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Car crashes with two-wheelers in China

Proposal and assessment of C-NCAP automated emergency braking test scenarios

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Abstract

In China, around 15,000 users of two-wheelers (TWs) die on the road every year. Passenger cars are the dominating crash opponent of TWs in road traffic crashes. Understanding the characteristics of car crashes with TWs is essential to enhance cars' safety performance and improve the safety of TW riders in China.

This thesis has three objectives. First, to define test scenarios of Automated Emergency Braking systems for cars encountering TWs (TW-AEB) in China (Paper I). Second, to assess whether cars with good ratings in consumer safety rating programs (e.g., New Car Assessment Program: NCAP) are also likely to perform well in the real-world. Finally, to understand the characteristics of the car crashes with TWs after the TW-AEB application.

To achieve the first objective, cluster analysis was applied to the China In-Depth Accident Study (CIDAS). The results were six test scenarios (Paper I), which are proposed for the Chinese NCAP (C-NCAP) TW-AEB testing.

To achieve the second and third objectives, counterfactual virtual simulations were performed with and without TW-AEB to a) a C-NCAP TW-AEB test scenario set ; b) an alternative scenario set based on the results of Paper I; and c) real-world crashes in China. Results show much higher crash avoidance rate and lower impact speed were found for C-NCAP scenario set than for the other two sets.

To better reflect car crashes with TW in China, longitudinal same-direction scenarios with the car or TW turning and perpendicular scenarios with high TW traveling speed are recommended to be included in C-NCAP future releases.

Future work will focus on assessing the combined benefit of preventive and protective safety systems for car-to-TW crashes in China.

Keywords: C-NCAP; cluster analysis; PTW; two-wheelers; motorcycles; ADAS; AEB; benefit assessment; future safety systems; China

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Table of contents

1. Introduction

Globally, more than 1.35 million people die from road traffic crashes and as many as 50 million people get injured every year (WHO, 2018a). Road traffic injury is now the eighth leading cause of death for all age groups and the first leading cause of death for children and young adults from 5–29 years old (WHO, 2018a).

This global public health issue calls for efforts involving international cooperation and partnerships across many sectors of society. The United Nations (UN) proclaimed that halving the number of global traffic fatalities and injuries by 2020 (WHO, 2018a) is a target of the Sustainable Development Goals (SDGs: 3.6). Despite initiatives to improve road traffic safety, the problem is not resolved; there are still many crashes on the road every day (Benlagha and Charfeddine, 2020). Recently, additional efforts have been made. For example, the World Health Organization (WHO), representing around 140 countries, has worked on improving road traffic safety using the Stockholm Declaration (WHO, 2020). The Declaration calls for new global targets: road deaths reduced by at least 50% by 2030 and traffic fatalities and serious injuries eliminated by 2050 (WHO, 2020).

China, with the largest population and largest automotive market in the world, accounted for about 26% of global traffic fatalities in 2016 (Benlagha and Charfeddine, 2020). Of the total traffic fatalities in China in 2013, two-wheelers (TWs) riders accounted for almost 30% (WHO, 2015). However, most existing studies on TW traffic safety improvement are from developed countries like Sweden, Germany and the USA (Chen et al., 2013). The traffic situations in a large, rapidly developing and highly populated country, such as China, can be quite different (Zhang et al., 2008; 2010). In order to improve TW road traffic safety in China, we must implement safety systems based on a thorough understanding of the car-to-TW crash characteristics of Chinese real-world data.

In this thesis I start by describing the traffic situation of TWs worldwide as well as in China, followed by an introduction of measures that are being, or can be, taken to improve TW safety in China. Chapter 2 covers safety system benefit assessment methods and the data used. In the next chapter, the objectives of the thesis and the whole Ph.D. project are explained. In Chapter 4, two paper summaries are provided. Chapter 5 presents a discussion on how to improve TW traffic safety in China and explores this thesis' contribution to sustainable development. Chapter 6 describes the conclusions of the thesis.

1.1 TW traffic situation worldwide and in China

1.1.1 Large number of TWs in China

In this thesis, TWs include both traditional pedal bicycles and powered two-wheelers (PTWs: combustion and electric engine powered TWs). The bicycle is environmentally friendly and has been popular worldwide for many years (Wang and Wei, 1993; Wayne and Pless, 2005; ESCAP, 2013; Davison and Curl, 2014; Oke et al., 2015; 2018). Oke et al. (2015) estimated that there were more than 580 million bicycles globally in 2012. The combustion engine PTWs are common as well: in 2006, their number was estimated at 313 million globally, with the majority (77%) in Asia, followed by Europe and North America (Rogers, 2008). Recently, the number of electric engine PTWs has been increasing worldwide, due to their convenience and economic benefits as well as an increased emphasis on reducing carbon emissions. Asia has the largest number of electric engine PTWs, followed by Europe and North America (TechSci Research, 2019). China is one of the largest markets for electric engine PTWs, with an estimated 290 million at the end of 2018; the number is predicted to increase to over 350 million by 2023 (Sina Car, 2019). In terms of market value, the TW market in China is predicted to surpass US$22,000 million by 2024 (TechSci Research, 2019).

