduce fatalities and serious injuries in the road transport system by 50 and 25 percent respectively by 2020 (Swedish Road Administration, 2008). To monitor the development of the safety of the road transport system, Sweden developed a set of SPIs to facilitate the targets. These included, for example, speed compliance, rate of seat belt wearing and proportion of new passenger cars with a five star rating in the Euro NCAP crash test. Three of the SPIs relate to cycling:
- Bicycle helmet usage
- Safe bicycle crossings
- Good quality maintenance of bicycle paths

The current target for bicycle helmet use is that at least 70% of cyclists should use a helmet by 2020. This indicator is followed by observational studies of bicycle helmet usage. The observational studies are not carried out on a national level, and are hence not fully representative. However, they are considered 'good enough' to provide an overall picture of an approximate level of helmet usage, and changes over time. In 2017, the observed helmet wearing rate was 44%, which is lower than the necessary development to reach 70% usage by 2020.

The 2020 target for good quality maintenance of bicycle paths is that 70 percent of municipalities will carry out good quality maintenance of priority bicycle routes. This indicator is restricted to municipalities with populations of at least 40,000 inhabitants and targets their most prioritized bicycle paths. Good quality is defined by standard requirements for winter and summer maintenance, gravel and leaf sweeping, as well as good quality control of these standard requirements. The results are provided by municipalities through a survey every two years. In 2017, 36% of the responding municipalities were in line with requirements for good quality maintenance, which is lower than the necessary development to reach 70% by 2020.

Safe bicycle crossings are included in the indicator 'safe pedestrian, bicycle and moped crossings'. The current target is that at least 35% of all crossings on main networks (both state and municipal roads) for cars should have a good safety standard by 2020. A crossing is defined as safe when:

- it is grade separated or
- 85 percent of motor vehicles drive at a maximum of 30 km/h.

The latter is most effectively achieved by means of a physical speed control hump in direct proximity to the crossing. Information on the configuration of crossings is collected from the national roads database (NVDB) and classified according to specific criteria. In 2017, 27% of bicycle crossings were classified as 'safe', which was considered to be in line with the required trend to reach 35% by 2020.

The traditional approaches for protection for bicyclists (speed management of motor vehicles, separating motor vehicles and vulnerable road users, and the use of bicycle helmets) was the basis for the first two SPIs for safe cycling. However, work presented in the Swedish Transport Administration´s bicycle strategy (Swedish Transport Administration, 2014) was an important input, which led to the introduction of the SPI related to Good quality maintenance of bicycle paths.

The Swedish strategy to improve bicycle safety

For the 2014 Swedish Transport Administration´s bicycle strategy, an analysis of 4000 randomly selected bicycle crashes reported in Strada was conducted (Niska & Eriksson, 2013). It was concluded that approximately 80% of bicycle crashes were single bicycle crashes, and that in 45% of single bicycle crashes the main cause was lack of operation and maintenance (e.g., de-icing or removal of loose gravel).A large potential for increasing and improving maintenance was thereby found, which consequently led to the SPI related to good quality maintenance of bicycle paths.

Besides improved operation and maintenance, the potential of a number of different countermeasures were considered, for example the use of bicycle helmets, adjustment of kerbstones and the use of winter bicycle tyres (studded tyres for bicycles). The analysis of the potential for different countermeasures was based on all hospital-reported crashes in Strada between 2007 and 2012,

and showed that improved operation and maintenance (removal of loose gravel/leaves, and effective deicing) had the largest combined potential of addressing 35-45% of crashes. Also, bicycle winter tyres and protective jacket and trousers showed high potential, 15-20% and up to 30%, respectively (Swedish Transport Administration, 2014).

While this was a first attempt to estimate the potential of different countermeasures to address hospital-reported bicycle injuries, there were several limitations. The estimates were based on mass data, which is a benefit as it includes many of cases. However, a large amount of data means that the level of detail is not very high and can therefore lead to uncertainties in the estimates. Further, as all hospital-reported crashes were included, injury severity was not considered.

Another limitation was that the issue of double counting was not taken into account. In this case, double counting refers to when a bicycle crash is addressed by more than one countermeasure. For example, a cyclist without a helmet loses control of the bicycle on an icy surface, falls and sustains a head injury. This head injury could potentially be prevented both by a helmet and by improved maintenance with de-icing. This issue of double counting is not purely methodological, but also has important practical implications. It is also relevant for the SPIs that are used today in Sweden to prioritize road safety work for bicycles, as it is not known how large a proportion of crashes these SPIs address together.

Lastly, Strandroth et al. (2012) has demonstrated the benefit of deriving a residual of crashes not addressed by existing countermeasures. The advantage of a logical reduction in crashes based on existing countermeasures makes it possible to investigate safety gaps. Thereby, crash characteristics that need to be addressed by future safety interventions can be identified. This has important practical implications that can help guide stakeholders when prioritizing their resources. This deriving of a residual of crashes has not yet been applied to bicycle crashes.

In summary, there are still limited studies based on in-depth bicycle crash data, reporting the potential of different countermeasures in Sweden, especially with regard to crashes resulting in non-fatal injuries with a high risk of health loss. Further, it is not known how the SPIs for safe cycling address these crashes

together. Lastly, a description of a residual of bicycle crashes not addressed by existing countermeasures is lacking. These issues make it difficult to properly address and prioritize both existing and future interventions for bicycle safety.

Summary of introduction

Today, different stakeholders in society recognize increased bicycling as an important contribution to increased physical activity and thus to improve health among the population, and as a way to make cities more sustainable by reducing emissions from motorized traffic. However, as bicyclists are vulnerable road users, they are at higher risk of being injured in a crash. The societal trends of moving towards more sustainable transportation need to be supported by creating safety for bicyclists in order to minimize the potential negative impacts in terms of serious injuries and fatalities, in line with Vision Zero. In Sweden, the consequences of road traffic injuries are described in terms of permanent medical impairment (PMI), which, according to the ICF model of health, is only one aspect of disability. In view of this, it is necessary to further investigate the consequences of injuries by also taking into account aspects other than medical impairment but also individuals' lived experience of impairment. This knowledge can increase the understanding of injuries for which prevention is important from a holistic perspective on health. Another knowledge gap is related to crash and injury prevention, as it is not known how crashes occur that involve injuries with higher risks of health loss. Further, it is not known how relevant the SPIs for safe cycling are in these crashes. Therefore, the need for additional safety improvements for cyclists cannot be properly described.

Aim

The overall aim of this thesis was to guide current and future safety improvements that address serious injuries among bicyclists. This was investigated over four studies, of which the first two aimed to identify injuries leading to loss of health from a biopsychosocial perspective, and the two following studies aimed to understand how these injuries occur and how they can be prevented.

Study I: Describe and compare road traffic injuries leading to problems in HRQoL, with regards to road user group, injury severity and injured body region

Study II: Investigate durations of SA after a bicycle crash in Sweden, in general and by injury type and injured body region

Output: Targeted injuries important to prevent

Output: Detailed description of crashes where cyclists sustained injuries with high risk of health-loss

Study III: Describe crash characteristics and circumstances in crashes where cyclists sustained injuries with high risk of health loss - defined here as injuries with high risk of leading to problems in HRQoL or long-term sickness absence

Study IV: Estimate the potential of different countermeasures to reduce crashes resulting in injuries with high risk of health-loss. As well as describing crashes not addressed by the analyzed countermeasures

Output: Guidance for future implementation of countermeasures to increase cycling safety

Figure 6. Aims and output of the included studies. A sequential approach was used, where the results guided the work forward.

The specific aims (Figure 6) of each study were as follows:

Study I: To describe and compare road traffic injuries leading to problems in HRQoL, with regard to road user group, injury severity and injured body region.

Study II: To investigate the occurrence and duration of SA after a bicycle crash, in general and by injury type and injured body region.

Study III: To describe crash characteristics and circumstances in crashes where cyclists sustained injuries with a high risk of health loss.

Study IV: To estimate the potential of different countermeasures to reduce crashes resulting in injuries with a high risk of health loss among cyclists in Sweden. A further aim was to describe the residual – i.e. crashes that were not considered to be addressed by the analysed countermeasures.

Materials and methods

This thesis comprises four studies. The studies are summarized in Table 4, and are described in further detail in the following sections.

Study I

Medical outcome data regarding injuries were obtained from the data acquisition system Swedish Traffic Accident Data Acquisition (Strada). HRQoL data were obtained from a self-report survey of individuals injured in road traffic crashes between 1st January 2007 and 31st December 2009. A stratified sample based on the injured part of the body and its corresponding AIS value was drawn from Strada, and a random sample of these individuals was included in the study. The EQ-5D was used to evaluate HRQoL. In November 2010, a questionnaire was sent out together with a cover letter explaining the purpose of the study. Two reminders were sent, the first after three weeks and one additional reminder after six weeks. For the purpose of this study, only persons with injuries from a car or a bicycle crash were included (n=3109).

Analysis

From the sample (n=3109), individuals having reported previous illness affecting their daily lives were excluded (n=219). Individuals were divided into two groups depending on whether they had reported problems in any of the five dimensions in the EQ-5D descriptive system, defined as HRQoL <1 (1 implies perfect health and no problems in any of the five dimensions). A two tailed Fisher's exact test was used to compare the injury outcome for bicyclists and car occupants depending on injured body region, and injury severity (MAIS and AIS). Injury outcome was described as a percentage of problems reported.

Table 4. Summary of included studies

	Study I	Study II	Study III	Study IV
Aim	Describe and compare road traffic injuries leading to problems in HRQoL, with regard to road user group, injury severity and injured body region.	Investigate durations of SA after a bicycle crash in Sweden, in general and by injury type and injured body region.	Describe crash characteristics and circumstances in crashes where cyclists sustained injuries with a high risk of health loss.	Estimate the potential of different countermeasures to reduce crashes resulting in injuries with a high risk of health loss among cyclists in Sweden and describe the residual crashes.
Design	Cross-sectional survey (EQ-5D), stratified sample + register data	Cross-sectional population-based register study	Cross-sectional survey, stratified sample + register data	
Data sources	Self-reported + Strada	National patient registry, cause of death register, LISA[1], MiDAS[2],	Self-reported + Strada	
Inclusion criteria	Bicyclists and car occupants injured in a road traffic crash and who visited emergency care hospital. No previous illness affecting daily life.	Individuals who have had inpatient or specialized outpatient medical care due to a non-fatal injury from a bicycle crash. 16-64 years old and living in Sweden on 31 December the year before the crash. Not on SA or full-time disability pension at the time of the crash. Injury diagnosis from ICD-10-SE chapters S00-T89 and Z041.	Injury specified in Table 6. >15 years old at time of crash.	Same as Study III + known crash circumstances.
Number of cases	959	22,045	947 (7720 weighted)	780 (7553 weighted)
Time period	2007-2009	2009-2011 follow-up to 2013	Jan 2013- May 2017	
Analytical method	Univariate statistics were used to describe the sample characteristics and the prevalence of problems in HRQoL distinguished by injured body region and injury severity. To investigate differences in subgroups (bicyclists versus car occupants), Fisher's exact test was used.	Univariate statistics were used to describe the sample characteristics and prevalence of SA distinguished by injured body region and injury types. Logistic regression analysis to assess OR for different durations of SA depending on injured body region and type of injury.	Crashes were classified based on crash circumstances. Comparisons were made between individuals reporting declined health and those who were not affected regarding personal and crash-related variables. The predicted number of impaired individuals was calculated and compared with the number of individuals rating their health as having declined after the crash.	Target groups for different countermeasures were defined. The potential of individual and combined interventions (without double counting) was assessed. Crashes not addressed by any of the included countermeasures were described in more detail.

[1]LISA: Longitudinal Integration Database for Health Insurance and Labour Market Studies [2]MiDAS: Micro Data for Analysis of Social Insurance

Study II

This was a population-based study, including all individuals who received inpatient or specialized outpatient medical care between 2009 and 2011 due to a non-fatal injury from a bicycle crash, and who were aged 16-64 years and living in Sweden on 31 December of the year before the crash (n=26,885). Several national registers were used to obtain information regarding injury diagnoses, sociodemographic variables, and information on SA for all individuals. Those who were already on SA or full-time disability pension at the time of the crash were excluded (n=2,592). Also, those without injury diagnoses from ICD chapters S00-T89 or ICD chapter Z041 were also excluded (n=635), leaving 22,045 individuals for analyses. An individual could have more than one visit/instance of hospitalization on the same day. Each visit is coded with a main diagnosis and any contributing secondary diagnoses. For those with more than one visit/instance of hospitalization and main injury diagnosis, the diagnosis from inpatient care was selected over outpatient care, and any injury diagnosis was selected before other types of diagnoses, in order to include only one main injury.

Analysis

The type of injury and injured body region were set in relation to the individual's SA following the bicycle crash, sociodemographic variables and duration of hospital stay. Descriptive statistics were used to outline study population characteristics and the prevalence of SA. Different durations of SA were categorized in four different groups: <30 days, 30-89 days, 90-179 days and ≥180 days. Odds ratios (ORs) with 95% confidence interval (CI) for various categories of different durations of SA were calculated by logistic regression analyses using SPSS (Version 23). For the regression analysis, three groups of duration of SA were used: <30 days, 30-89 days and ≥90 days.

Further analysis of results from Studies I and II

In order to combine the results from the first two studies, and to compare the results with other measures of injuries, additional injury distributions for MAIS 2+ and 3+, as well as PMI 1+ and PMI 10+, for the years 2007 to 2014 were obtained from Strada. Body regions were grouped to make the measures comparable, and external (skin) injuries were excluded.

Further, the size of the different populations needed to be considered, and also how the size changes depending on which measure is used. For this purpose, the average number of emergency care visits involving Swedish bicyclists from 2013 to 2014 and the corresponding number of different injury severity outcomes (MAIS 2+ and 3+, and PMI 1+ and PMI 10+) was used. The number of MAIS 1, 2 and 3+ from Study I was calculated to match the national levels in Strada. This was done by calculating and applying the proportion of MAIS 1, 2 and 3+ injuries found in Strada for the years 2007 to 2014.

In addition, the proportion of long-term problems in HRQoL and SA ≥90 days for different body regions (excluding external injuries) was assessed. For this purpose, ICD-10 diagnoses from the Strada data in Study I were obtained and grouped in the same manner as in Study II. The proportion of reported problems in HRQoL (HRQoL <1) as well as of SA ≥90 days (among those who had a SA spell), was calculated for the each body region. SA ≥90 days was chosen due to the limited number SA spells ≥180 days.

Lastly, among those reporting problems in HRQoL in Study I, and among those with SA ≥180 days, the most common ICD 10 diagnoses in body regions with higher proportion of long-term problems in HRQoL and SA ≥90 days, were listed and grouped. These diagnoses served as the basis for inclusion criteria in the data collection for Studies III and IV.

Study III

In Study III, hospital reported data from the Swedish Traffic Accident Data Acquisition (Strada) were combined with a questionnaire obtaining more detailed information regarding the crash and consequences from injuries. A sample of individuals (above 15 years of age) injured in bicycle crashes between January 2013 and April 2017 was drawn from Strada. The sample was based on specific diagnoses identified in Study 1 and Study II as common among cyclists reporting problems in HRQoL and cyclists on SA ≥180 days after a bicycle crash. A total of 7641 injured cyclists included in Strada had at least one such diagnosis. These diagnoses were grouped into different body regions (Hip & upper leg, Lower leg & ankle, Shoulder & upper arm, Spine & back, Traumatic brain injury, Multiple). 500 individuals with injuries from each body region were randomized to be included, except for traumatic brain injuries where all 325

injured were included. Among the randomized sample (n=2825) postal information was available for 2678 individuals who were invited to participate in the study. The questionnaire contained six different sections with questions related to traffic habits, personal circumstances, road environment, crash sequence, factors contributing to the crash, and injuries. In total, the questionnaire contained 39 multiple-choice questions, and most questions included a free-text option.

Analysis

A comparison was conducted between the crashes included in the study and all hospital reported bicycle crashes that occurred during the same time period, in order to understand if and how the study population differed compared with all bicycle crashes reported to emergency care hospitals during the same time period. Information on age, sex, type of crash and helmet-use was obtained for all crashes reported in Strada that occurred between January 2013 and April 2017, including the crashes in the present study population. Crashes were classified based on the crash circumstances e.g., depending on collision opponent (if any), road environment, and other circumstances (eg road surface condition, braking prior to collision etc. As the sampling was made from injury groups of different sizes, the crash types were weighted to match how the injuries were represented in Strada. This was done by dividing the number of included cases for each body region by the corresponding number of that body region in Strada from which the sample was drawn, multiplied by the inverse proportion of the included cases.