Along with the large number of TWs worldwide, a variety of TW design styles can be found. Generally, the styles of bicycles and combustion engine PTWs are quite uniform across the world. However, a spectrum of designs exists for electric engine PTWs, from bicycle-style to scooter-style, with varying performance characteristics (Cherry et al., 2009; Rose, 2012; Fishman and Cherry, 2016). In the top row (a-c) of Figure 1, bicycle-style electric engine PTWs, with big wheels, are shown. In the bottom row (d-f), scooter-style electric engine PTWs with small wheels are shown. In China, all electric engine PTWs must be equipped with pedals by law. However, pedals are rarely used on the scooter-style electric PTWs. Most electric engine PTWs in Europe and North America are bicycle-style, while all types shown in the figure can be found on Chinese roads (Fishman and Cherry, 2016). Scooter-style electric PTWs, with a higher travel speed than the bicycle-style PTWs, are more popular in some Chinese cities (Fishman and Cherry, 2016). One thing to note is that, according to the Chinese national regulation: GB17761-2018, electric engine PTWs should weigh less than 55 kg and have a maximum speed of 25 km/h (Ministry of Industry and Information Technology of the People’s Republic of China); however, the scooter-style PTWs can usually reach 45 km/h, due to loose enforcement of the law and strong demands for speed (Weinert et al., 2007; Cherry and Cervero 2007).

Although electric engine PTWs generally travel faster than bicycles, in most cities in China they are allowed to share infrastructure (like bicycle paths) with bicycles, which increases the complexity of the traffic situation (Cherry and He, 2010).

Figure 1. Different types of electric engine PTWs: bicycle-style in the top row and scooter-style in the bottom row (From Fishman and Cherry, 2016, included with permission from the Transport Review journal editorial office).

Not only do TWs have different design characteristics, their usage is different in different areas of the world. In China, TWs are used more for transportation, whereas in Europe they are used more for exercise and leisure (Haworth, 2012; Chen and Dai, 2018). Overall, these differences result in different traffic situations and traffic conflicts for TW riders in China compared to European countries.

1.1.2 Critical safety issue of TWs in China

As the number of TWs on the road increases, road traffic crashes involving TWs increase as well. Around 30% of the 1.35 million road traffic deaths globally in 2016 were two- or three-wheeled vehicle users (WHO report, 2018). In China, over 15,000 TW users died and 56,000 were injured in road traffic in 2018 (National Bureau of Statistics of China, 2018). The actual number is likely to be higher, however, since crashes are under-reported in China (Duan et al., 2017; Hu et al., 2011; Huang et al., 2017).

The increase in the number of (non-TW) motor vehicles is also an important factor contributing to the high number of TW-involved crashes, as the majority of the TW road fatalities are caused by crashes with other motor vehicles (DESTATIS, 2016; Duan et al., 2017; Chang et al., 2019). What makes it worse is that TW riders have a higher risk of being fatally injured than passenger car occupants on the road. A comparison of fatalities per billion vehicle-kilometres for combustion engine PTW and passenger car occupants in Germany reveals that the former is 20 times higher because of the higher fatality risk (2.5 times) and crash risk (7 times) of motorcyclists (Wu and Lubbe, 2020).

Helmets are effective at reducing TW riders' injuries and fatalities. The use of helmets has been recommended and/or legally required in many countries (ITF/OECD, 2018). In China, helmet usage has been mandatory for combustion engine PTWs since 1988 (The State Council of the People's Republic of China, 1988). In May 2004, the penalty for not wearing a safety helmet was raised from five RMB (less than €1) to 20–200 RMB (approximately €3–30). However, the reported helmet usage rate remains low, with estimates ranging from 30% to 60%, due to poor enforcement of the law (Zhang et al., 2004; Li et al., 2008). At present, electric engine PTW riders in China are not required to wear a helmet or have a driving license (Weinert, and Cherry, 2007; Wu et al., 2012; Fishman and Cherry, 2016).

In summary, a variety of factors are responsible for the high risk of injury for TW riders in China: the failure to keep to the design speeds, a mix of bicycles, PTWs, and pedestrians in the traffic, etc. (Weinert, and Cherry, 2007; Wu et al., 2012; Fishman and Cherry, 2016).

1.2 Potential safety systems for TW riders' protection

There are two main types of in-vehicle safety systems available: protective and preventive. Protective safety systems were the first type of safety system added to passenger cars to mitigate the injuries of car occupants once a crash was unavoidable. Common examples include seatbelts and airbags. Other protective safety systems were developed later for vulnerable road users (VRUs; including TW and three-wheeled vehicle users and pedestrians) outside the car, such as "friendly" car-front designs (e.g., energy-absorbing bumpers), pedestrian protection airbags (PPA) and active pop-up hoods (Huang and Yang, 2010; Fredriksson et al., 2010; Strandroth et al., 2011; Moran et al., 2017). Although these systems were initially designed for pedestrian protection, they have recently been modified to protect TW riders as well (Fredriksson et al., 2012; Ohlin et at., 2016).

The second type, preventive safety systems, which acts earlier than protective safety systems, has the goal of avoiding crashes (or, at least, mitigating their consequences) by warning drivers or automatically intervening (e.g., braking). They are effective at saving lives and reducing injuries (Capitani et al., 2009; Coelingh et al., 2010; Bärgman et al., 2017; Jeong and Oh, 2017). Preventive safety systems can be car-based—for example, Forward Collision Warning (FCW) and Automated Emergency Braking (AEB), or TW-based—for example, Anti-lock Braking System (ABS) and motorcycle AEB (MAEB).

1.2.1 Preventive safety systems

Impact speed reduction has been identified as critical for VRU protection, since impact speed is highly correlated with VRU injury severity for head, chest, and leg injuries (Fredriksson et al., 2007; 2010). Rosén and Sander (2009) showed that the pedestrian fatality risk at an impact speed of 50 km/h was twice as high as the risk at 40 km/h, and five times as high as the risk at 30 km/h. Thus, reducing the impact speed is an important priority for preventive safety systems when the crash cannot be avoided. The following paragraphs provide an overview of the safety systems available for cars and TWs which are intended to reduce the impact speed before the crash.

Car-based preventive safety systems

FCW

FCW is an on-board electronic safety device with forward-looking object detection capability (Jamson et al., 2008; Guillen and Gohl, 2019). The system typically uses radar to continuously monitor traffic obstacles in front of the car (Jamson et al., 2008; Aust et al., 2013). It was first implemented to help drivers avoid or mitigate rear-end collisions. Recently it has been improved so that it also warns drivers of a potential collision with a cyclist crossing the road (Guillen and Gohl, 2019).

Many studies have highlighted the benefits of FCW systems in improving road safety and reducing crash-related traffic congestion (Fitch et al. 2008; Jamson et al., 2008; Kusano and Gabler, 2012; Cicchino 2017). However, there is one crucial problem with the design of FCW systems: the timing of the warning. Earlier triggering of the warning will make it less likely a collision will occur. On the other hand, more false alarms (false positives) will also be triggered (Seller et al., 1998), increasing the risk that the driver will turn off the system during daily driving (Jamson et al., 2008; Guillen and Gohl, 2019) or just choose not to buy that brand of vehicle again. Later triggering could be interpreted as a design failure, since it produces a less effective system: the car driver will have less time to react to the warning (Jamson et al., 2008).

AEB

Unlike FCW, AEB acts automatically, without any driver action needed. The aim of AEB systems is to avoid or mitigate a crash by braking automatically. Mitigation is obtained by decreasing the impact speed of a collision, decreasing the risk of injury for the persons involved. AEB was first introduced to avoid or mitigate rear-end crashes (Coelingh et al., 2006; Lindman et al., 2010). With the development of improved sensor detection capabilities and advanced algorithms, coupled with improved brake system activation, AEB can prevent or mitigate pedestrian and TW injuries as well (Rosén et al., 2010; Rosén, 2013; Ohlin et al., 2017).

The AEB system's specifications affect its safety performance substantially. Rosén et al. (2010) showed that AEB effectiveness increased when the sensor field of view (FoV) and maximum brake deceleration were increased and the brake activation delay was reduced. Further, Jeppsson et al. (2018) found that adding Vacuum Emergency Braking (VEB), which can increase a car's deceleration from 9 m/s^2 to 16 m/s^2, decreases pedestrian fatalities by an additional 8% to 22%. Thus, we can conclude from these studies that AEB systems have the potential to continue to improve road safety with the development of more advanced technologies. Further research and evaluation of AEB performance when cars encounter VRUs is needed to ensure accurate detection and reasonable algorithm decision-making (Cao et al., 2009). Furthermore, as TWs travel at higher speeds and exhibit more diverse manoeuvres than pedestrians (Cao et al., 2019), designing the AEB for cars encountering TWs (TW-AEB) is even more challenging than designing pedestrian-AEB (the car-based AEB system to detect and avoid pedestrians on the road).

1.3 TW-based preventive safety systems

In addition to preventive safety systems installed in cars, preventive safety systems on TWs have been developed and studied. Two examples of such systems are outlined below.

Anti-lock Braking System (ABS)

The ABS has already been introduced on motorcycles and has proven to be effective at reducing crashes and injuries (Teoh et al., 2010; Rizzi et al., 2009). The system monitors wheel speed and reduces brake pressure when wheel lock is detected. Riders can apply full brakes without the risk of falling or losing control due to wheel lock (Eric, 2011). There are indications that motorcycles with ABS are more likely to keep the rider in an upright position when a crash does occur than motorcycles without ABS, thus reducing injury from ground impact. To date, ABS is mostly available for combustion engine PTWs (Rizzi et al., 2009; Roll and Hoffmann, 2009; Giovannini et al., 2013). For other types of TWs, including bicycles and bicycle-style electric engine PTWs, ABS is rarely available.

Motorcycle Automated Emergency Braking (MAEB)

Researchers have investigated the potential for crash-avoidance and injury-mitigation benefits of AEB systems for motorcycles (MAEB) (Grant et al. 2008; Rizzi 2011). One of the first prototypes of an MAEB system was developed to detect and classify an object in front of the motorcycle (Grant et al. 2008). Based on in-depth crash data from three countries (Australia, Italy, and Sweden), Savino et al. (2014) found that, on average, a 10% reduction in impact speed could be achieved by automatically applying a maximum deceleration of about 2.94 m/s^2 if the rider does not react before the collision becomes unavoidable. In a study using virtual simulations, Savino et al. (2013) found that MAEB was effective in reducing impact speed by up to 4 m/s in seven fatal PTW crashes that occurred in Sweden. Real-world benefits of MAEB need further study, with more data and more realistic models of the TW (here, motorcycle) rider and the MAEB.