Comparisons were made between those with self-reported declined health and people with non-affected health regarding traffic habits, personal circumstances related to the crash, road environment, crash-types, injured body region, sickness absence, need for rehabilitation, and whether the injury kept them from continue cycling. A separate analysis was carried out regarding the speed of the motor vehicle as reported by the cyclist.

In all comparisons, chi squared tests with a 95% significance level were used to test for statistical significance. To exemplify, the difference in distribution of gender among people with declined health and people without declined health was tested in a 2x2 contingency table with chi square statistics in Excel. The p-value is provided when a statistically significant difference is found.

Study IV

This study was based on the same material as Study III. A weighted number of crashes served as the basis for the analysis, with the exception of crashes with unknown circumstances which were excluded (2% of the material, n=167), resulting in 7553 weighted cases available for analysis.

Analysis

The potential of countermeasures currently included in the Swedish Safety Performance Indicators (SPI) was assessed. These are the use of bicycle helmets, good quality maintenance of bicycle paths (shared or separate) and safe bicycle crossings (Swedish Transport Administration, 2018). Secondly, the potential of countermeasures that could be described as "existing but not fully implemented" was assessed. The reason behind this was to assess the potential of countermeasures that could be rapidly implemented, with a limited need for further research and development. These included existing vehicle technologies such as autonomous emergency braking (AEB) with cyclist detection, improved and extended bicycle infrastructure, use of reflective clothing and studded tyres for bicycles. The overall potential of all countermeasures assessed was calculated, thus giving a grand total without double counting. The overall potential of the countermeasures included in Sweden's SPIs and five additional countermeasures that together would result in the highest potential, taking double counting into consideration, was also investigated. Cases that were considered not to be addressed by any of the countermeasures included (i.e., the residual crashes) were described in more detail.

Further analysis based on residual crashes

The crashes not addressed by any of the considered countermeasures in paper IV, i.e., the residual crashes, were described in more detail. Based on the description of the residual crashes, further countermeasures were considered:

- Shoulder protection
- Anti-lock brakes (ABS) for bicycles
- More stable bicycles for people under 75 years
- Soft asphalt (excluding bicycle crossings)
- Soft asphalt (including bicycle crossings)

These additional countermeasures differed compared with the countermeasures included in paper IV, as these were considered to be in need of further research and development before any broad scale implementation would be possible.

Ethical considerations

In all research, ethical considerations need to be taken into account in order to protect individuals from various forms of harm (Vetenskapsrådet, 2011). Further, if the research involves sensitive information regarding individuals (e.g. health status, ethnicity, income, etc.), the research must be approved by an ethical committee. All studies included were approved by an ethical committee. Study 1 and Study II were both approved by the Regional Ethical Review Board in Stockholm, Sweden (Protocol Study I: 2009/5:12, Protocols Study II: 2007/762:31; 2009/23:32; 2011/806:32). The local ethical review board in Gothenburg, Sweden approved the data collected and used for Studies III and IV (ref. 679-17).

In Study II, data were collected from several registers, and no information was collected from individuals. The people in the different registers were linked by Statistics Sweden (SCB), and hence were anonymous in the dataset and subsequent analysis. In Studies I, III and IV, which were based on data collected from individuals, special attention was paid to informing subjects that participation in the study was voluntary, and to treating the collected data in accordance with the requirements specified by the ethical committee.

Results

Study I

1178 (38%) out of the 3109 people injured in a bicycle or car crash answered the survey. After excluding people with previous problems in HRQoL, the final sample consisted of 959 respondents, of which 402 were injured in a bicycle crash and 557 in a car crash. Females reported a higher share of problems compared with males, at 57% and 48% respectively. The share of problems reported was lowest among persons aged <10 years (21%), and highest among persons aged ≥80 years (67%). For bicyclists, it was most common to report problems after being struck by a motor vehicle (65%). Overall, 59% of car occupants and 44% of bicyclists reported problems. The most frequently reported problems were pain/discomfort followed by anxiety/depression (Table 5).

Table 5. Overview of bicyclists' and car occupants' self-reported problems in HRQoL for the different EQ-5D dimensions.

EQ-5D dimension	Self-reported problems, n (%)		
	Bicyclists	Car occupants	Total
Mobility			
"*I have some problems walking around*" or "*I am confined to bed*"	44 (11%)	62 (11%)	106 (11%)
Self-care			
"*I have some problems washing or dressing myself*" or "*I am unable to wash or dress myself*"	6 (1%)	17 (3%)	23 (2%)
Usual activities			
"*I have some problems performing my usual activities*" or "*I am unable to perform my usual activities*"	38 (9%)	103 (18%)	141 (15%)
Pain/discomfort			
"*I have moderate pain or discomfort*" or "*I have extreme pain or discomfort*"	147 (37%)	282 (51%)	429 (45%)
Anxiety/depression			
"*I am moderately anxious or depressed*" or "*I am extremely anxious or depressed*"	78 (19%)	171 (31%)	249 (26%)

The proportion of reported problems increased as overall injury severity increased (Figure 7). When comparing the proportion of reported problems with regard to injured body region, car occupants reported significantly more problems. The differences were statistically significant for all body regions apart from the spine and lower extremities and pelvis. The injured body region where both bicyclists and car occupants most often reported problems were lower extremity and pelvis, at 78% and 87% respectively. Problems after spinal injuries were also common in both road user groups. For bicyclists, spinal injuries and injuries to lower extremities led to problems in HRQoL to a much higher extent compared with other body regions.
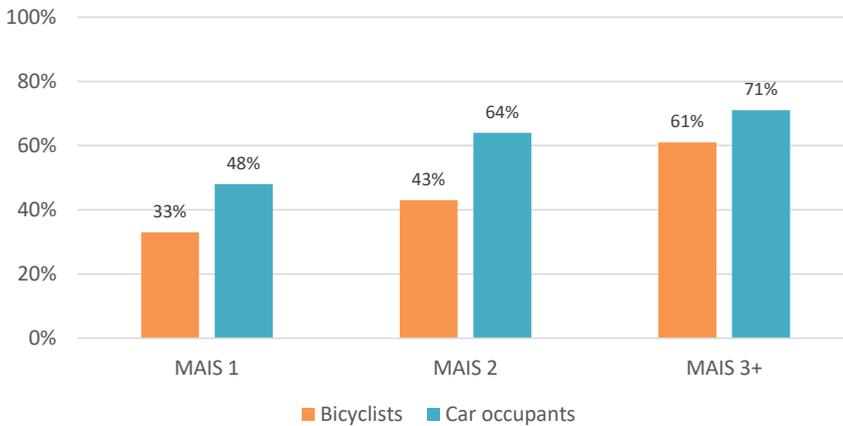
Figure 7. Proportion of problems in HRQoL among MAIS 1, 2 and 3+ injured bicyclists and car occupants.

When combining injury severity and injured body regions for bicyclists, the proportion of reported problems increased greatly as injury severity to the lower extremities and pelvis increased. The increase in reported problems was from 38% on AIS 1 level to 86-88% on AIS 2 and AIS 3+. For car occupants' spinal injuries, there was a large increase in reported problems when comparing injury severity AIS 1 with AIS 2 and AIS 3+. The increase in reported problems was from 53% on AIS 1 level to 80 and 85% on AIS 2 and AIS 3+ levels.

Study II

In the three years from 2009 to 2011, 22,045 individuals aged 16 to 64

(excluding persons already on SA or full-time disability pension) received inpatient or specialized outpatient medical care due to a new injury from a bicycle crash. The majority (57%) of the injured individuals were men, but women more often had SA compared with men; 23% of the women and 18% of the men had a SA spell in connection with the crash. A lower proportion of individuals aged 16 to 24 had a new instance of SA (5%), whereas a new SA spell was most common among individuals aged 55 to 64 years (32%).

In total, 4387 (20%) individuals had a new SA spell in connection with the crash. 61% of those injured receiving inpatient care for ≥2 days had a new instance of SA in connection with the crash, compared with 15% of new SA for those receiving only outpatient care. External (skin) injuries were most common, but the majority (94%) of these did not result in subsequent SA. Fractures were the second most common type of injury, and around 38% of fractures resulted in subsequent SA.
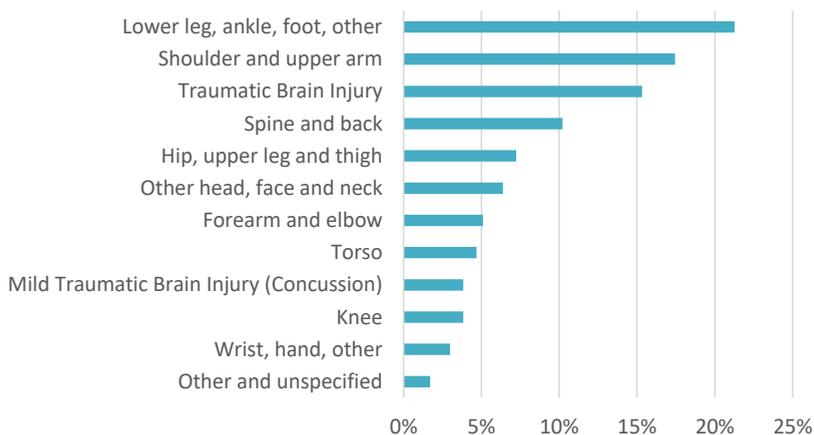
Figure 8. Distribution of injuries among those with a SA spell lasting ≥180 days (n=235).

About 1% (n=235) of the individuals had a SA spell lasting ≥180 days. Among those with a SA spell lasting ≥180 days, the most common injuries were to the lower leg (21%) followed by shoulder and upper arm (17%), and traumatic brain injuries (15%) (Figure 8). In around 12% of traumatic brain injuries, the SA spell lasted ≥180 days. Five percent of the injuries to the spine and neck led to a SA spell lasting ≥180 days.

Compared with internal injuries, fractures showed higher ORs across all durations, with the highest OR for SA 30-89 days (8.09, CI 6.30–10.39). Regarding body region, the OR for SA 15-29 days was highest for upper extremity injuries (3.44, CI 2.95-4.00) in relation to other head, face and neck injuries. Injuries to upper extremities also had the highest OR for SA 30-89 days (9.83, CI 7.55-12.80), followed by spine and back injuries (7.99, CI 5.38-11.87) and lower extremity injuries (7.51, CI 5.69-9.92). Spinal injuries had the highest OR for SA ≥90 days (11.98, CI 7.38-19.46), followed by traumatic brain injuries other than concussion (6.64, CI 4.01-10.98) and injuries to lower extremities (5.28, CI 3.58-7.78).

Combined results of Studies I and II – Overview of injuries

With the results from the two studies, the overview of injuries can now be revisited. In the following sections, the results from the two included studies will be presented in relation to previous measures of injury severity and long-term consequences, firstly by comparing injury distributions and secondly with a more detailed comparison between HRQoL and SA.

Extended injury distribution

In Figure 9, the distribution of injuries among individuals who reported problems in HRQoL after a bicycle crash (Study I) and among individuals who were on SA beyond six months after a bicycle crash (Study II) are added to previous measures.
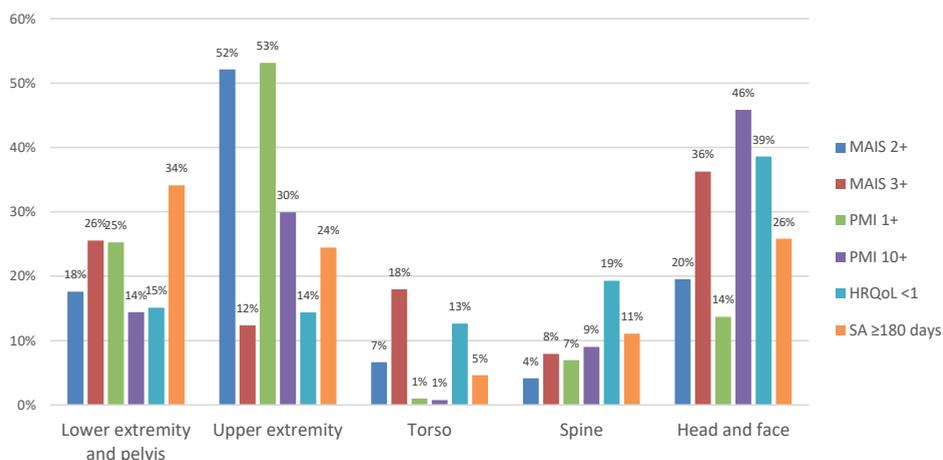
Figure 9. The distribution of injuries by different measures of injury severity (MAIS) and long-term consequences (PMI, HRQoL & SA). Note that the percentages add up to 100% for each measure.

It should be kept in mind that PMI injuries are based on a predictive method rather than the actual outcome, and that the distributions of PMI injuries are based on the accumulated RPMI for each injury, and not the injury distribution among individuals who are predicted to sustain a certain level of PMI (see also the description in the Introduction). Figure 9 shows that among MAIS 2+ bicyclists, the most common injuries are to the upper extremities, followed by head and face injuries. For MAIS 3+, injuries to the head and face are the most common, followed by injuries to the lower extremities. For PMI 1+ injuries, the most common injuries are to the upper extremities, followed by the lower extremities. Among PMI 10+ injuries, injuries to the head and face are most common, followed by injuries to the upper extremities. Among people with problems in HRQoL, injuries to the head and face are the most common, followed by spinal injuries. Among those with SA beyond six months, injuries to the lower extremities are the most common, followed by head and face injuries.

In conclusion, extending measures of injury severity and long-term consequences by adding HRQoL and SA actually do change the scope of which injuries affect health after a bicycle injury. For example, injuries to lower extremities are far more common among SA spells beyond six months, and

spinal injuries become more relevant among those reporting problems in HRQoL. Another difference is that both HRQoL and SA have much smaller proportions of upper extremity injuries compared with PMI 1+.
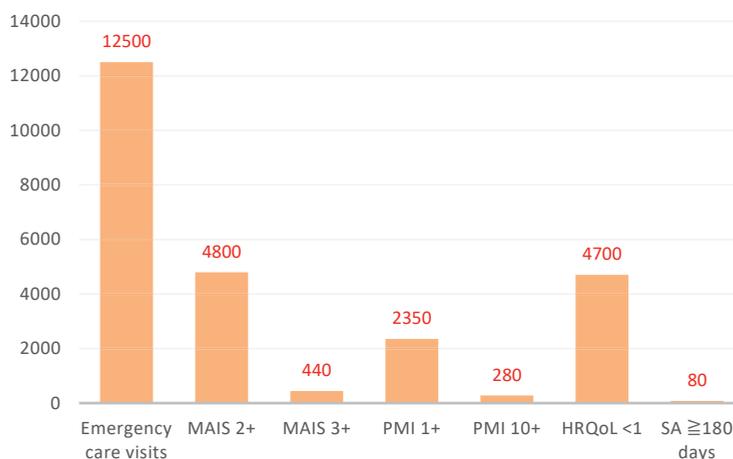
Figure 10. Estimated average number of emergency care visits involving Swedish bicyclists in 2013-2014 and corresponding number of different injury severity outcomes and long-term consequences.

What should also be considered is that the number of injured individuals or the number of injuries changes depending on which measure is used. Therefore, the magnitude of bicyclist injuries and the injury consequences will differ. To exemplify this, some calculations were made and are presented in Figure 10. In an average year (based on hospital-reported bicyclist crashes in Strada in 2013 and 2014), there are approximately 12,500 injured bicyclists reported at emergency care hospitals in Sweden. Of these individuals, around 4800 are MAIS 2+ injured and 440 are MAIS 3+ injured, while 2350 are expected to be PMI 1+ and 280 are expected to be PMI 10+. In Study I, 44% of bicyclists reported problems in HRQoL. Compared with the total distribution in Strada, MAIS 2+ and MAIS 3+ were overrepresented in the material due to the stratified sampling method. Therefore, for the purpose of comparing the populations, the number of MAIS 1, 2 and 3+ from Study I were calculated to match the national levels in Strada, resulting in approximately 4700 individuals with problems in HRQoL. Regarding SA, Study II only included individuals aged 16 to 64 years, and covered all inpatient and specialized outpatient care

(not only emergency care hospitals). In total, 20% of the individuals were on SA and approximately 1% of the total population of injured bicyclists were on SA beyond six months. This 1% corresponds to approximately 80 individuals in one year. The average number of fatally injured bicyclists can also be added. On average, between 2011 and 2015, 17 bicyclists were fatally injured each year.