Automated vehicles

With the development of sensors, dynamic maps, artificial intelligence, and other technologies, preventive safety systems are becoming increasingly smart and "connected". Hence, they provide strong support for the development of automated vehicles (Noy et al., 2018; Li et al., 2019). Automated vehicles have the potential to improve traffic safety substantially, while reducing congestion and emissions (Gavanas, 2019). In addition, increased productivity and mobility for the non-driving population have been predicted (Zhang et al., 2020). Industry is responding to these potential advantages by developing highly automated, self-driving systems. It has been estimated that crashes could be reduced by up to 90% with a 100% automated-vehicle penetration rate (Fagnant and Kockelman, 2015). Although such a huge reduction may be possible in some countries, it might be difficult to achieve in developing countries such as China, due to the complicated traffic environment (Pizzuto et al., 2019), with many TWs on the road (Rose, 2012; Fishman and Cherry, 2016).

1.3.1 Protective safety systems

Car-based protective safety systems

Protective safety systems aim to reduce the injury severities for everyone involved in a crash. Car-based protective safety systems for pedestrians have shown clear benefits in mitigating pedestrian injuries (Strandroth et al., 2011). Pastor (2013), whose results are based on the German National Accident Records, compared the injury severity of pedestrians involved in crashes with vehicles: less severe injuries were associated with vehicles which scored higher in pedestrian crash tests performed by safety assessment programs. Similar findings were observed based on Swedish crash data (Strandroth et al., 2014). These systems are believed to reduce TW riders' injuries as well. There are indications that protective safety systems aimed at reducing pedestrian injuries can be redesigned in order to optimise protection for TW riders as well (Strandroth et al., 2014; Ohlin et al., 2017). For example, research on the pedestrian head-form test area (the area on the car where pedestrian head impacts are most likely) has led to safety systems (e.g., deployable hood and windshield airbags) which also protect TW riders to some extent (Fredriksson and Rosén, 2012; Zander and Hamacher, 2017). However, the existing test procedures and safety system requirements might not provide adequate protection for TW riders. For example, the study by Otte (2015), based on the analysis of German In-Depth Accident Study (GIDAS) data, found that the WAD (Wrap Around Distance: the distance from the ground to the head impact point on the vehicle) in car-frontal crashes was higher for bicyclists than for pedestrians.

Friendly car-front design

Friendly car-front designs which have already been implemented, such as energy-absorbing bumper areas and headlights as well as a lower stiffener at mid-tibia level to decrease loading, have been shown to reduce pedestrian injuries in crashes (Strandroth et al., 2014). Similar bicyclist injury reductions due to these designs were found in real-world crashes, although the reduction was slightly smaller for bicyclists (Ohlin, et al., 2017). Further efforts need to be undertaken to protect TW riders by improving the structural design of cars' front ends.

Active pop-up hood and windshield airbag

To mitigate pedestrians' head and chest injuries caused by the car bonnet, A-pillars, and lower windshield, a protective safety system consisting of an active pop-up hood and a windshield airbag has been proposed (Fredriksson et al., 2001； Shin et al., 2008; Fredriksson and Rosén, 2012a; 2012b; Shi et al., 2019). The pop-up hood is designed to reduce pedestrian head injuries by reducing the hood's structural stiffness and providing extra deformation space (Fredriksson et al., 2011; Lim et al., 2015). The windshield airbag is a U-shaped airbag inflated from the lower part of the windshield and A-pillar, as shown in Figure 2.

Many studies have shown the effectiveness of these safety systems in reducing pedestrian injury risk, especially for the primary impact (when the car first hits the pedestrian) (Krenn et al., 2003; Bovenkerk et al., 2009; Huang and Yang, 2010; Fredriksson and Rosén, 2012a; Ames and Martin, 2015; Lim et al., 2015). To increase the system's injury reduction capabilities for TW riders, airbag coverage of higher parts of the windshield area has been recommended (Fredriksson and Rosén, 2012b). However, there is some evidence that the active pop-up hood and windshield airbag might not only fail to reduce injury risk when the pedestrian hits the ground (the secondary impact) but might even cause more severe injuries (Shi et al., 2019). More research is needed to determine the benefit of these safety systems in real-world traffic.

Figure 2. Windshield airbag for pedestrian protection (From Autoliv Inc., with permission): a TW-based protective safety system

Motorcycle airbag

To enhance motorcyclist's protection during frontal collisions with opposing vehicles or objects, airbags on the motorcycle itself have been developed. They could be fitted to the instrument panel or the top of the petrol tank (Haworth and Schulze, 1996). Honda was first to develop a prototype of a motorcycle airbag, aiming to reduce the rider's injuries by absorbing the kinetic energy and reducing the rider's separation velocity in the forward direction, as shown in Figure 3 (Yamazaki et al. 2001; Kuroe et al. 2005). The airbag was expected to not only save riders' lives but also reduce their injuries, based on physical crash tests (ADAC,2020). It has been estimated that this airbag may save seven motorcycle riders per year (13% of average annual crashes) in Sweden (Rizzi et al., 2011). However, since no real-world benefits have yet been measured due to low market penetration of the product, the effectiveness of the airbag in daily traffic is still unclear (Rizzi et al., 2011).

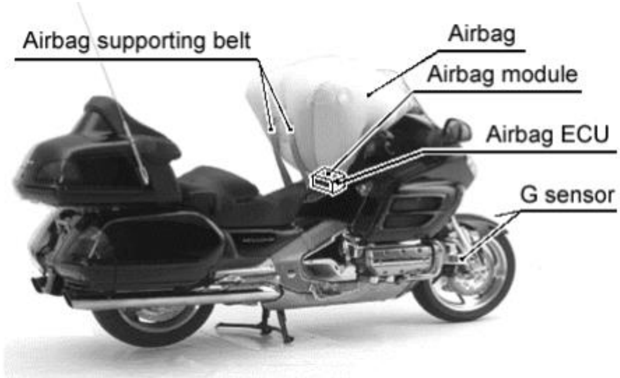

Figure 3. Prototype motorcycle airbag system installed on GL 1800 motorcycle (From Kuroe et al., 2005, with permission from the administration of the conference: Enhanced Safety of Vehicles)

TW rider-based protective safety system

In addition to in-vehicle based safety systems listed above, there are also TW rider-based protective safety systems, which I include here for completeness.

Helmet

Head injuries, typically skull fractures and brain injuries (Fernandes and Alves, 2013), are among the most frequent severe injuries of TW riders (MacLeod et al., 2010; Liu et al., 2008; Abbas et al., 2012; WHO, 2018a). It has been estimated that helmets could reduce the risk of head injury by 69% and the risk of death by 42% for motorcyclists (Liu et al., 2008). According to a study by NHTSA, helmets saved 1,892 motorcyclists in the USA in 2009, and an additional 823 lives could have been saved if the motorcycle riders had used helmets (NHTSA, 2008). However, there have been some concerns that helmet usage might increase the risk of injury to other body parts, such as the neck (Krantz, 1985), as well as decreasing the FoV of TW riders in traffic (Liu et al., 2008; Fernandes and Alves, 2013).

Inflatable jacket

Another airbag designed for motorcycle rider safety is the inflatable jacket (Capitani et al., 2010; Grasi et al., 2017). It can provide protection by inflating when the sensor—mounted in the jacket (Capitani et al., 2010) or on the front wheel (Serre et al., 2019)—detects the impact. Different shapes are available, depending on the airbag chamber volume and the body area the airbag is intended to protect: neck, shoulder, lumbar spine, and so on (Capitani et al., 2010; Serre et al., 2019). Generally, airbag performance in real-world crashes depends on various considerations such as crash dynamics, the airbag inflation pressure, the chamber volume, and the shape and presence of the holes on its surface (Capitani et al., 2010). Optimising these factors poses a challenge to the jacket's widespread use in the real world.

2. Safety systems benefit assessment

A key part of developing effective safety systems is quantitatively assessing their safety performance in terms of avoidance or mitigation of crashes in the real world. Stakeholders in the automotive industry, such as car manufacturers, automotive suppliers, public organisations, governments, and end users, each have specific concerns about the performance of safety systems (Page et al., 2015; Dobberstein et al., 2017; Sander, 2018). End users (customers) want to know the potential benefits of the system available for their vehicles (Dobberstein et al., 2017). Car manufactures and automotive suppliers need to understand the current traffic safety problems on the one hand, and on the other hand they need to make sure that the system they develop can provide the most possible benefit for the end user, in terms of crash avoidance and injury mitigation (Dobberstein et al., 2017). Public organisations, such as regulation agencies and New Car Assessment Programs (NCAPs), are interested in the benefits of safety systems for two reasons. Regulation agencies want to know which systems to promote and possibly legislate; consumer rating programs want to ensure that the consumers can get accurate, reliable information in order to make informed choices about safety when they purchase cars (van Ratingen et al., 2016). For these reasons, benefit assessment is an important aspect of the development of safety systems.

2.1. Data for safety benefit assessment

Real-world data is an essential part of vehicle safety development (Isaksson-Hellman and Norin, 2005; Tivesten, 2014). First of all, current safety issues can be addressed through analysis of real-world data (Tivesten, 2014). Then, based on crash data analysis, the most common accident scenarios and injury mechanisms can be prioritised in future vehicle safety development and improvement (Almqvist et al., 1982; Isaksson-Hellman and Norin, 2005). Further, real-world data can be used to estimate the safety system's performance (see examples in Rosén, 2013 and Jeppsson et al., 2018). Safety system performance can be further validated through real-world data after the system has been introduced to the market (Tivesten, 2014). For example, using real-world crash data from Sweden, Rizzi et al. (2009) analysed the overall effectiveness of ABS for motorcycles, and Ohlin et al. (2017) found that AEB with pedestrian detection was 70% effective at reducing car-to-pedestrian and -bicyclist crashes.

To obtain reliable and accurate estimates of safety system performance, high-quality data are important; incomplete or distorted crash data might not only mislead policy-makers and researchers, but also misdirect prevention efforts, such as which systems are developed and how they are tuned (Isaksson-Hellman and Norin, 2005; Tevesten,2014; Huang et al., 2018).

In this thesis, a differentiation between three types of real-world data for use in safety benefit assessments has been made: in-depth crash data, Event Data Recorder (EDR) data and naturalistic driving study data (NDD).

2.1.1. In-depth crash databases (crash data)

Crash data have long been used in car safety development for injury prevention analysis in crashes (Korner, 1989; Isaksson-Hellman and Norin, 2005). In order to help us understand real-world traffic conflicts and develop suitable safety systems, crash data must, on the one hand, provide detailed information about the vehicle, road users and environment at the time of the crash; on the other hand, they must be representative of all of the crashes that the safety system is designed to address. Normally, two levels of crash data can be distinguished: macroscopic and microscopic (OECD 1998; Habibović, 2012).