Comparison between HRQoL and SA

In Figure 11, a more detailed view of injuries leading to long-term problems in HRQoL and SA beyond 90 days is given. Based on the material from Study I and Study II, the proportion of problems in HRQoL and SA beyond 90 days is presented for different body regions.
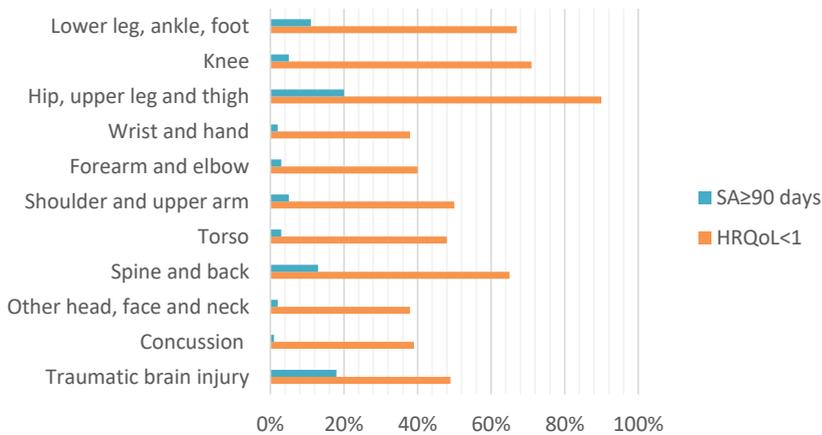
Figure 11. Proportion of long-term problems in HRQoL and SA ≥90 days, for different body regions.

Overall, the proportion of problems in HRQoL is high, but clearly there are differences between different body regions. For example, the proportion of injuries to the elbow, forearm, wrist and hand is lower compared to shoulder and upper arm injuries. The highest proportion of problems in HRQoL is for injuries to the hip, upper leg and thigh. This is also the case for SA, where 20% of those who were on SA with injuries to the hip, upper leg or thigh led to SA beyond 90 days. The proportion of SA beyond 90 days is lowest for concussive injuries, but concussive injuries are more often associated with reporting problems in HRQoL. The proportion of problems in HRQoL is high for knee injuries; whereas the proportion of SA beyond 90 days for knee injuries is lower (5%).

In conclusion, even though a large proportion of head injuries are concussive injuries that rarely result in SA, the longest durations of SA were related to severe head injuries. Secondly, leg injuries were relatively common and were also associated with problems in HRQoL 1-3 years after the crash. Further, leg injuries often resulted in SA and often lead to SA beyond 90 days. Thirdly, injuries to the shoulder and upper arm were more common among those reporting problems in HRQoL, as well as among those on SA beyond 90 days, compared with injuries to other parts of the arm.

Output from Studies I and II

The ICD 10 diagnoses commonly present among the injured body regions identified above were listed and grouped (Table 6). These diagnoses served as inclusion criteria in the data collection for Studies III and IV. On a general level, these diagnoses included fractures of the hip and upper leg, fractures of the lower leg and ankle, fractures of the upper arm, fractures and sprains of the shoulder, traumatic brain injuries (excluding mild concussion), and fractures and strains to the spine.

Table 6. Defined body regions and ICD-10 diagnoses common among people reporting problems in HRQoL and people on SA beyond 180 days.

Body region	ICD-10 SV codes
Hip, upper leg	S72.00, S72.10, S72.30, S72.40, S72.80, S72.90, S72.91, S73.1
Lower leg, ankle	S82.10, S82.11, S82.20, S82.21, S82.3, S82.31, S82.4, S82.41, S82.6, S82.61, S82.90, S82.91
Traumatic brain injuries	S06.2, S06.3, S06.31, S06.4, S06.5, S06.6, S06.8, S06.9
Shoulder, upper arm	S42.00, S42.01, S42.10, S42.20, S42.21, S42.40, S42.41, S43.0, S43.1, S43.4, S43.5
Spine and back	S12.8, S13.4, S14.0, S14.1, S14.2, S14.3, S14.6, S22.0, S32.0, S32.70, S32.80, S32.81, S34.0, S34.2, S34.3
Multiple	Any of the above from at least two different body regions

Study III

In total, 964 individuals answered the survey, of whom 947 were included in the analysis. The overall response rate was 36% and did not differ significantly

across the different injured body regions. The present study included a higher proportion of people above the age of 55, as well as a lower proportion of people aged 15-25, comparing all crashes reported in Strada from January 2013 to April 2017 with the crashes included in the present study. There was also a slight overrepresentation of women and an underrepresentation of men compared with Strada (p=0.02). Compared with single bicycle crashes, crashes involving motor vehicles are also overrepresented in the present study (19% compared with 11%) (p=<0.01). Further, the rate of helmet-wearing was slightly higher in the study population, at 47% compared with 40% in Strada (p=0.03). The mean overall RPMI 1+ was 46% in the study population, compared with 19% in Strada, which indicates that more severe injuries were included in the present study (which is in line with the purpose of the study, as only injuries previously identified as showing a higher proportion of health loss were included). The predicted number of impaired individuals (PMI 1+) was calculated to be 427. This figure corresponded rather well to the number of individuals experiencing declined health (n=421).

Crash characteristics and crash scenarios

Most crashes occurred during leisure-time cycling (48%), or when cycling to or from work (38%). The majority of crashes occurred during the daytime, and the traffic environment at the time of the crash was most often perceived as calm. Most crashes occurred on shared bicycle paths (35%). In total, 53% of crashes occurred on some type of designated bicycle infrastructure (e.g. bicycle paths and lanes), 24% on local streets and 15% on rural roads. 51% reported being on SA after the crash, and as many as 64% needed some type of rehabilitation (e.g. physical therapy or medical treatment) for their injury.

The majority of crashes (68%) were single bicycle crashes, 17% were collisions with motor vehicles and a further 11% were collisions with other cyclists or pedestrians. Of the 17% of crashes with motor vehicles, almost all involved passenger cars. The most common type of crash involving a passenger car occurred on a bicycle crossing (4% of all crashes). The second most common type was crashes occurring at four-way junctions (3% of all crashes) and crashes where the car crossed a bicycle crossing while turning (2% of all crashes). These three crash types accounted for 55% of all crashes involving a passenger car. 49% of crashes involving motor vehicles occurred while the cyclist was cycling

on designated cycling infrastructure (e.g., on bicycle crossings or on bicycle paths).

Collisions with other VRUs (11%) were mostly collisions involving another cyclist (9%), most commonly in a head-on crash (3%).

Most of the single bicycle crashes were related to some type of loss of control (46%), mainly due to skidding on winter surface conditions (14%), followed by loss of control during braking (6%) and loss of balance at no or low speed (5%) and skidding on gravel (5%). Collisions with stationary objects mainly involved curbstones, where falls occurred both when cycling into a curbstone (e.g., trying to cross it or unintentionally drifting into the curbstone) and when descending across a curbstone. 6% of the crashes occurred due to road surface conditions, e.g., potholes or uneven surface.

There were no significant differences in the crash distribution when comparing all crashes with crashes among people with declined health.

Study IV

Analysis of potential for current Swedish SPIs for safe cycling

The current Swedish SPIs that relate to safe cycling addressed 22% of the 7553 crashes. In some cases, more than one countermeasure was relevant, resulting in an overlap of countermeasures for the same crash. Therefore, the sum of the individual potentials (i.e., with double counting) was 1834 of 7553 crashes (24%). Improved maintenance by de-icing and removal of snow from bicycle infrastructure was found to have the highest potential (8%), followed by improved crashworthiness of passenger cars (5%) and safer bicycle crossings (4%).

Analysis of potential for existing but not fully implemented countermeasures

The greatest potential was found for AEB with cyclist detection for passenger cars (12%), followed by studded winter tyres for bicycles (12%). An additional 11% of crashes could be addressed if improved maintenance (e.g., de-icing and removal of loose gravel) were to be extended to include non-bicycle

infrastructure in urban areas. In total, it was found that the sum of the individual potentials of all safety improvements in Step 2 was 67%. However, as a greater number of countermeasures was considered, the overlap of different safety improvements was more pronounced than for the SPIs. For example, improved maintenance, including de-icing, would address the same crash population as studded winter tyres. When double counting was taken into account, the combined potential of the "existing but not fully implemented" safety improvements was 56%. In total, taking double counting into consideration, all safety improvements could address 64% of all crashes.

'Top five' combination of countermeasures

An analysis was carried out to identify the combination of five different countermeasures that, together with Sweden's SPIs for safe bicycling, would result in the highest overall potential (i.e., the combination with the smallest overlap). The analysis showed that the highest potential of 51% of crashes potentially addressed (n=3888) was given by the SPIs combined with:

- AEB with cyclist detection on passenger cars
- Improved maintenance in urban areas on non-bicycle infrastructure
- Improvement of curbstones
- Separation from motor vehicles
- Separation from pedestrians

However, it was also found that adding improved design of construction work, or improved maintenance in rural areas instead of separation from pedestrians, had almost the same overall potential.

Residual crashes not addressed by considered countermeasures

It was found that 36% of crashes could not be addressed by any of the countermeasures included in the current Swedish SPIs or other existing but not fully implemented countermeasures. 69% of residual crashes were single bicycle crashes. Most of the remaining single bicycle crashes were related to LoC, where the considered countermeasures for safe bicycles were mainly limited to elderly people.

Table 7. Potential for additional countermeasures considered based on the residual crashes.

Intervention area	Countermeasure	%* and (n) of crashes addressed	
Crash protection	Shoulder protection	46% (3499)	
Safe bicycles	ABS for bicycles	5% (349)	51% (3848)
	More stable bicycle	46% (3499)	
Infrastructure	Soft asphalt (excluding bicycle crossings)	31% (2360)	
	Soft asphalt (including bicycle crossings)	40% (2997)	
	SafeRails**	2% (173)	
Sum of individual potentials		**159% (12012)**	
Total without double counting		**78% (5918)**	
Total without double counting, including paper IV countermeasures		**92% (6979)**	

*% of total N (7553)
**a profile which can be implemented in existing tramrails' gutters to support a bicycle wheel in parallel to the gutter, simultaneously allowing a tram wheel to pass without hindrance by deforming elastically (https://saferails.nl/)

Among the residual crashes, the majority were single bicycle crashes, most of which were related to wheels locking during braking, losing balance at no or low speed, or while getting on or off the bicycle. The issue of instability was only addressed in the countermeasures among older people, but clearly this is not only a problem among the elderly. Therefore, in the subsequent analysis of additional countermeasures, a more stable bicycle, in terms of both stability during braking with bicycle ABS and a more stable bicycle (not limited to a tricycle), was considered. Another additional countermeasure that was considered was soft (energy-absorbing) asphalt. Instead of identifying multiple countermeasures that would only address a small proportion of the remaining crashes, a systematic implementation of a countermeasure that can relate to any type of bicycle crash, as long as it results in a fall with ground impact on bicycle infrastructure, was considered. Further, the majority of remaining injuries were injuries to the shoulder and upper arm. Therefore, additional crash protection for the shoulder and upper arm was considered. As injuries to the shoulder and upper arm were common in Strada, this type of injury had a high weighting, resulting in a high potential for shoulder protection. As 10% of remaining crashes were single bicycle crashes where a bicycle wheel had been caught in a tram track, the implementation of a device to prevent bicycle wheels from entering a tram track was also considered. In Table 7, the additional

countermeasures are presented together with the individual potentials and combined with the countermeasures included in paper IV.

Summary of results

The studies included in the present thesis resulted in a number of findings. Study I showed that injuries to the spine and injuries to the lower extremities led to problems in HRQoL to a much higher extent compared with other body regions. In Study II, it was shown that about 1% (n=235) of the individuals had a SA spell lasting 180 days or longer. Among these, the most common injuries were to the lower leg (21%), followed by the shoulder and upper arm (17%) and traumatic brain injuries (15%). Spinal injuries had the highest OR for a SA spell lasting 90 days or longer. The most common injury diagnoses from the study population in Study I (limited to the cyclists) who reported problems in HRQoL, and in Study II who were on SA beyond 180 days, were summarized. On a general level, these diagnoses included fractures of the hip, the upper and lower leg, the ankle, the upper arm, fractures and sprains of the shoulder, traumatic brain injuries (excluding mild concussion), and fractures and strains to the spine. Based on the diagnoses identified in Studies I and II, a sample was drawn from Strada to further investigate the circumstances of crashes where individuals had sustained these types of injuries. Study III showed that the majority of these crashes (68%) were single bicycle crashes, 17% were collisions with motor vehicles and a further 11% were collisions with other cyclists or pedestrians. Of the 17% of crashes with motor vehicles, almost all involved passenger cars. Most of the single bicycle crashes were related to some type of loss of control (46%). A comparison with all bicycle crashes reported in Strada during the same time period showed that crashes involving motor vehicles were slightly overrepresented in the study population (19% compared with 11%). However, the types of crashes leading to health loss did not substantially differ from those that did not result in health loss. In Study IV, the potential for different countermeasures to address the crashes described in Study III was investigated. The current Swedish SPIs that relate to safe cycling could address 22% of the crashes. Improved maintenance by de-icing and removal of snow from bicycle infrastructure was found to have the highest potential (8%), followed by improved crashworthiness of passenger cars (5%) and safe bicycle crossings (4%). Among countermeasures considered to be "existing but not fully implemented", the greatest potential was found for AEB with cyclist

detection for passenger cars (12%), followed by studded winter tyres for bicycles (12%). An additional 11% of crashes could be addressed if improved maintenance (e.g., de-icing and removal of loose gravel) were to be extended to include non-bicycle infrastructure in urban areas. In total, taking double counting into consideration, all safety improvements could address 64% of all crashes. The residual crashes not addressed by any of the considered countermeasures were mainly single bicycle crashes at no or low speed, or single bicycle crashes related to wheels locking during braking. If ABS for bicycles, soft asphalt, SafeRails, more stable bicycles for people younger than 75 years, and shoulder protection were also developed and implemented, a total of 92% of all crashes could potentially be addressed.

Discussion

The overall aim of this thesis was to increase the understanding of how to guide current and future safety improvements that target serious injuries among bicyclists. This was investigated over four studies, of which the first two aimed to identify injuries leading to loss of health, and the two following studies aimed at understanding how these injuries occur and how they can be prevented. This discussion section will begin with a joint discussion of the results from Studies I and II, followed by a joint discussion of the results from Studies III and IV, along with a discussion regarding priorities for increased cycling safety. Subsequently, the RPMI compared with a subjective experience of health is discussed. Further, methodological considerations, including strengths and limitations, are discussed. Lastly, the results are discussed in relation to crash and injury prevention, as well as in relation to the context of sustainability.

Discussion of results from Studies I and II

The results from Study I showed that 59% of car occupants and 44% of bicyclists reported problems in HRQoL after a road traffic injury. This result can be compared with Ulvik et al. (2008), who also used the EQ-5D. Among 210 mixed patients in an intensive care unit (where overall injury severity could be assumed to be higher than in the population included in Study I), 80% reported problems. Pain/discomfort followed by anxiety/depression were the dimensions where both injured bicyclists and car occupants experienced the most problems in Study I, which is in line with results from Ulvik et al. (2008). Another finding was that car occupants, consistently through all EQ-5D dimensions, reported more problems. This is in line with results from Mayou and Bryant (2003), who showed that vehicle occupants reported problems with pain/discomfort more frequently compared with other groups.

Injuries to the lower extremities and pelvis accounted for the highest proportion of problems for both road user groups, a result which is supported by previous research by Nhac-Vu et al. (2014), who found lower limb injuries to be predictive of poorer outcomes in quality of life one year after being

injured. 42% of the bicyclists reported problems after suffering a head injury, and head injuries accounted for 20% of injuries among the bicyclists who reported any problems in HRQoL. In Rizzi, Stigson, and Krafft (2013), head injuries accounted for 9% of PMI 1+ injuries, which is lower than in Study I. However, looking at severe PMI 10+, head injuries account for a much higher proportion.