On the macroscopic level, crash data are collected with general information about involved vehicles, road users, and the environment to describe the main problems in real-world traffic (Habibović, 2012). They are usually collected by government offices, administrations, hospitals, or insurance companies (Benlagha et al., 2020). This type of data can provide statistically representative information on a national level and can be used to illustrate past trends and indicate future ones (Shinar et al., 1983; Tivesten, 2014; Huang et al., 2017). Police crash reports are widely used as macroscopic-level data, since they can be accessed easily through national publishing documents or websites (Huang et al., 2017). Another advantage of police-reported data is that they typically include many crashes; data for whole countries are often available. However, police reports have limited information about crash causation mechanisms and are biased towards severe crashes (Shinar et al., 1983; Aptel et al., 1999; Hu et al., 2001; Abay, 2015). While severe injuries are more likely to be reported than slight injuries, all are susceptible to under-reporting, as evidenced by comparing these data to traffic injury data from hospitals (Bull et al., 1973; Cercarelli et al., 1996; Aptel et al., 1999; Dandona et al., 2008; Hu et al., 2011; Jeorg et al., 2017).

Because of the limitations of police-reported data, hospital data are used to complement them: together they provide a good picture of the real-world traffic situation (Rosman and Knuiman, 1994). The hospital data provide detailed and accurate injury information, while the police-reported data focus on crash characteristics. However, there is usually a gap between the two sources of data, due to under-reporting of crashes in police-reported data (Tainter et al., 2020). Many researchers have applied a data-linkage procedure—the process of linking information from two independent records that are expected to belong to the same individual—to bridge the gap, obtaining more accurate information about crashes (Abay, 2015; Kamaluddin et al., 2019; Tainter et al., 2020). The benefit of combining the data is a better understanding of traffic safety problems, leading to more accurate recommendations for suitable safety systems (Cryer et al., 2001; Slesak et al., 2015; Kamaluddin et al., 2019).

Insurance data are another macroscopic type of crash data which can be used to estimate crash injuries on the national level. They are typically collected by insurance companies in written insurance claim reports, offering comprehensive information about the crashes. Insurance data contain more crashes (including damage-only crashes) and provide more detailed information than police-reported data (Hutchingson, 1987; Daniels et al. 2010). However, one disadvantage is that, because they focus on legal liability between crash participants, they do not include crash and injury causation coding (Hutchingson, 1987; Tivesten, 2012).

In order to improve road traffic safety globally, the WHO and the Global Burden of Disease (GBD) study group have regularly collected and released road traffic data worldwide on the macroscopic level since 2009 (Mathers et al., 2006; World Health Organization, 2009; Huang et al., 2017). They both also make estimations of the true road traffic situation based on advanced statistical models (Papadimitriou et al., 2019). However, even with such models, limitations caused by the absence of high-quality, reliable data cannot be avoided fully (Hu and Keita, 2013; Huang et al., 2017).

On the microscopic level, detailed crash information describes the crash mechanisms via in-depth crash investigations. Typically, this work is done by a specialised investigation team arriving at the scene shortly after the crash (Larsen, 2004). In-depth crash data, including pre-crash, in-crash and after-crash information, are collected through interviews with the involved road users and witnesses, as well as by inspection of the environment and involved vehicles (Larsen, 2004). Unlike police-reported data or insurance data, in-depth crash data can provide information on causation, which is crucial in car safety development. One well-known example is the data collected in the German In-Depth Accident Study (GIDAS) in and around Dresden and Hannover. All road traffic crashes involving at least one moving vehicle and one injured person are collected (Johannsen et al., 2017). The GIDAS investigation teams consists of physicians and engineers available 24 hours a day. Approximately 2000 in-depth traffic crash investigations are performed each year (Otte et al., 2003; Jaensch et al., 2009; Johannsen et al., 2017). More than 2000 details about the crash are coded, including personal injury, vehicle deformation patterns, driving and collision speeds, and other information obtained by questioning persons involved (Otte et al., 2003; Bruehning et al., 2005). The value of in-depth crash investigations has been recognised globally, which is evident from the vast amount of studies performed on the resulting data (Evans, 1999; Sunnevång et al., 2009; Jakobsson et al., 2010; Chen and Dai, 2018; Cao et al., 2019). Many other countries have similar databases: the China In-Depth Accident Study (CIDAS) in China (Chen et al., 2014), the Road Accident Sampling System India (RASSI) in India (Puthan et al., 2018), and the Crashworthiness Data System of the National Automotive Sampling System (NASS-CDS) in the USA (NTHSA, 2020).

One of the most detailed and complete crash databases in China, CIDAS, has been collecting 500-600 crashes annually since 2010 in five cities: Changchun, Beijing, Weihai, Ningbo, and Foshan (Chen and Dai, 2018). These cities not only encompass different geographical areas—plains, mountains, and coasts—but also different types of roadway as well—urban, rural, and highway (Chen and Dai, 2018). The criteria of crash selection in CIDAS are: (1) at least one four-wheeled vehicle is involved, (2) at least one person has been injured, and (3) on-site information is preserved for the investigators (Chen and Dai, 2018). The teams of specialists who conduct the investigations collect general crash information and information about the environment, vehicle damage, and the road, as well as interviews of the involved road users (Chen et al., 2014; Chen and Dai, 2018). The injury information is collected based on clinical reports provided by the traffic police. In this way, extensive and detailed information of the crash is coded in CIDAS (Chen and Dai, 2018).

Another in-depth crash database in China is the Shanghai United Road Traffic Safety Scientific Research Centre database (SHUFO; Deng et al., 2013). It started collecting crash data in the Jiading District, Shanghai in 2005, covering an area of 463 km^2 with a population of 1.58 million (Deng et al., 2013). The inclusion criteria for its crash data are: a) at least one four-wheeled vehicle is involved in the crash, and b) at least one airbag has been deployed or at least one person has a medium-level injury, such as a bone fracture (Sui et al., 2017). The crash data are collected retrospectively by the investigation team. SHUFO information includes data on vehicle damage, personal injury, and the traffic environment. In addition, for each case, a scale drawing of the crash scene is available, including the markings observed on the scene (skid, debris, braking traces, etc.), the traffic environment (traffic lines, zebra crossings, traffic lights), the final positions of the participants after the crash, and the estimated impact locations and pre-crash travelling paths of the participants.

Generally, microscopic data can provide more detailed records of crashes than macroscopic data. However, one issue in using microscopic data is that the number of geographical areas represented is typically limited. As a result, the data do not represent the whole country, leading to a lack of generalisability. This sampling bias impedes accurate estimations and predictions about the population (Hautzinger et al., 2004) unless a weighting factor from microscopic data to national data can be used. In NASS-CDS (US data), for example, around 5,000 cases were collected from 24 Primary Sampling Units (PSUs) in the country each year (NASS, 2015). To ensure that the data were representative of the whole country's population, the collected data were compared to the official national crash statistics, and a weighting factor was assigned to each crash (NASS, 2015; Viano et al., 2018). Unfortunately, so far, no such weighting process is available for the Chinese crash data, neither in CIDAS nor in SHUFO (Paper I).

2.1.2. Event Data Recorder (EDR)

Data from EDRs can also be used in the assessment of safety systems. The EDR is typically a component of the vehicle's airbag control module which can record information for a brief period before, during, and after a crash (NHTSA; Kusano and Gabler 2011; Rao 2017). The data typically include pre-crash vehicle dynamics and driver behaviour (often indirectly, through vehicle motion recording, rather than steering wheel and pedal use), restraint system deployment, and post-crash data, such as an automatic collision notification (ACN) system (NHTSA; Scanlon et al., 2016; Rao, 2017).

EDR has long been regarded as a promising data collection tool, complementing in-depth crash data to better define safety problems and understand crash causation mechanisms (NHTSA; Kusano and Gabler 2011; Rao 2017; Famiglietti et al., 2020). Furthermore, the National Highway Traffic Safety Administration (NHTSA) has incorporated EDR data into their crash databases (such as NASS/CDS) to support crash investigations by facilitating detailed pre-crash information retrieval (Kusano and Gabler 2011; 2012).

Two main limitations of EDR data include variable sampling rates across different EDR systems and vehicle manufacturers, and a lack of contextual information (the behaviours of other road users and environment information; Rao 2017). Fortunately, combining EDR data with data from in-depth crash data can, at least partially, make up for these shortcomings (Bärgman, 2016; Rao, 2017).

2.1.3. Naturalistic Driving Data (NDD)

The third type of real-world data that can be used for assessing the performance of safety systems is naturalistic driving data (NDD), which provide a way to investigate driver behaviour and traffic safety in detail (Neale et al., 2005; LeBlanc et al., 2006; Dozza 2012; Carsten et al., 2013; Victor et al., 2014). In a typical naturalistic study targeting traffic safety, the participants drive a car instrumented with multiple video cameras and sensors that continuously record the drivers driving as part of their everyday lives. Typically, information about the driver, the vehicle, and the environment are collected to capture the full chain of events leading up to incidents of interest, usually safety-critical events such as near-crashes and crashes (Dozza and González 2013). That is, the continuous data collection in NDSs (Naturalistic Driving Studies) makes it possible for researchers to perform data analysis on both everyday driving and safety-critical events (NHTSA 2010). Studying both driving exposure and contributing factors to critical situations makes it possible to estimate the crash or near-crash risk and the overall safety impact of different driver behaviours.

While NDD provide detailed information on real-world traffic, they have some clear limitations. First, the costs of NDS are higher than traditional data studies (NHTSA, 2010), unless commercially collected NDD is used (Bärgman, 2016). Secondly, the fact that there are few crashes and even fewer severe or fatal crashes in NDD makes it hard to reach statistically significant conclusions related to crashes. Thirdly, NDSs are typically only run in a specific area and drivers are recruited on a voluntary basis, potentially biasing results. However, NDD can complement traditional crash data (e.g., in-depth crash databases and EDR data) to inform the design of vehicle safety systems (Bärgman, 2016).

2.2. Assessment methods

There are several approaches available to assess a safety system's effectiveness. Two broad assessment categories are retrospective and prospective (Eichberger, 2010; Sander 2018; Kovaceva et al., 2020).

A retrospective assessment evaluates the effectiveness of a safety system based on data from the real world, collected after its implementation. For example, the safety performance of vehicles with and without the safety system in question can be compared (Hautzinger et al., 2007). There are several issues with retrospective assessment. First, it can only be used after the system is in production. Secondly, retrospective assessment typically requires years to achieve deep enough market penetration to evaluate the system (Kovaceva et al., 2020). Thirdly, vehicles are typically equipped with several safety systems, making it hard to evaluate the effectiveness of an individual system in the real world (Östling et al., 2019; Ljung Aust et al., 2011).