The findings in Study II suggest that SA exceeding two weeks is a rather common outcome after a bicycle crash. For the majority of those with a new SA (47%), the spell had ended within 30 days, the duration was 30-89 days for around a third (38%), a further 10% were on SA for 90-179 days, and 5% were on SA for ≥180 days. This suggests that societal costs related to bicycle crashes are high, which has been shown in previous studies (Aertsens et al., 2010; de Geus et al., 2012; de Geus et al., 2014). The duration of the SA spell was also related to injury type and injured body region. Fractures were common and often led to subsequent SA. Traumatic brain injuries also often led to SA, with 12% of these injuries leading to SA beyond six months.

Among the cases resulting in SA beyond six months, the majority of the injuries were to the lower leg (21%), shoulder and upper arm (17%), or traumatic brain injuries (15%). In one previous study, injuries to these body regions have been shown to be common PMI injuries among injured bicyclists (Rizzi, Stigson, & Krafft, 2013). It was found that injuries to the upper extremities (arm and shoulder) were the most common of all impairing injuries (46%), followed by leg injuries (22%). In a Finnish study including 264 adult casualties at emergency hospitals, the mean duration of SA after a non-fatal bicycle injury was 82 days among inpatients, and for outpatients the mean duration was 11 days (Olkkonen et al., 1993). In the same study, it was found that injuries to the upper extremities were the most common (33%). Over half the cases with SA longer than 30 days were due to upper extremity injuries. The results from Study II support this finding, and also show that upper extremity injuries (with the exception of hand and wrist injuries) most often account for around 50% of SA >30 days.

In Study II, traumatic brain injuries were not common, but they most often led to SA ≥180 days. This indicates that traumatic brain injuries can also lead to severe consequences for SA, in line with Larsson et al. (2010). Several other

studies have shown that long-term consequences from both mild and severe traumatic brain injuries are common, and have an impact on both SA (Larsson et al., 2010) and quality of life (Scholten et al., 2015; Dikmen et al., 2003), as well as cognitive, functional and psychosocial impacts (Hellawell, Taylor, & Pentland, 1999; Sinha et al., 2013). Even if the results from Study I suggested that problems in HRQoL after head injury were not very common compared with injuries in other body regions, this should be interpreted as an opportunity to highlight that bicycle helmets, while important, will not solve all problems related to bicycling. Even if helmet usage rates increase, there will still be a large proportion of injuries to address if the ultimate goal is to reduce injuries that have long-term effects on people's health. Therefore, in addition to encouraging helmet usage, other measures will also need to be considered.

Among car occupants in crashes, a high rate of spinal (whiplash) injuries has been found to lead to long-term SA (Berecki-Gisolf, Collie, & McClure, 2013; Bylund & Björnstig, 1998). In Study II, spinal injuries were uncommon, accounting for 2% of all injuries. Nevertheless, they accounted for around 10% of the injuries among individuals with SA ≥180 days, and also had the highest OR for SA ≥90 days. It was also found that leg injuries were the most common among cases with SA ≥180 days. This is in line with the results from Study I, which found leg injuries to be common among people reporting long-term problems in HRQoL. This indicates that leg injuries among bicyclists might need additional preventive measures.

Discussion of the combined results from Studies I and II

In Figure 9, the distribution of injuries for different measures of injury severity and long-term consequences was shown. As it shows, the distribution of injuries changes depending on which measure is used. If injury prevention is to be based on the injury distribution, the more common injuries will be prioritized for prevention. The distribution of injuries was shown to be different depending on which measure is used as the target measure.

The injury distribution among those with problems in HRQoL (HRQoL <1) is, compared with the other measures, more even. Considering that the body regions 'head' and 'face' had to be collapsed, the injury distribution would have

been even more had these body regions been shown separately. As HRQoL, measured with EQ-5D, is a much more generic measure which takes into account a broader perspective on health compared with the other measures, this is not very surprising.

If looking at injury prevention from the perspective of PMI 1+ injuries, which is the current measure used to define a serious injury, hand injuries to the upper extremities, followed by injuries to the lower extremities and head and face injuries, are the three most common injuries to target. Both HRQoL and SA have much smaller shares of upper extremity injuries compared with PMI 1+. The pattern is quite similar for MAIS 2+, which mainly focuses on the same injuries as PMI 1+. However, from the perspective of long-term SA (≥180 days), lower extremity injuries, not upper extremity injuries, would be the main focus for injury prevention. This is the only one of the six measures for which lower extremity injuries are the most common. In a study from the Netherlands examining the health burden from MAIS 2+ injuries, lower leg injuries were found to have significant health impacts (Weijermars, Bos, & Stipdonk, 2016).

In Figure 10, the sizes of different injury populations are illustrated. Out of a yearly total of 12,500 emergency care visits, around 4700 people would be expected to report problems in HRQoL one to three years after their injury, whereas only 80 people would be expected to be on SA beyond six months. Clearly, the large size of the HRQoL population showcases the generic aspect of the instrument, and the large population would be difficult to handle when attempting to design preventive measures. Also, the PMI injuries might be difficult to handle from an injury prevention perspective, drawing the line from injury to crash, as the populations related to PMI injured are made up of accumulated RPMI for each individual, which gives a predicted number of PMI individuals. Even if the number of fatally injured people were not included in the figure, on average 17 bicyclists are fatally injured each year, and it would be interesting to further investigate whether and how the crashes that result in fatalities differ from other crashes resulting in non-fatal injuries.

The difficulties in setting a threshold between acceptable and unacceptable health loss

There are different strategies for targeting injury prevention. The focus can be on addressing the injuries that are most common (depending on the outcome measure), irrespective of what risk the injury has for the chosen outcome. Another approach would be to target injuries with a high risk of a certain outcome, regardless of how common they are. It could be argued that society would gain the most from targeting the injuries that are most common. However, these injuries would also have to involve an outcome that is unacceptable to society.

With the results presented in the present thesis, one can initiate a discussion on what an acceptable or unacceptable health loss can be. When it comes to fatalities, this is not a difficult question to answer; they are unacceptable. However, for non-fatal injuries, the answer is neither easy nor clear. Based on the definition of health and the ICF framework adopted in the present thesis, the consequences of injuries should not only be related to impairments in bodily functions and structures. Also, according to Vision Zero, some injuries can be acceptable to society if they involve minor consequences. Looking beyond biomedical consequences to biopsychosocial consequences of injuries, the results of this thesis suggest a few specific injuries incurred by bicyclists that might be categorized as unacceptable and should thus be prevented from a Vision Zero perspective. Firstly, even though a large proportion of head injuries are concussive injuries that rarely result in SA, the longest durations of SA are related to severe head injuries. The severity of these consequences has also been shown in many previous studies (e.g. Scholten et al., 2015; Dikmen et al., 2003; Hellawell, Taylor, & Pentland, 1999; Sinha et al., 2013). Secondly, injuries to the lower extremities need to be addressed. These types of injuries are relatively common, often affect peoples' HRQoL and often lead to SA (both shorter and longer periods). Thirdly, injuries to the shoulder and upper arm have more severe consequences in terms of HRQoL and SA, compared with injuries to other parts of the arm (which is in line with results on medical impairment). By addressing the shoulder and upper arm injuries, a large proportion of upper extremity injuries could be prevented. Also, compared with previous measures of injury severity, this thesis shows a higher proportion of spinal injuries, indicating a need to address these types of injuries among bicyclists.

One could argue that by taking a holistic approach to health, all injuries should be avoided and the focus should be on crash prevention rather than injury prevention. However, in the light of Vision Zero, not all injuries have the same impact on health. Therefore, in the context of this thesis, a holistic approach to health relates to the understanding of health impacts from injuries. This is essential for stakeholders in society who need to make decisions on how to allocate resources related to injury prevention. The results presented in this thesis provide new insights into the discussion on what an unacceptable outcome might be. It has been shown that different injuries have different impacts on quality of life. Based on the results, it could be argued that an injury to the hand or wrist should be more acceptable than an injury to the shoulder or upper arm. In other words, we will, for example, still accept a crash as long as it does not result in an injury to the shoulder or upper arm.

One can also take the reasoning on acceptable outcome a step further. There is evidence suggesting that post-traumatic stress disorder (PTSD) is common after a road traffic injury (Haagsma et al., 2011; Mayou & Bryant, 2003). In Study I, problems related to anxiety/depression and pain/discomfort were the most common. Other studies have reported similar findings. Mayou and Bryant (2003) found that anxiety, depression and travel anxiety phobia were reported after a road traffic crash. Nhac-Vu et al. (2014) also reported problems regarding psychological health and PTSD. The experience of being involved in a traffic crash can in itself negatively impact a person's health. But does this mean that the goal should be to eliminate all types of traffic crashes? According to Vision Zero, crashes that occur are acceptable, as long as they do not result in an unacceptable outcome. If for example PTSD was to be considered an unacceptable outcome, then prevention in relation to road traffic crashes should shift its focus from injury prevention to crash prevention. This means that the lower the threshold for an acceptable outcome, the higher the sacrifice could be in terms of resources and mobility. Even if this question of acceptable outcome cannot be solved easily, policymakers should keep discussing these issues, and the results from this thesis add new understanding to this topic.

On a concluding note, the Swedish definition of serious injury is based on the RPMI, which means that injuries at lower severity levels (AIS 1 and 2) are also considered within the national definition, as some of these injuries also lead to long-term impairment (Malm et al., 2008). As shown in Study I, injuries of lower

AIS severity were common among people reporting problems in HRQoL. It is important, especially among cyclists, to focus also on injuries of lower severity levels as cyclists most often sustain AIS 2+ injuries (many of which result in long-term impairments). Therefore, it is suggested that the target set by the European Commission to use MAIS 3+ to define serious injury would lead to an underestimation of the burden of injuries among cyclists (Tingvall et al., 2013). However, a positive addition to the MAIS 3+ target was formulated in the Marrakech Declaration on Better Safety Data for Better Road Safety Outcomes, which states that "it is recommended to further study the impact of different levels of injuries on the quality of life and health losses, as an example lifelong disability" (IRTAD, 2017). This important formulation captures the fact that concepts like HRQoL might be used in future developments of the definition of serious injury.

Discussion of results from Studies III and IV

Studies III and IV investigated circumstances in crashes where cyclists had sustained a relevant diagnosis based on results from Studies I and II, and further estimated the potential of different countermeasures to reduce these crashes.

As both studies were based on a very specific sample, a comparison with other studies of bicycle crashes was rather limited. However, one of the main findings in Study III was that the crashes included in the study that resulted in declined health did not differ substantially from the crashes that did not. Even though a slightly higher proportion of crashes involving motor vehicles was found when comparing the present sample with all crashes during the same period, the majority (68%) of crashes were still single bicycle crashes, which is slightly lower but similar to other studies of bicycle crashes in Sweden reported in Strada (Rizzi, Stigson, & Krafft, 2013; Niska & Eriksson, 2013). In the Netherlands, 50% of the total burden of serious road traffic injuries (MAIS 2+) in 2011 were attributed to bicycle crashes without motor vehicle involvement, which is an increase compared with 30% in 2000 (Weijermars, Bos, & Stipdonk, 2016). Similar to the Netherlands, among injured cyclists admitted to hospital following a bicycle crash in Victoria, Australia, 56% were reported as being injured in single bicycle crashes (Beck et al., 2016). Among injured cyclists treated at emergency care hospitals in Vancouver, Canada, 34% of crashes did not involve another road user (MV or other VRU) (Cripton et al., 2015).

Compared with other countries, Sweden seems to have a higher proportion of single bicycle crashes.

Findings from Study IV showed that the countermeasures with the highest potential to address single bicycle crashes were improved maintenance on non-bicycle infrastructure, improved maintenance (de-icing and removal of snow) on bicycle paths, use of studded tyres on bicycles and improvement of curbstones. However, single bicycle crashes were still the most common crash type after all countermeasures had been considered (69%).

Therefore, one cannot imply that by focusing on preventing bicycle-motor vehicle crashes, injuries leading to loss of health will be prevented to a large extent, which is often the case in relation to fatalities which most often occur in bicycle-motor vehicle collisions (Bil et al., 2016; Gaudet et al., 2015; Nicaj et al., 2009). However, recent studies of fatal bicycle crashes in Australia and the Netherlands show an increasing trend of fatal bicycle crashes without motor vehicle involvement (Boufous & Olivier, 2016; Schepers et al., 2017). A similar parallel can be drawn to Sweden, where in 2017 it was reported for the first time that as many cyclist fatalities occurred in single bicycle crashes as in collisions with motor vehicles (Swedish Transport Administration, 2018). Clearly, a focus on improving safety for cyclists in single vehicle scenarios is needed.

However, the results showed that a slightly larger share of motor vehicles were involved in the crashes included in the present study, compared with all injured cyclists in Sweden during the same period. This finding is in line with previous research indicating that crashes involving motor vehicles result in more severe injuries for cyclists (Langley et al., 2003; Bostrom & Nilsson, 2001; Cripton et al., 2015; Hamann & Peek-Asa, 2013; Heesch, Garrard, & Sahlqvist, 2011; Rivara, Thompson, & Thompson, 1997).

These results highlight the need for separating cyclists from motorized traffic. Speed management is important where there are limited opportunities to separate VRUs from motorized traffic, for example on bicycle crossings. Study IV showed that the countermeasure with the highest potential to address bicycle-MV collisions were AEB with pedestrian detection. As vehicles equipped with this technology still represent a small share of all vehicle mileage in Sweden, incentives to increase the proportion of vehicles with this

technology should be encouraged. Therefore, the newly adopted proposal from the European Commission to make advanced safety features, including advanced emergency braking for vulnerable road users, mandatory for new vehicles in Europe is promising (European Commission, 2018). Another intervention related to passenger cars was the score in the Euro NCAP pedestrian test. It should be mentioned that specific features, such as active bonnet or pedestrian airbag, while not separately studied, is included in the score of the Euro NCAP pedestrian test, and thereby indirectly included as an intervention in study IV.

The potential for different countermeasures in paper IV can be compared to Kullgren et al. (2019) that used a similar approach to assess the potential of different countermeasures to prevent cyclist fatalities on state and municipal roads in Sweden between 2006-2016 (n=184). As Kullgren et al. (2019) include only fatal bicycle crashes, some differences compared with paper IV should be expected. For example, most of fatal crashes were collisions with motor vehicles, where the largest proportion (46%) were passenger cars, while only 21% were single bicycle crashes. Therefore, the potential of different safety systems in cars (mainly AEB) was found to be large, 62%, compared with 12% in Study IV. Even though both Kullgren et al. (2019) and Study IV showed that countermeasure related to infrastructure had a high potential, there was a difference related to maintenance. Study IV showed that improved maintenance of bicycle infrastructure could address 14% of crashes, whereas only 2% of fatal crashes would be addressed. Another difference was related to helmet use, where as many as 37% of cyclist fatalities could have been prevented with a helmet. In the present study, only 2% of crashes would be addressed with a helmet. This low potential could appear to be an unexpected result; however, it can be explained by a number of reasons. Firstly, it should be kept in mind that specific injuries were included in Study III, and also that traumatic brain injuries had a lower weighting, due to the fact that this type of injury is (fortunately) relatively rare. Further, the helmet use rate was quite high among the included cases in the present study (47%), whereas it was only 25% in Kullgren et al. (2019).

According to the Vision Zero design principles, vulnerable road users should not be exposed to motorized vehicles at speeds exceeding 30 km/h in order to avoid fatal injuries (Johansson, 2009). An interesting finding was that only 5%

of crashes would be addressed by speed calming measures. This is, however, not very surprising considering that most crashes included were single bicycle crashes, and the fact that at least 50% of the cyclists reported the speed of the MV to be below 30 km/h, which is considered to be a safe speed. Folksam (2018) showed that there had been no cyclist fatalities in Sweden on a bicycle crossing with speed calming measures implemented. However, as indicated by this study, and as suggested by Kröyer (2015a), 30 km/h might not be sufficiently low to prevent severe injuries to pedestrians and cyclists. As the cyclist injured in the crash reported this information, it is obviously not as reliable as an objective measure of speed. On the other hand, in a recent study it was found that pedestrians could estimate vehicle speeds lower than 40 km/h more accurately compared with higher speeds (Sun et al., 2015).

Priorities for increased bicycle safety

Implemented and existing countermeasures largely address bicycle-motor vehicle crashes. In fact, 92% of bicycle-motor vehicle crashes could potentially be addressed by existing countermeasures, mainly by passenger car technology (AEB with cyclist detection). The implementation of such safety systems is increasing, largely as a result of Euro NCAP, and in Sweden at least 38% of new cars were sold with AEB for VRU in 2017, which is almost double compared with 20 % in 2016 (Ydenius & Kullgren, 2019). Of course, it will take a long time before all vehicles on the roads are fitted with AEB VRU, and efforts to increase the speed of implementation should be encouraged. However, with this technology already existing, most of the need for innovation and development should focus on single bicycle crashes. One such area involves improving bicycle stability, and this development should be encouraged by stakeholders. For example, a lot could be gained from developing a bicycle ABS that could be retrofitted. This could be technically easier for e-bikes since they already have an electric source. However, the benefits of making the retrofitting of ABS on conventional bicycles possible should not be underestimated. Another example of a technology with great potential could be a gyrostabilizer at low speed.

The development of bicycle infrastructure is another area of importance. The development and implementation of a systematic bicycle infrastructure that is more 'crashworthy' than today is something that could greatly improve the level

of safety. The use of soft asphalt is an example of such infrastructure. In a recent project, new functional pavements for pedestrians and cyclists were developed and evaluated, showing that injury risk (in terms of Head Injury Criteria) from falls can be decreased, while still maintaining friction (Wallqvist et al., 2017). Even if further questions remain, such as rolling resistance, seasonal effects, maintenance, and capability to protect against injuries to other parts of the body (Trivector Traffic, 2018) this type of energy absorbing paving seems promising. However, it is not reasonable to assume that people will not fall on non-bicycle infrastructure, and the use of personal crash protection (e.g., helmets and shoulder protection) should continuously be encouraged. A systematic bicycle infrastructure should also include separating cyclists from pedestrians and ensure that bicycle paths are wide enough to avoid bicycle-bicycle collisions.

One countermeasure that could be rapidly implemented and address a large proportion of single bicycle crashes would be to extend improved maintenance to also include non-bicycle infrastructure in urban areas. This could also be achieved by extending the bicycle infrastructure, which would be preferable from a long-term perspective. The Swedish SPI for good quality maintenance only includes municipal 'high-priority' bicycle infrastructure, and this SPI at least should include all bicycle infrastructure.

It should be further stressed that the potential for the different safety interventions presupposes a 100% systematic implementation, and not only include e.g., specific road sections or routes. It should also be kept in mind the difference between a relevant intervention and its effectiveness. Not all falls will be prevented by improved maintenance, just as not all head injuries will be prevented with a helmet. However, by systematically combining different interventions, for example the use of a helmet with impact absorbing paving, the possibility to completely prevent a serious head injury will increase.

Methodological considerations

Studies I and II

If experiencing any problems in HRQoL can be seen as a general view on health, being entitled to SA could be seen as a quite narrow part of health. It

can also indicate a job that is dependent on physical aspects, like manual labour, and therefore more affected by physical limitations caused by the injury. In that sense, those with less physically demanding jobs might still be able to work despite their injury. On the other hand, those who are able to work might still be affected in other health-related areas, aspects which are not captured when the injury outcome is described in terms of SA. Work is, of course, related in some ways to the dimensions of health covered in EQ-5D, but experiencing problems in HRQoL does not mean that a person by definition is entitled to SA. However, in line with the ICF framework, both measures capture different aspects related to health, and together they cover disability not only by impairments but by activity limitations and participation restrictions according to the ICF framework. Also, it should again be mentioned that Study I and Study II related to different timeframes. HRQoL was investigated one to three years after the injury, while the results for SA were limited to a follow-up of beyond six months. Even though this could possibly be seen as a limitation, it should be kept in mind that an injury that initially affects a person's capability to work can still be limiting in other ways, including after SA has ended.

In this thesis, 'long-term' has been used in relation to consequences from injuries. Regarding SA, there is no agreed definition of long-term sickness absence in Sweden. According to Statistics Sweden, this is sometimes referred to as sickness absence longer than 14 days, i.e. sickness benefit is compensated by social insurance and not by the employer (Statistics Sweden, 2004). In this thesis, sickness absence beyond 180 days was defined as long-term. In relation to long-term impact from injuries described in Vision Zero, it is suggested that injuries that heal within three weeks can be seen as an acceptable outcome (Tingvall, 1997). In that sense, even if SA beyond 180 days might not be long-term compared with e.g. life-long impairments, it could still be considered long-term in relation to SA in general. Also, in the case of leg fractures for example, the healing time is generally between three and four months, or longer than six months (Massari et al., 2012). Related to HRQoL, 'long-term impact' has also been used in different ways, ranging from e.g. two months (Jagnoor et al., 2015), or ≥ 1 year (Alghnam et al., 2014), to up to four years (Maraste, Persson, & Berntman, 2003). Depending on how long-term impact is defined, this will affect the design of studies involving health impact from injuries, and further which injuries will be labelled as 'non-acceptable'.

Even in the normal population, the average score of the EQ-5D would be below 1 (perfect health). The corresponding mean EQ-5D index value in a general population (n=3069) in Stockholm County was reported to be 0.84 (Burström, Johannesson & Diderichsen, 2001). The results from Study I showed that the prevalence of problems related to anxiety/depression and anxiety/depression was the highest. This is also in line with results for the general population (Burström, Johannesson & Diderichsen, 2001). Among the sample in Study I, the mean index value was equivalent to the general population in Stockholm (0.84), and among those injured in a bicycle crash, the average index value was 0.88. In general, the mean index value is lower among older people compared with younger people and is also affected by socio-economic status and disease. The fact that the mean index value was higher in the study population compared with the general population could raise questions about whether the results are reliable. An argument that strengthens the results in this sense could be that respondents were asked to answer the survey *in relation to* their traffic injury and how it had affected their daily life. This would be different compared with a study among the general population with regard to their general health. Besides this, it could also be suggested that physical activity has been shown to have a positive association with HRQoL (Bize, Johnson, & Plotnikoff, 2007), and the physical activity gained from bicycling might indicate a higher general level of health among this group compared with the normal population. This aspect was not investigated in Study I as no data were available on the respondents' bicycling habits.

The EQ-5D is a generic instrument and could therefore be difficult to use when a high degree of sensitivity is needed to discriminate between different injury groups. With a more sensitive instrument (e.g. with more discriminative qualities), it might have been possible to better differentiate between different injuries. It is possible that other results could have been found if another instrument had been used, for example the SF-36 which covers more health-related dimensions compared with the EQ-5D and has also been used in traffic injury related studies (e.g. Kenardy et al., 2015; Polinder et al., 2010). Nevertheless, the EQ-5D is a valid instrument to use in HRQoL studies and it has previously been validated for injuries (Öster et al., 2009; Hung et al., 2015), and has also for example been used to evaluate HRQoL after major trauma (Ulvik et al., 2008), polytrauma (Gross et al., 2010) and general injury patients (Meerding et al., 2004; Polinder et al., 2007). Some studies have used the EQ-

5D to evaluate HRQoL specifically after road traffic injury, for example Jagnoor et al. (2015). However, the design of the instrument might have had an impact on the results. For example, one question that relates to mobility is asked in relation to walking, and the high proportion of reported problems related to leg injuries might therefore have been affected by the formulation of this question. The EQ-5D is a simple instrument, and in studies including large populations it might be beneficial to use a short instrument that does not require too much effort from the respondent to complete. Another argument for choosing a generic instrument is that traffic injuries can be located in any body region and hence may have different consequences. Therefore, it is not possible to use a diagnosis-specific instrument.

Another limitation, which refers to both Study I and Study II, is that there was a limited possibility to show causality between the injuries sustained in the crash and the outcome in terms of problems in HRQoL or SA. In other words, it could be argued that the reported HRQoL might not be the result of the injury itself but a reflection on other life events that happened within this period. In Study I, an attempt to deal with this limitation was made by informing participants that the survey was to be considered in relation to the respondent's traffic injury. Further, people who had reported previous illnesses that had affected their daily lives were excluded from the analysis. In Study II, people who had been involved in any traffic-related crash within three years prior to the 'current' crash, or who were already on SA or full-time disability pension, were excluded. An important step in Study II was to identify incident cases of SA, i.e. that the SA started as a result of the injury. Regarding this, an assumption had to be made that the date of the crash was the same as the date of the specialized in- or out-patient care visit. Incident cases of SA were defined as cases starting +/- 4 days in connection with the date of the specialized in- or out-patient care visit. As only one main injury diagnosis was chosen, the effect of some injuries might have been underestimated as 23% of the study population had more than one injury diagnosis. According to guidelines from the National Board of Health and Welfare, the injury that is the cause of the visit should be regarded as the main injury diagnosis, and is assigned at the end of the medical visit/treatment. In case of multiple causes (e.g., multiple injuries requiring different treatments) the injury requiring most resources should be chosen as the main injury diagnoses (National Board of Health and Welfare, 2016). Future studies should also consider including secondary diagnoses to

better understand the effect of multi-trauma, and also to include the SA diagnoses for comparison with the injury diagnoses to further strengthen the relationship between injury and outcome in SA.

In Study I, only a subset of the EQ-5D was used (i.e. the descriptive system) and the analysis was based on whether or not people reported *any* problems in HRQoL. It could be argued that this was a too simplistic a measure of HRQoL. The limited number of cases did not make it possible to distinguish those who had reported severe problems in HRQoL from those who reported moderate problems. It would have been interesting to investigate whether the results would differ between these groups, making it possible to use a different statistical method, e.g. Anova where three or more groups can be analysed.

Finally, besides considering alternative instruments, or SA as an outcome measure, different results could have been obtained using a qualitative method, i.e. interviews. In-depth interviews or semi-structured interviews could have offered insights into what type of problems people experience. In a survey, people have to consider their situation in relation to the questions or statements given to them, rather than providing their own experiences. Future studies could use interviews to better capture peoples' experiences of being injured in a bicycle crash in order to better understand what problems they face and how their health and life situation has been affected by the injury.

Studies III and IV

First of all, it is important to acknowledge that the inclusion criteria for Studies III and IV were based on the combined results of Studies I and II. Therefore, it is not entirely possible to exclude the possibility that if other methods or indicators for health had been used in papers I and II, different results would have been found in papers III and IV. On the other hand, the fact that those included in Studies III and IV had more than 50% higher mRPMI compared with all injured cyclists during the same time period suggests that the methods used in Studies I and II did identify more serious injuries.

The response rate was relatively low, at 36%, and was lower among those aged ≤25 years (18%) and those whose crash occurred in 2013-2014 (28%). However, the response rate was similar for men and women (35% and 37%

respectively). The response rate was also similar across the body regions included, suggesting that no bias from the type of injury influenced the results. As the focus of Study III was to investigate crashes involving specific injuries, the results should still be regarded as representative of the study population.

Even though the material was large compared with similar studies (Beck et al., 2016; Cripton et al., 2015), parts of the analysis included too few cases, which limited their statistical strength. On the other hand, the present study included a unique link between a crash and an individual's self-reported health status as a consequence of the crash, which is not common in previous research. As the type of crash and the injured body region are the main variables assumed to have the greatest effect on the results and conclusions, it is important to consider if and how these variables differ among non-respondents compared to the respondents. Comparing non-respondents with the respondents, collisions with motor vehicles were less common (16% vs 19%) and single bicycle crashes were more common (76% vs 70%) for non-respondents and respondents respectively. This indicates that had the response rate been 100%, a slightly larger share of crashes would be single bicycle crashes. However, these differences were small and should not have any great impact on the results, especially considering that the proportion of people with declined health was similar for these crash types. This is also the case for the impact of age, where if the response rate among younger people had been higher, the proportion of people with declined health would not be affected considering the similarities in proportion of people with declined health between different age groups.

The sample included individuals with varying time since the injury, and it is thus likely that some were still recovering at the time they participated in the study. In fact, it could be calculated that if the percentage of people reporting declined health had been the same among those with a more recent injury as among those injured 4-5 years earlier, a total of 406 people (instead of 421) would have reported declined health. Therefore, it should be kept in mind that some of the people who reported declined health might improve and recover from their injury.

It should be noted that the assessments of potentials in Study IV were based on self-reported data, and not on in-depth studies of fatal crashes as, for instance, in Kullgren et al. (2019). This means that information about for

example the use of alcohol, which is reported in fatal crashes, could not be taken into account. The presence of alcohol has been reported in 15% of fatal bicycle crashes in Sweden as well as Australia (Kullgren et al., 2019; O´Hern & Oxley, 2018) and 25% of fatal bicycle crashes in rural Canada (Gaudet et al., 2015). Even though alcohol use could have been inquired in the survey, it is a difficult question from both an ethical (information about possible criminal offense), as well as methodological perspective (would the answer be reliable). It could be argued that in a truly safe road transport system, driving or riding under the influence of alcohol will not be a major concern, as long as protective equipment (both personal as well as infrastructure) has the capability to protect in case of a crash. However, especially for cyclists and other vulnerable road users, this may still be a theoretical line of thought.

While great efforts were made to design the questionnaires in Study III to be as clear as possible, it cannot be excluded that some participants might have misinterpreted some of the questions. Furthermore, depending on how much information was provided by the respondent, there is always a certain degree of subjectivity when interpreting a course of events or which factors contributed to the crash. However, it should be noted that some self-reported data may be more sensitive than others, for example the estimation of the speed of the motor vehicle, although it is interesting to note that at least 50% of the cyclists reported speeds below 30 km/h.

It should be made clear that Study IV assessed the potential of countermeasures, not their real-life effectiveness. The difference between these two can be illustrated with an example. It could be argued that AEB with cyclist detection, as suggested by Ohlin et al. (2017), would reduce impact speed and thereby influence the effectiveness of the helmet. However, the potential of helmets, as assessed in this paper, would still be unchanged, i.e. any head injury sustained without a helmet. So, clearly, whether or not the combined potential of two countermeasures differs from the individual potentials also depends on how the target populations for the countermeasures are defined. Also, in Study IV it was not possible to take into account any possible behavioural adaptation that could, at least theoretically, follow the implementation of certain countermeasures. For instance, it could be argued that improved winter maintenance (or the use of studded winter tyres) could prevent loss-of-control crashes, but at the same time could also lead to higher riding speeds and thereby

contribute to a 'new' set of crashes. While these aspects could lead to an overestimation of the potentials of countermeasures, it should again be noted that Study IV aimed at assessing the potential of countermeasures, not their real-life effectiveness.

Clearly, the choice of countermeasures included in Study IV could be further discussed. While the list of included countermeasures was quite extensive, other or additional countermeasures could have been considered, for example lowered urban speed limits. Unfortunately, speed limits are not included in Swedish hospital reports, and the only way to fully assess the potential of lowered speed limits would have been merging the present dataset with the National Road Database (NVDB). Nevertheless, it should be noted that in the present material the collision speed was estimated to be over 40 km/h in around 20% of the crashes involving a motor vehicle, which suggests that the potential of lowering urban speed limits from 50 km/h to 40 km/h would be limited.

Comparing PMI with subjective evaluation of health

In Study III, it was shown that the predicted number of individuals with a permanent medical impairment (PMI) corresponded well to the number of respondents who reported declined health after the crash. Medical impairment is based on the functional reduction caused by an injury, and does not take into account other circumstances, for example occupation or hobbies, which are probably important aspects in the injured person's life. One can imagine that it is more important to a person how the limitation affects other areas in life, and that how many degrees they can move their arm is less important. However, despite the differences in how medical impairment 'defines' health loss, compared with a person's own experience, the RPMI seems to perform well in predicting the number of people experiencing loss of health, at least in a population with a high overall RPMI 1+ (the mean overall RPMI 1+ in the present study was 46%.) As the predicted number of PMIs is simply a sum of many individual risks, it can never identify specific individuals who will have a PMI. Therefore, it is well understood that the predicted number of PMIs is a fictive population, rather than actual individuals. This means that it could not be verified whether the respondents with declined health would also have permanent medical impairments. This remaining question of how the degree of

medical impairment correlates with perceived health loss should be investigated in future studies. A further aspect of medical impairment is that over time, effects such as improved medical treatments and rehabilitation, as well as possible changes in insurance companies' policy for granting medical impairment, might impact both the level and number of medical impairments. Therefore, if the predictive RPMI (Malm et al., 2008) should be updated today, the same injury might not have the same risk for medical impairment, which in turn would influence the number of predicted medical impairments.

It should be noted that in all bicycle crashes in Strada during the period 2013-2017, the mean overall RPMI 1+ was 19%, which is more than 50% lower compared with the study population in Study III. It could be argued that it is not unexpected that more severe injuries will lead to health loss more often, and it is therefore not surprising that the RPMI metric performed well. On the other hand, as all crashes in Sweden involve a higher proportion of lower injury severity, the question remains how accurate the RPMI metric may be when it comes to the national target measure of the predicted number of seriously injured people. Therefore, further research is needed to understand how a larger number of injured people with a lower overall RPMI1+ may affect the total number of predicted seriously injured people. For instance, a study similar to the present one could be carried out, but focusing only on less severe injuries.

Cycling safety in relation to crash and injury prevention

In traffic safety, it is not uncommon to talk about risks and risk reduction. While this type of analysis can give important insights for comparing different risks, it is clear from Vision Zero that the target set by society is not to address risks per se, but rather to eliminate deaths and serious injuries. In other words, it is not about reducing risks, but instead about reducing the number of fatalities and serious injuries, even if exposure increases. An example of such an issue is the 'safety in numbers' phenomenon which has been investigated in relation to cycling (as well as other areas). 'Safety in numbers' refers to the non-linear relationship between exposure and risk per capita (for accident and/or injury). Studies have shown that such a non-linear relationship exists for pedestrians and bicyclists in collision with motor vehicles (e.g., Jacobsen, 2003; Elvik, 2009), and even for single bicycle accidents (Schepers, 2012). With an increased

number of cyclists or pedestrians, the individual risk of each pedestrian or bicyclist being involved in an accident is lower. In other words, the number of accidents does not increase proportionally to the increase in number of pedestrians and bicyclists. While this correlation has not been fully explained (Kröyer, 2015b), several possible explanations have been identified. For example, the presence of more pedestrians and cyclists may increase car drivers' awareness and hence adjust their behaviour, which increases safety for pedestrians and cyclists (Jacobsen, 2003), or the higher exposure of cyclists and pedestrians may lead municipalities to increase their efforts to make the environment safer (e.g., with good quality maintenance) (Schepers, 2012; Wegman, Zhang & Dijkstra 2012). Or it may simply be that pedestrians and cyclists choose to travel in locations they perceive as safe (Bhatia & Wier, 2011).

The 'safety in numbers' effect is often (mistakenly) used to argue that the problem of accidents and injuries will 'solve itself' simply by increasing the number of cyclists. However, regardless of possible explanations for the observed 'safety in numbers' phenomenon, accidents and injuries will increase with an increased number of cyclists. Therefore, accident and injury prevention strategies are needed. According to Vision Zero, a fundamental aspect is that crashes can be acceptable, as long as they do not result in unacceptable outcomes. That is, there is a significant difference between zero crashes and zero injuries. The results from paper IV showed that it is clearly difficult (if not impossible) to prevent all bicycle crashes. The challenge with cyclists, and all vulnerable road users, is that given a crash, the risk of injury is much higher compared with protected road users such as car occupants (e.g., Nilsson et al., 2017). Further, the bicycle is an unstable vehicle (as is the nature of two-wheelers), and cycle safety must therefore take into account the fact that crashes will happen. This presupposes that impact from collisions needs to be 'handled' with crash protection.

If we were instead to imagine that the goal was to eliminate all bicycle crashes, a lot more would have to be demanded of e.g. the cyclist. Consider for example airplane safety. For obvious reasons, the goal of airplane safety is clearly to eliminate crashes, because when a crash occurs, the crash severity is far too great to be managed with today's crash protection. The integrated chain of events can be used to illustrate how a system is designed that aims to be free from crashes (Figure 12). The driver (or in this case the pilot) would have to go

through extensive training and education to become a licensed driver. He or she also needs to be in good shape and not suffer from any illness. Also, while operating the airplane, he or she will be supported by advanced supportive, monitoring and automated systems. These high demands mean that very few people will become pilots. But when it comes to cycling, we want to make this as accessible as possible, and to encourage people of all ages to cycle for health and environmental benefits. Putting great demands on cyclists would be counterproductive for a goal of increased cycling.
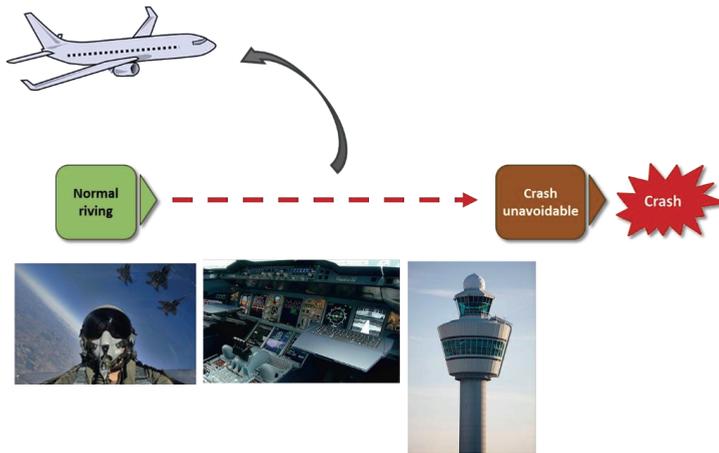

Figure 12. Airplane safety demands illustrated in the integrated chain of events.

In fact, we currently have very few regulations when it comes to cycling. The bicycle has to be equipped with a bell and functioning brakes, as well as headlights and taillights and reflectors on the front, rear and side of the bicycle. Since 2005, children in Sweden under the age of 15 have been obliged by law to wear helmets while cycling.

In conclusion, it might be regarded as counterproductive and even utopic to promote cycling and at the same time aim for 'crash-free' cycling, as 'crash-free' cycling would involve increased demands as well as limitations for cyclists. Therefore, at least some components of crash protection are necessary to accomplish safe cycling.

Cycling and traffic safety within the context of sustainability

In 2015, the United Nations formulated the agenda for sustainable development, and 17 goals to achieve a better world by 2030 (United Nations, 2015) (Figure 13). Two of the 17 goals specifically involve traffic safety. Target 3.6 under goal 3 for good health and well-being is to halve the number of global deaths and injuries from road traffic accidents by 2020. A second goal specifically targeting road safety is goal 11 regarding sustainable cities and communities. Target 11.2 is to provide access to safe, affordable, accessible and sustainable transport systems for all by 2030, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons.

Figure 13. The United Nations' global goals for sustainable development.

With traffic safety on the UN's agenda for sustainability, traffic safety becomes a way to create sustainability. Simultaneously, the high demand for more sustainable transport modes brings a need to improve safety for bicyclists, making safety for bicyclists one of the prioritized areas for a sustainable road transport system in the future. From a societal point of view, efforts to increase the level of bicycling will continue, based on the many positive impacts. However, from an ethical perspective, this should not happen at the cost of

increased injuries and deaths related to bicycle crashes. With the sustainable development goals, it is clear that this is not only an ethical question, but safety is instead a boundary condition that needs to be fulfilled in order to create sustainability. In other words, societal goals of increased cycling should not happen at the expense of increased injuries.

Conclusions and recommendations

Conclusions

- A holistic biopsychosocial perspective on health adds new understanding to the negative health impacts of bicycle injuries that could be used to prioritize which injuries need to be prevented.
- From a biopsychosocial perspective on health, i.e., the impacts on HRQoL and SA, the focus of injury prevention among bicyclists should be on severe head injuries, leg injuries (mainly hip, upper leg and thigh, and also lower leg), injuries to the shoulder and the upper arm, and spinal injuries.
- Bicycle safety has traditionally focused on helmets and on separating cyclists from motorized traffic. While these are important countermeasures, this thesis highlights that additional interventions targeting single bicycle crashes need to be prioritised by road authorities in order to prevent health loss among bicyclists.
- On a general level, the distribution of crash types involving injuries associated with health loss do not substantially differ from all other hospital reported crashes involving bicyclists with other types of injuries. This suggests that there are no 'shortcuts', in fact, a wide spectrum of crash types needs to be considered in order to address health loss among cyclists.
- Up to 90% of bicycle crashes involving injuries associated with health loss could be addressed with existing safety interventions. This means that few crashes occur under such circumstance where modern safety countermeasures are not at all relevant. Therefore, increased safety for bicyclists is very much a question of implementation.
- The development of additional countermeasures should focus on increasing the stability of the bicycle, anti-lock brakes (including retrofitting on conventional bicycles) and developing soft asphalt to decrease the risk of injury in ground impacts.

Recommendations

Based on the results from the present thesis, the following specific recommendations are given:

- The number of people regarded as seriously injured is greatly affected depending on the outcome measure used. Therefore, additional steps to identify a "threshold" for what is regarded as a serious injury should be taken, for instance by start examining the impact on health from injuries with a low risk for permanent medical impairment.

- Most crashes involving injuries associated with a higher proportion of health-loss are single bicycle crashes, which are expected to be as common also in the future; road authorities should focus their efforts on single bicycle crashes.

- In addition to the current safety performance indicators, the following five actions should be the focus of more rapid implementation: autonomous emergency braking with cyclist detection on passenger cars, extended maintenance to include all urban roads used for cycling, improved design of curbstones, and to separate cyclists from both motor vehicles and pedestrians.

References

AAAM, Abbreviated Injury Scale 2005, *Association for the Advancement of Automotive Medicine*: Barrington, IL, USA, 2005.

Aertsens, J., de Geus, B., Vandenbulcke, G., Degraeuwe, B., Broekx, S., De Nocker, L., et al. (2010). Commuting by bike in Belgium, the costs of minor accidents. *Accident Analysis and Prevention*, 42(6):2149-57.

Ainsworth, B.E., Macera, C.A. (2012). *Physical activity and public health practice.* Boca Raton: CRC Press.

Alexanderson, K., Norlund, A. Swedish Council on Technology Assessment in Health Care (SBU). (2004). Chapter 1. Aim, background, key concepts regulations, and current statistics. *Scand Journal of Public Health*, 32(Supplement 63):12-30.

Alghnam, S., Palta, M., Remington, P.L., Mullahy, J., Durkin, M.S. (2014). The association between motor vehicle injuries and health-related quality of life: a longitudinal study of a population-based sample in the United States. *Qual of Life Research*, 23:119–127.

Amoros, E., Chiron, M., Martin, J.L., Thelot, B., Laumon, B. (2012). Bicycle helmet wearing and the risk of head, face, and neck injury: a French case-control study based on a road trauma registry. *Injury Prevention,* 18(1):27-32. doi:10.1136/ip.2011.031815

Amoros, E., Martin, J.L., Laumon, B. (2006). Under-reporting of road crash casualties in France. *Accident Analysis and Prevention,* 38(4):627-35.

Andersen, L.B., Schnohr, P., Schroll, M., Hein, H.O. (2000). All-cause mortality associated with physical activity during leisure time, work, sports, and cycling to work. *Archives of Internal Medicine,* 160(11), 1621-1628.

Annerstedt, C. (2007). In Swedish: Från gymnastik till idrott/idrottsvetenskap som akademiskt ämne. I: Utvärdering av grund- och forskarutbildning i idrott/idrottsvetenskap vid svenska universitet och högskolor. [From gymnastics to sports/sports science as academic subject]. Högskoleverket, Stockholm.

Attewell, R.G., Glase, K., McFadden, M. (2001). Bicycle helmet efficacy: a meta-analysis. *Accident Analysis and Prevention,* 33(3):345-352.

Baker, S. P., O'Neill, B., Haddon, W., Jr., & Long, W. B. (1974). The injury severity score: a method for describing patients with multiple injuries and evaluating emergency care. *J Trauma, 14*(3), 187-196.

Beck, B., Stevenson, M., Newstead, S., Cameron, P., Judson, R., Edwards, E. R., . . . Gabbe, B. (2016). Bicycling crash characteristics: An in-depth crash investigation study. *Accid Anal Prev, 96*, 219-227. doi:10.1016/j.aap.2016.08.012

Bengtsson, K. (2017). In Swedish: En jämförelse mellan Strada och PAR 2012. [A comparison between Strada and PAR 2012]. *Swedish Transort Agency*.

Berecki-Gisolf, J., Collie, A., McClure, R. (2013). Work disability after road traffic injury in a mixed population with and without hospitalisation. *Accident Analysis and Prevention,* 51:129-34.

Bhatia, R., & Wier, M. (2011). "Safety in Numbers" re-examined: can we make valid or practical inferences from available evidence? *Accid Anal Prev, 43*(1), 235-240. doi:10.1016/j.aap.2010.08.015

Bil, M., Bilova, M., Dobias, M., Andrasik, R. (2016). Circumstances and causes of fatal cycling crashes in the Czech Republic. *Traffic Injury Prevention,* 17(4):394-399.

Bize, R., Johnson, J. A., Plotnikoff, R. C. (2007). Physical activity level and health-related quality of life in the general adult population: a systematic review. *Preventive Medicine,* 45(6), 401-415.

Björketun, U., Nilson, G. (2006). Skaderisker för Motorcyklister [Accident Risks for Motorcyclists]. *VTI report 11-2006*. Swedish National Road and Transport Research Institute (VTI). Linköping, Sweden.

Björkenstam, E., Ringbäck Weitoft, G., Lindholm, C., Björkenstam, C., Alexanderson, K., Mittendorfer-Rutz, E. (2014). Associations between number of sick-leave days and future all-cause and cause-specific mortality: A population-based cohort study. *BMC Public Health,* 14:733.

Blaxtor, M. What is health? In: Davey, B., Gray, A., Seale, C., editors. Health and Disease: A reader. 2nd ed. Philadelphia: Open University Press; 2001. pp. 21-7.

Blair, S. N., Kampert, J. B., Kohl, H. W., 3rd, Barlow, C. E., Macera, C. A., Paffenbarger, R. S., Jr., & Gibbons, L. W. (1996). Influences of cardiorespiratory fitness and other precursors on cardiovascular disease and all-cause mortality in men and women. JAMA, 276(3), 205-210.

Boorse, C. (1977). Health as a theoretical concept. *Philosophy of Science,* 44:542-573.

Bostrom, L., & Nilsson, B. (2001). A review of serious injuries and deaths from bicycle accidents in Sweden from 1987 to 1994. *J Trauma, 50*(5), 900-907.

Boufous, S., & Olivier, J. (2016). Recent trends in cyclist fatalities in Australia. *Inj Prev, 22*(4), 284-287. doi:10.1136/injuryprev-2015-041681

Bryngelson, A. (2009). Long-term sickness absence and social exclusion. *Scandinavian Journal of Public Health*, 37(8):839-45.

Brüssow, H. (2013). What is Health? Microbial Biotechnology, 6:341–348.

Bull, F.C., Gauvin, L., Bauman, A., Shilton, T., Kohl, H.W. 3rd, Salmon A. (2010). The Toronto Charter for Physical Activity: a global call for action. J Phys Act Health, 7(4):421-422.

Burström, K., Johannesson, M., Diderichsen, F. (2001). Swedish population health-related quality of life results using the EQ-5D. *Quality of Life Research,* 10:621-635.

Bylund, P.O., Bjornstig, U. (1998). Sick leave and disability pension among passenger car occupants injured in urban traffic. *Spine* (Phila Pa 1976), 23(9):1023-8.

Cavill, N., Buckland, J. (2012). Investigating the potential health benefits of increasing cycling in the Cycling City and Towns. Report: *Department for Transport, UK.*

Chapman, R., Howden-Chapman, P., Keall, M., Witten, K., Abrahamse, W., Woodward, A., et al. (2014). Increasing active travel: aims, methods and baseline measures of a quasi-experimental study. *BMC Public Health, 14*, 935. doi:10.1186/1471-2458-14-935

Cieza, A., Stucki, G. (2005). Content comparison of health-related quality of life (HRQOL) instruments based on the international classification of functioning, disability and health (ICF). *Quality of Life Research,* 14(5): 1225-1237.

Cripton, P.A., Shen, H., Brubacher, J.R., et al. (2015). Severity of urban cycling injuries and the relationship with personal, trip, route and crash characteristics: analyses using four severity metrics. *BMJ Open,* 5(1), e006654. doi:10.1136/bmjopen-2014-006654

de Geus, B., Vandenbulcke, G., Int Panis, L., Thomas, I., Degraeuwe, B., Cumps, E., et al. (2012). A prospective cohort study on minor accidents involving commuter cyclists in Belgium. *Accident Analysis and Prevention*, 45:683-93.

de Geus, B., Aertsens, J., Devos, S., Int Panis, L., Putman, K., Meeusen, R. Costs for society related to major bicycle accidents in Flanders (Belgium). Proceedings from the International Cycling Safety Conference 2014, Gothenburg, Sweden.

Dikmen, S.S., Machamer, J.E., Powell, J.M., & Temkin, N.R. (2003). Outcome 3 to 5 years after moderate to severe traumatic brain injury. *Arch Phys Med Rehabil, 84*(10), 1449-1457.

Ds 2016:20. (2016). In Swedish: Strada Transportstyrelsens olycksdatabas [Strada, the Swedish Transport Agencys accident database].Accessed: Retrieved from: https://www.regeringen.se/rattsliga-dokument/departementsserien-och-promemorior/2016/11/strada-transportstyrelensens-olycksdatabas/. Accessed July 20th 2019.

Ekblom-Bak, E., Ekblom, Ö., Andersson, G., Wallin, P., Söderling, J., Hemmingsson, E., & Ekblom, B. (2019). Decline in cardiorespiratory fitness in the Swedish working force between 1995 and 2017. *Scandinavian Journal of Medicine & Science in Sports*, 29(2), 232-239.

Elvik, R. (2009). The non-linearity of risk and the promotion of environmentally sustainable transport. *Accid Anal Prev, 41*(4), 849-855. doi:10.1016/j.aap.2009.04.009

ERSO, European Road Safety Observatory. (2016). Traffic Safety Basic Facts 2016 – Cyclists. Available at: http://ec.europa.eu/transport/road_safety/sites/roadsafety/files/pdf/statistics/dacota/bfs2016_cyclists.pdf. Accessed July 29th 2019.

Engel, G. L. (1977). The need for a new medical model: a challenge for biomedicine. *Science, 196*(4286), 129-136.

European Commission (EC). (2015). Serious Injuries - Summary. European Commission, Directorate General for Transport, September 2015. Available at: https://ec.europa.eu/transport/road_safety/sites/roadsafety/files/ersosynthesis2015-seriousinjuries-summary5_en.pdf. Accessed August 8th 2019.

European Commission (EC). (2016). Road safety evolution in the EU by population. Available at: http://ec.europa.eu/transport/road_safety/sites/roadsafety/files/pdf/observatory/historical_evol_popul.pdf. Accessed December 6th, 2016.

European Commission (EC). (2018). Proposal for a regulation of the European Parliament and of the Council on type-approval requirements for motor vehicles and their trailers, and systems, components and separate technical units intended for such vehicles, as regards their general safety and the protection of vehicle occupants and

vulnerable road users, amending Regulation (EU) 2018/… and repealing Regulations (EC) No 78/2009, (EC) No 79/2009 and (EC) No 661/2009. Available at: https://eur-lex.europa.eu/resource.html?uri=cellar:f7e29905-59b7-11e8-ab41-01aa75ed71a1.0003.02/DOC_1&format=PDF. Accessed March 29th, 2019.

European Transport Safety Council (2001) *Transport Safety Performance Indicators.* Brussels, Belgium: European Transport Safety Council.

Fagerlind, H., Ring, L., Brülde, B., Feltelius, N., Lindblad, Å.K. (2010). Patients' understanding of the concepts of health and quality of life. *Patient Education and Counseling*, 78(1):104-10.

Finch, C. (2006). A new framework for research leading to sports injury prevention. *J Sci Med Sport, 9*(1-2), 3-9; discussion 10. doi:10.1016/j.jsams.2006.02.009

Floderus, B., Goransson, S., Alexanderson, K., Aronsson, G. (2005). Self-estimated life situation in patients on long-term sick leave. *Journal of Rehabilitation Medicine*, 37(5):291-9.

Folksam. (2018). In Swedish: Analys av dödsolyckor med cyklister på statligt och kommunalt vägnät [Analysis of fatal accidents with cyclists on the state- and municipal road network]. Available at: https://www.folksam.se/media/analys-av-dodsolyckor-med-cyklister-2018_tcm5-37450.pdf. Accessed May 2nd 2019.

Franzén, C., Bjornstig, U., Brulin, C., & Lindholm, L. (2009). A cost-utility analysis of nursing intervention via telephone follow-up for injured road users. *BMC Health Serv Res, 9*, 98. doi:10.1186/1472-6963-9-98

Fraser, R. (1946). What is Health? *Health Education Journal,* 4:80 DOI: 10.1177/001789694600400209

Gaudet, L., Romanow, N. T., Nettel-Aguirre, A., Voaklander, D., Hagel, B. E., Rowe, B. H. (2015). The epidemiology of fatal cyclist crashes over a 14-year period in Alberta, Canada. *BMC Public Health,* 15:1142

Gibson, J. A. (1961). The Contribution of Experimental Psychology to the Formulation of the Problem of Safety – A Brief for Basic Research. *Behavioral Approaches to Accident Research.* New York: Association for the Aid of Crippled Children. 77-89. Reprinted in *Accident Research: Methods and Approaches.* 1964. Edited by W. Haddon, Jr., et al. New York: Harper & Row. 296-304.

Glanz, K., Rimer, B. K., & Viswanath, K. (Eds.). (2008). *Health behavior and health education: Theory, research, and practice.* Retrieved from https://ebookcentral-proquest-com.ezproxy.ub.gu.se

Gross, T., Attenberger, C., Huegli, R.W., Amsler, F. (2010). Factors Associated with Reduced Longer-Term Capacity to Work in Patients after Polytrauma: A Swiss Trauma Center Experience. *American College of Surgeons,* doi:10.1016/j.amcollsurg.2010.02.042

Gustafsson, H., Nygren, Å., Tingvall, C. (1985). Rating system for serious consequences (RSC) due to traffic accidents. Risk of death or permanent disability. In: Proceedings of the 10th International Conference on Experimental Safety Vehicles 1985, Oxford, National Highway Safety Administration, USA, pp. 556-560

Haagsma, J.A., Polinder, S., Toet, H., Panneman, M., Havelaar, A.H., Bonsel, G.J., van Beeck, E.F. (2011). Beyond the neglect of psychological consequences: post-

traumatic stress disorder increases the non-fatal burden of injury by more than 50%. *Injury Prevention,* 17(1):21-26. doi:10.1136/ip.2010.026419

Haddon, W. Jr. (1963). A note concerning accident theory and research with special reference to motor vehicle accidents. *Ann NY Acad Sci.* 1963; 107: 635-46.

Haddon, W. Jr. (1980). Advances in the Epidemiology of Injuries as a Basis for Public Policy. *Public Health Reports* 1980; 95: 411-421.

Haddon, W., Jr. (1995). Energy damage and the 10 countermeasure strategies. 1973. *Inj Prev, 1*(1), 40-44.

Hakkert A S, Gitelman, V and Vis M A (Eds.) (2007a) *Road Safety Performance Indicators: Theory.* Deliverable D3.6 of the EU FP6 project SafetyNet.

Hakkert A S and V Gitelman (Eds.) (2007b) *Road Safety Performance Indicators: Manual.* Deliverable D3.8 of the EU FP6 project SafetyNet.

Hamann, C., & Peek-Asa, C. (2013). On-road bicycle facilities and bicycle crashes in Iowa, 2007-2010. *Accid Anal Prev, 56*, 103-109. doi:10.1016/j.aap.2012.12.031

Hansson, P.G. (1976). Sick-leave after road traffic accidents. *Scandinavian Journal of Social Medicine*, 4(2):103-7.

Hartog, J. J, Boogaard, H., Nijland, H., Hoek, G. (2011). Do the health benefits of cycling outweigh the risks? *Environmental Health Perspectives,* 118(8):1109-1116. doi:10.1289/ehp.0901747

Heesch, K. C., Garrard, J., & Sahlqvist, S. (2011). Incidence, severity and correlates of bicycling injuries in a sample of cyclists in Queensland, Australia. *Accid Anal Prev, 43*(6), 2085-2092. doi:10.1016/j.aap.2011.05.031

Hellawell, D.J., Taylor, R.T., & Pentland, B. (1999). Cognitive and psychosocial outcome following moderate or severe traumatic brain injury. *Brain Inj, 13*(7), 489-504.

Holm, A.L., Glumer, C., Diderichsen, F. (2012). Health Impact Assessment of increased cycling to place of work or education in Copenhagen. *BMJ Open,* 2(4). doi:10.1136/bmjopen-2012-001135

Hughner, R., Kleine, S. (2004). Views on health in the lay sector: a compilation and review of how individuals think about health. *Health*, 8:395-422.

Hung, M.C., Lu, W.S., Chen, S.S., Hou, W.H., Hsieh, C.L., Wang, J.D. (2015). Validation of the EQ-5D in Patients with Traumatic Limb Injury. *Journal of Occupational Rehabilitation*, 25:387-393.

Insurance Sweden [Försäkringsförbundet]. (2004). In Swedish: Medicinsk Invaliditet – Gradering av Medicinsk Invaliditet [Medical Impairment – Grading of Medical Impairment]. Stockholm, Sweden.

International Traffic Safety Data and Analysis Group [IRTAD]. (2012). *Road Safety Annual Report 2011*, OECD/ITF 2012.

International Traffic Safety Data and Analysis Group [IRTAD]. (2017). Marrakech Declaration on Better Safety Data for Better Road Safety Outcomes. International Transport Forum, OECD, 2017

Jacobsen, P. L. (2003). Safety in numbers: more walkers and bicyclists, safer walking and bicycling. *Inj Prev, 9*(3), 205-209.

Jagnoor, J., De Wolf, A., Nicholas, M., et al. (2015). Restriction in functioning and quality of life is common in people 2 months after compensable motor vehicle crashes: prospective cohort study. *Injury Epidemiology*, 2:8. doi:10.1186/s40621-015-0042-7.

Johansson, R. (2009). Vision Zero – Implementing a policy for traffic safety. *Safety Science*, 47(6):826-831. doi: 10.1016/j.ssci.2008.10.023

Juhra, C., Wieskotter, B., Chu, K., et al. (2012). Bicycle accidents – do we only see the tip of the iceberg? A prospective multi-centre study in a large German city combining medical and police data. *Injury*, 43(12):2026-2034. doi:10.1016/j.injury.2011.10.016

Kanianthra, J. (2007) *Government Status Report - United States*. In proceedings of the 20th ESV Conference; Lyon, France.

Karlsson, N., Carstensen, J., Gjesdal, S., Alexanderson, K. (2008). Risk factors for disability pension in a population-based cohort of men and women on long-term sick leave in Sweden. *European Journal of Public Health*, 18(3):224-31.

Kelly, P., Kahlmeier, S., Gotschi, T., et al. (2014). Systematic review and meta-analysis of reduction in all-cause mortality from walking and cycling and shape of dose response relationship. *International Journal of Behavioral Nutrition and Physical Activity*, 11:132. doi:10.1186/s12966-014-0132-x

Kenardy, J., Heron-Delaney, M., Warren, J., Brown, E. (2015). The effect of mental health on long-term health-related quality of life following a road traffic crash: results from the UQ SuPPORT study. *Injury*, 46(5):883-890

Kohl, H. W., 3rd, Craig, C. L., Lambert, E. V., Inoue, S., Alkandari, J. R., Leetongin, G., . . . Lancet Physical Activity Series Working, G. (2012). The pandemic of physical inactivity: global action for public health. *Lancet, 380*(9838), 294-305. doi:10.1016/S0140-6736(12)60898-8

Kröyer, H. R. G. (2015a). Is 30km/h a 'safe' speed? Injury severity of pedestrians struck by a vehicle and the relation to travel speed and age. IATSS Research, 39(1), 42-50.

Kröyer, H.R.G. (2015b). *Accidents betveen pedestrians, bicyclists and motorized vehicles [Elektronisk resurs] : accident risk and injury severity*. Diss. (sammanfattning) Lund : Lunds universitet, 2015. Lund.

Kullgren, A., Stigson, H., Ydenius, A., Axelsson, A., Engström, E., Rizzi, M. (2019). The potential of vehicle and road infrastructure interventions in fatal bicyclist accidents on Swedish roads – what can in-depth studies tell us? In proceedings of the 26th ESV Conference: paper number 19-016; Eindhoven, Netherlands.

Langley, J. D., Dow, N., Stephenson, S., & Kypri, K. (2003). Missing cyclists. *Inj Prev, 9*(4), 376-379.

Larsson, J., Esbjornsson, E., Bjorkdahl, A., Morberg, I., Nilsson, M., & Sunnerhagen, K.S. (2010). Sick leave after traumatic brain injury. The person or the diagnosis – which has greater impact? *Scand J Public Health, 38*(5), 541-547.

Lett, R., Kobusingye, O., & Sethi, D. (2002). A unified framework for injury control: the public health approach and Haddon's Matrix combined. *Inj Control Saf Promot, 9*(3), 199-205. doi:10.1076/icsp.9.3.199.8708

Lindroth, J. (2010). In Swedish: Idrottshistorisk forskning – den långa vägen till akademin [Sports history research - the long way to the academy]. *Svensk Idrottsforskning*,

2010:1:26-29.

Lindström, M. (2008). Means of transportation to work and overweight and obesity: a population-based study in southern Sweden. *Preventive Medicine,* 46(1): 22-28. doi:10.1016/j.ypmed.2007.07.012

Malm, S., Krafft, M., Kullgren, A., Ydenius, A., Tingvall, C. (2008). Risk of permanent medical impairment (RPMI) in road traffic accidents, *Annual Proceedings of the Association for the Advancement of Automotive Medicine*, 52**:**93-100.

Maraste, P., Persson, U., Berntman, M. (2003). Long-term follow-up and consequences for severe traffic injuries – treatment costs and health impairment in Sweden in the 1960s and the 1990s. *Health Policy,* 66:147-158.

Massari, L., Falez, F., Lorusso, V., Zanon, G., Ciolli, L., La Cava, F., et al. (2012). Can a combination of different risk factors be correlated with leg fracture healing time? *J Orthopaed Traumatol,* 14:51-57.

Matthews, C.E., Jurj, A.L., Shu, X.O., et al. (2007). Influence of exercise, walking, cycling, and overall nonexercise physical activity on mortality in Chinese women. *American Journal of Epidemiology,* 165(12):1343-1350. doi:10.1093/aje/kwm088

Mayou, R., Bryant, B. (2003). Consequences of road traffic accidents for different types of road user. *Injury – International Journal of the Care of the Injured,* 34:197–202.

Meerding, W.J., Looman, C.W., Essink-Bot, M.L., Toet, H., Mulder, S., van Beeck, E.F. (2004). Distribution and determinants of health and work status in a comprehensive population of injury patients. *Journal of Trauma,* 56(1):150-161.

Medin, J., Alexanderson, K. (2000). In Swedish: Begreppen hälsa och hälsofrämjande – en litteraturstudie [The terms health and health promotion - a review of the literature]. Upplaga 1:17 Lund: Studentlitteratur.

Nhac-Vu, H.T., Hours, M., Chossegros, L., et al., 2014. Prognosis of outcome in adult survivors of road accidents in France: one-year follow-up in the ESPARR cohort. *Traffic Injury Prevention*, 15(2):138–147.

Nicaj, L., Stayton, C., Mandel-Ricci, J., et al. (2009). Bicyclist fatalities in New York City: 1996-2005. *Traffic Injury Prevention,* 10(2):157-161.

Nilsson, P., Stigson, H., Ohlin, M., Strandroth, J. (2017). Modelling the effect on injuries and fatalities when changing mode of transport from car to bicycle. *Accident Analysis and Prevention,* 100:30-36.

Niska, A., & Eriksson, J. (2013). In Swedish: Statistik över cyklisters olyckor: Faktaunderlag till gemensam strategi för säker cykling [Cycling accident statistics: Background information to the common policy strategy for safe cycling]. VTI Report 801. Linköping: Statens väg- och transportforskningsinstitut. http://vti.diva-portal.org/smash/get/diva2:694821/FULLTEXT01.pdf

Nordenfelt, L. (1995). On the nature of health: an action-theoretic approach. *Philosophy and Medicine, v* 26.

Nordenfelt, L. (1996). On the notion of health as ability. *Scandinavian Journal of Occupational Therapy* 3: 101–105

OECD. International Transport Forum (2013), *Cycling, Health and Safety*, OECD Publishing/ITF. *http://dx.doi.org/10.1787/9789282105955-en*

O'Hern, S., & Oxley, J. (2018). Fatal cyclist crashes in Australia. *Traffic Inj Prev, 19*(sup2), S27-S31. doi:10.1080/15389588.2018.1497166

Ohlin, M., Strandroth, J., Tingvall, C. (2017). The combined effect of vehicle frontal design, speed reduction, autonomous emergency braking and helmet use in reducing real life bicycle injuries. *Safety Science,* 92:338–344.

Oja, P., Titze, S., Bauman, A., et al. (2011). Health benefits of cycling: a systematic review. *Scandinavian Journal of Medicine & Science in Sports,* 21(4):496-509. doi:10.1111/j.1600-0838.2011.01299.x

Oja, P., Vuori, I., Paronen, O. (1998). Daily walking and cycling to work: their utility as health-enhancing physical activity. *Patient Educ Couns,* 33(1 Suppl):87-94.

Olivier, J., Creighton, P. (2016). Bicycle injuries and helmet use: a systematic review and meta-analysis. *International Journal of Epidemiology.* doi:10.1093/ije/dyw153

Olkkonen, S., Lahdenranta, U., Slatis, P., Honkanen, R. (1993). Bicycle accidents often cause disability—an analysis of medical and social consequences of nonfatal bicycle accidents. *Scandinavian Journal of Social Medicine,* 21(2):98-106.

Olsson, D., Alexanderson, K., Bottai, M. (2015). Sickness absence and the time-varying excess risk of premature death: a Swedish population-based prospective cohort study. *Journal of Epidemiology and Community Health*, 69(11):1052-7.

Page, Y., Cuny, S., Zangmeister, T., Kreiss, J. P., & Hermitte, T. (2009). The evaluation of the safety benefits of combined passive and on-board active safety applications. *Ann Adv Automot Med, 53*, 117-127.

Polinder, S., van Beeck, E.F., Essink-Bot, M.L., et al. (2007). Functional outcome at 2.5, 5, 9, and 24 months after injury in the Netherlands. *Journal of Trauma*, 62(1):133-141.

Polinder, S., Haagsma, J. A., Belt, E., et al. (2010). A systematic review of studies measuring health-related quality of life of general injury populations. *BMC Public Health,* 10:783.

Pucher, J., Dill, J., Handy, S. (2010). Infrastructure, programs, and policies to increase bicycling: an international review. *Preventive Medicine,* 50 (Supplement 1):106-125. doi:10.1016/j.ypmed.2009.07.028

Rivara, F. P., Thompson, D. C., & Thompson, R. S. (1997). Epidemiology of bicycle injuries and risk factors for serious injury. *Inj Prev, 3*(2), 110-114.

Rizzi, M., Stigson, H., Krafft, M. (2013). Cyclist injuries leading to permanent medical impairment in Sweden and the effect of bicycle helmets. In proceedings of the Int. IRCOBI Conf. on the Biomechanics of Injury: paper number IRC-13-46; Gothenburg, Sweden.

Rizzi M. (2016) Towards a Safe System Approach to Prevent Health Loss among Motorcyclists - The Importance of Motorcycle Stability as a Condition for Integrated Safety. Thesis for the degree of Doctor in Philosophy. Chalmers University of Technology, Gothenburg, Sweden.

Rojas-Rueda, D., de Nazelle, A., Teixido, O., Nieuwenhuijsen, M.J. (2013). Health impact assessment of increasing public transport and cycling use in Barcelona: a morbidity and burden of disease approach. *Preventive Medicine,* 57(5):573-579. doi:10.1016/j.ypmed.2013.07.021

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

Sahlqvist, S., Goodman, A., Simmons, R.K., et al. (2013). The association of cycling with all-cause, cardiovascular and cancer mortality: findings from the population-based EPIC-Norfolk cohort. *BMJ Open,* 3(11), e003797. doi:10.1136/bmjopen-2013-003797

Schantz, P. (2015). In Swedish: Om gång och cykling, hälsa och en hållbar utveckling [Walking and cyckling, health and a sustainable development]. Swedish Transport Administration publication: 2015:153. Borlänge, Sweden.

Schepers, P. (2012). Does more cycling also reduce the risk of single-bicycle crashes? *Inj Prev, 18*(4), 240-245. doi:10.1136/injuryprev-2011-040097

Schepers, P., Stipdonk, H., Methorst, R., & Olivier, J. (2017). Bicycle fatalities: Trends in crashes with and without motor vehicles in The Netherlands. *Transportation Research Part F: Traffic Psychology and Behaviour, 46*, 491-499. doi:https://doi.org/10.1016/j.trf.2016.05.007

Scholten, A.C., Haagsma, J.A., Andriessen, T.M., Vos, P.E., Steyerberg, E.W., van Beeck, E.F., & Polinder, S. (2015). Health-related quality of life after mild, moderate and severe traumatic brain injury: patterns and predictors of suboptimal functioning during the first year after injury. *Injury, 46*(4), 616-624.

Seedhouse, D. (2001). What is health? In: Seedhouse, D., editor. Health: The Foundations for Achievement. 2nd edition. John Wiley & Sons Ltd; pp. 5-14. West Sussex, England.

Sinha, S., Gunawat, P., Nehra, A., & Sharma, B.S. (2013). Cognitive, functional, and psychosocial outcome after severe traumatic brain injury: a cross-sectional study at a tertiary care trauma center. *Neurol India, 61*(5), 501-506. doi:10.4103/0028-3886.121920

Statistics Sweden. (2004). Publication 2004:3; Sjukfrånvaro och ohälsa i Sverige - en belysning utifrån SCB:s statistik [Sickness absence and ill health in Sweden – based on statistics from Statistics Sweden]. Örebro, Sweden.

Stigell, E., Schantz, P. (2015). Active Commuting Behaviors in a Nordic Metropolitan Setting in Relation to Modality, Gender, and Health Recommendations. *Int J Environ Res Public Health, 12*(12), 15626-15648. doi:10.3390/ijerph121215008

Strandroth, J., Sternlund, S., Tingvall, C., Johansson, R., Rizzi, M., & Kullgren, A. (2012). A new method to evaluate future impact of vehicle safety technology in Sweden. *Stapp Car Crash J, 56*, 497-509.

Suls, Jerry M., Karina W. Davidson, and Robert M. Kaplan. (2010). *Handbook of Health Psychology and Behavioral Medicine*. New York: Guilford Publications, 2010. Web.

Sun, R., Zhuang, X., Zhao, G., & Zhang, K. (2015). The estimation of vehicle speed and stopping distance by pedestrians crossing streets in a naturalistic traffic environment. *Transportation Research Part F: Traffic Psychology and Behaviour.* 30, 97-106.

Swedish Association of Local Authorities and Regions & Swedish Transport Administration. (2013). In Swedish: Trafiksäkra staden: handbok för ett målinriktat kommunalt trafiksäkerhetsprogram [Traffic safety in the city: guide for a targeted municipal traffic safety programme]. Stockholm, Sweden.

Swedish Government (1997a). Bill 1996/97:137: In Swedish: Nollvisionen och det trafiksäkra samhället [Vision Zero and the traffic safety society]. Stockholm, Sweden.

Swedish Government (1997b). In Swedish: På väg mot det trafiksäkra samhället [En route to safe traffic society] (Ds 1997:13). Stockholm, Sweden.

Swedish Government (2002). Bill 2002/03:6: In Swedish: Obligatorisk redovisning av sjukfrånvaro [Compulsory reporting of sickness absence]. Stockholm, Sweden.

Swedish Government Offices. (1965). *SFS 1965:561. last update in SFS 2014:1244, 2014*. http://rkrattsbaser.gov.se/sfst?bet=1965:561.

Swedish Parliament (1997). Committee on Transport and Communications. Committee report 1997/98:TU4. Protocol 1997/98:13. (In Swedish). Stockholm, Sweden.

Swedish Road Administration (2008) *Management by objectives for road safety work – Stakeholder collaboration towards new interim targets 2020*, Publication no. 2008:31.

Swedish Transport Administration. (2014) *Safer Cycling – A Common Strategy for the period 2014-2020*. STA publication 2014:030, Borlänge, Sweden.

Swedish Transport Administration. (2015). Analysis of Road Safety Trends 2014 – Management by objectives for road safety work towards the 2020 interim targets. Publication 2015:103. Borlänge, Sweden.

Swedish Transport Administration. (2018). In Swedish: Analys av Trafiksakerhetsutvecklingen 2017 [Analysis of traffic safety developments 2017]. Borlänge, Sweden: STA Publication 2018:143.

Swedish Transport Agency. (2016). In Swedish: Vägtrafikolyckor - handledning vid rapportering [A guide for reporting of road traffic accidents]. Retrieved from*: www.transportstyrelsen.se/sv/Publikationer/Vag/STRADA/Vagtrafikolyckor---handledning-vid-rapportering/*.

The EuroQol Group. (1990). EuroQol-a new facility for the measurement of health-related quality of life. *Health Policy*, 16(3):199-208.

The National Board of Health and Welfare (2012). In Swedish: Övergripande principer för sjukskrivning [Principles for sickness absence]. Available at: http://www.socialstyrelsen.se/riktlinjer/forsakringsmedicinsktbeslutsstod/overgripandeprinciperforsjukskrivning. Accessed January 18th, 2017.

The National Board of Health and Welfare (2016). In Swedish: Anvisningar för val av huvud- och bidiagnos [Guide for choosing main- and secondary diagnoses]. Version 4.1. Rev 2016-05-11. Available at: https://www.socialstyrelsen.se/globalassets/sharepoint-dokument/artikelkatalog/klassifikationer-och-koder/2016-5-21.pdf. Accessed July 29th, 2019.

The Swedish Social Insurance Agency (SIA). (2015). Social Insurance in Figures 2015.

The WHOQOL Group. (1995). The World Health Organization Quality of Life assessment (WHOQOL): Position paper from the World Health Organization. *Social Science and Medicine*, 41:1403.

Tingvall, C. (1997). *The Zero Vision – a road transport system free from serious health losses*. In: van Holst, H., Nygren, Å., Thord, R. (Eds.). Transportation, traffic safety and health. pp:37-57. Springer, Berlin, Heidelberg.

Tingvall, C. (2008). Distraction from the View of Governmental Policy Making. In: Driver Distraction: Theory, Effects, and Mitigation. Editor(s): Kristie Young, Monash University, Clayton, Victoria, Australia; John D. Lee, University of Iowa, USA; Michael A. Regan, French National Institute for Transport and Safety Research (INRETS), Lyon, France/CRC Press, Monash University, Accident Research Centre, Melbourne, Australia.

Tingvall, C., Ifver, J., Krafft, M., et al. (2013). The Consequences of Adopting a MAIS 3 Injury Target for Road Safety in the EU: a Comparison with Targets Based on Fatalities and Long-term Consequences. In proceedings of the International IRCOBI Conference on the Biomechanics of Injury: Paper number IRC-12-10; Gothenburg, Sweden.

Transport Analysis (2015). In Swedish: Cyklandets utveckling i Sverige 1995-2014 - en analys av de nationella resvaneundersökningarna [Evolution of cycling in Sweden 1995-2014 - analysis of the national travel surveys].Trafikanalys 2015:14. Stockholm, Sweden.

Trivector Traffic. (2018). In Swedish: Förlåtande beläggning på cykelbanor - var ska den placeras [Forgiving paving on bicycle paths - where should it be implemented]? Report 2018:52.

Ulvik, A., Kvåle, R., Wentzel-Larsen, T., Flaatten, H. (2008). Quality of life 2-7 years after major trauma. *Acta Anaesthesiol Scand*; 52: 195-201.

United Nations (2015). The Global Goals for Sustainable Development. Available at: http://www.globalgoals.org/ Accessed February 2nd, 2017.

University of Gothenburg. General study plan for doctoral degree in sport science. [Internet]. University of Gothenburg, Department of Food, Nutrition, and Sport Science; 2016. Available at: https://iki.gu.se/digitalAssets/1572/1572275_allma--n-studieplan-mot-doktorsexamen-i-idrottsvetenskap.pdf. Accessed August 5th 2019.

Veisten, K., Saelensminde, K., Alvaer, K., et al. (2007). Total costs of bicycle injuries in Norway: correcting injury figures and indicating data needs. *Accident Analysis and Prevention,* 39(6):1162-1169. doi:10.1016/j.aap.2007.03.002

Vetenskapsrådet (2011). In Swedish: God forskningssed [Good research practice]. Stockholm, Sweden.

Vingard, E., Alexanderson, K., Norlund, A. Swedish Council on Technology Assessment in Health Care (SBU). (2004). Chapter 9. Consequences of being on sick leave. *Scandinavian Journal of Public Health,* 32(Supplement 63):207-15.

Wahlgren, L., & Schantz, P. (2012). Exploring bikeability in a metropolitan setting: stimulating and hindering factors in commuting route environments. *BMC Public Health, 12*, 168. doi:10.1186/1471-2458-12-168

Wallqvist, V., Kjell, G., Cupina, E., Kraft, L., Deck, C., & Willinger, R. (2017). New functional pavements for pedestrians and cyclists. *Accid Anal Prev, 105*, 52-63. doi:10.1016/j.aap.2016.04.032

Warburton, D.E., Nicol, C.W., & Bredin, S.S. (2006). Health benefits of physical activity: the evidence. *CMAJ, 174*(6), 801-809. doi:10.1503/cmaj.051351

Wegman, F., Zhang, F., & Dijkstra, A. (2012). How to make more cycling good for road safety? *Accid Anal Prev, 44*(1), 19-29. doi:10.1016/j.aap.2010.11.010

Weijermars, W., Bos, N., Stipdonk, H. (2016). Health burden of serious road injuries in the Netherlands. *Traffic Injury Prevention,* 17(8):863-869.

WHO, World Health Organization (1948). WHO Constitution. Geneva, Switzerland.

WHO, World Health Organization (1993). International Statistical Classification of Diseases and Related Health Problems, Tenth Revision (ICD-10). Geneva, Switzerland

WHO, World Health Organization (2001). International Classification of Functioning, Disability and Health: ICF. Geneva, Switzerland.

WHO, World Health Organization (2002). Towards a Common Language for Functioning, Disability and Health, ICF. Geneva, Switzerland.

WHO, World Health Organization (2015). Global Status Report on Road Safety 2015. Geneva, Switzerland. Available at: http://apps.who.int/iris/bitstream/10665/189242/1/9789241565066_eng.pdf?ua=1. Accessed December 7th, 2016.

WHO, World Health Organization (2018). Global Status Report on Road Safety 2018. Geneva, Switzerland. Available at: https://www.who.int/violence_injury_prevention/road_safety_status/2018/en/. Accessed June 17th, 2019.

Winters, M., Brauer, M., Setton, E.M., Teschke, K. (2013). Mapping bikeability: a spatial tool to support sustainable travel. *Environment and Planning B: Planning and Design*, 40:865 – 883.

Wirén Åkesson, J. Idrottens akademisering: idrottsvetenskaplig kunskap inom forskning, utbildning och på arbetsmarknaden [The academisation of sport: scientific knowledge within research, higher education and on the labour market]. [thesis on the Internet]. Malmö: Malmö University; 2014 [cited 2019 May 03]. Available from: http://hdl.handle.net/2043/17006.

Wood-Dauphnee, S. (1999). Assessing Quality of Life in Clinical Research: From Where Have We Come and Where Are We Going? *Journal of Clinical Epidemiology,* 52(4):355–363.

Ydenius, A., Kullgren, A. (2019). Guideline for a vehicle purchase policy aiming at a safe and sustainable vehicle fleet. In proceedings of the 26th ESV Conference: paper number 19-0290; Eindhoven, Netherlands.

Öster, C., Willebrand, M., Dyster-Aas, J., Kildal, M., Ekselius, L. (2009). Validation of the EQ-5D questionnaire in burn injured adults. *Burns,* 35:723-73.