One way to perform a retrospective assessment is to use a case-control study design. Safety system benefits, in terms of crash avoidance rate and injury mitigation, can be obtained by two simple, independent random samples: case (accident-involved) and control (no-accident-involved) vehicles from the same general population (Hautzinger et al., 2007). One example of a case-control study is based on induced exposure: Ohlin et al., (2017) retrospectively assessed how well pedestrian-AEB prevents pedestrian or cyclist crashes. The cases were crashes involving pedestrians or cyclists, and the controls were rear-end crashes (involving two cars). It was found that the AEB is 70% effective at reducing crashes with pedestrians and cyclists. However, due to a limited number of crashes involving pedestrian-AEB-equipped cars, the result was not statistically significant (Ohlin et al., 2017).

In contrast to retrospective safety assessments, prospective assessments estimate the effectiveness of safety systems before they are available on the market (Eichberger, 2010). Different methods are available for prospective assessments, such as real-world crash data analysis, Field Operation Tests (FOTs), controlled physical testing, driving simulator studies, and virtual simulations (Sander, 2018; Kovaceva et al., 2020). The following section describes these methods in turn.

2.2.1. Real-world crash data analysis

Real-world crash data can be used to estimate the preventive safety system's performance in the real world by allowing us to test assumptions about which types of crash they address. For example, Lubbe et al., (2018) used high-level filtering to investigate the potential of vehicle safety technologies for avoiding and mitigating crash severity. That is, they applied filters to the GIDAS database based on the assumed performance of safety systems. The results are high-level estimates of the way that the system may have performed in recorded crashes. A similar study, requiring more in-depth, manual work, was performed by Strandroth et al., (2012). They manually applied assumptions about a safety system's performance to actual crash data, categorizing individual crashes as avoidable or non-avoidable. Thus, they conducted a manual "counterfactual" (what-if) assessment of in-depth crash data to estimate the potential performance of the safety system in the real world. The result is also an estimate of which (e.g., how many) crashes the system under assessment may have avoided. Notably, this method was further validated in a later study by Strandroth et al. (2015).

2.2.2. Field Operational Tests (FOTs)

Typically, FOTs assess preventive safety systems' performance under real-life conditions (Benmimoun et al., 2013; Bärgman, 2016). Drivers are asked to drive an instrumented vehicle on a real road, so the data collected provide information about driving behaviour—which is important for the assessment of preventive safety systems (Helmer et al., 2013).

There are two types of FOTs, naturalistic and controlled (Bärgman, 2016). In naturalistic FOTs, drivers are asked to drive with the systems as part of everyday life for a period of weeks to years. In controlled FOTs, the drivers are told where and when to drive. For both types, the system(s) under study is/are available to the drivers for only part of the driving time. Typically, the safety systems' performance is evaluated by comparing data from the two situations: when the system is available and when it is not. It usually takes several months—or even years—to collect enough information to perform an assessment analysis (Benmimoun et al., 2013). As naturalistic FOT studies are undertaken on real roads under normal driving conditions, the results have high ecological validity (LeBlanc et al., 2006; Bärgman, 2016). While controlled FOTs are commonly performed in industry (Dozza, 2013; Helmer et al., 2013; Bärgman 2016), naturalistic FOTs are not at all common, since they require more time and cost more.

2.2.3. Controlled physical testing

Controlled physical testing, estimating system benefits by evaluating how the system works according to a set of specific requirements (Kovaceva et al., 2020), is less costly than FOTs. One well-known example is the Euro NCAP, which aims to reflect overall optimum values in road safety through their rating scores (Hobbs and McDonough, 1998; Pastor et al., 2013; van Ratingen et al., 2016). Euro NCAP evaluates safety system performance by providing public test protocols and issuing safety scores for the tested cars (Euro NCAP, 2020). This approach has been applied globally: for example, by C-NCAP in China, JNCAP in Japan, and U.S. NCAP in the USA.

Protective safety assessment

To evaluate the pedestrian-protection performance of the frontal design of new car models, Euro NCAP took the initiative to include test configurations of the cars' frontal structures in 1997 (van Ratingen et al., 2016). Subsystem tests of a leg form impactor against the bumper and head form impactor (either for adult or child) against the hood were included. These tests replicated car-to-pedestrian crashes at an impact speed of 40 km/h (Euro NCAP, 2020). Several studies have shown a correlation between improvements in car design (due to regulations and competition resulting from NCAP testing) and a reduction in pedestrian injuries from real-world crashes (Pastor et al., 2013; Strandroth et al., 2014).

To date, Euro NCAP has not introduced a car-frontal design test for TW (Euro NCAP, 2020). However, according to the study by Ohlin et al. (2017), cars that performed well in the Euro NCAP pedestrian test reduced injuries among bicyclists as well as pedestrians in the real world. Euro NCAP is now considering including assessments of cyclist head impact and enhanced leg impact to the current pedestrian subsystem tests (Euro NCAP 2018b).

Preventive safety assessment

Controlled physical testing for preventive safety systems, in the form of track tests with performance ratings, have been developed by consumer rating programs. For example, Euro NCAP introduced car-to-pedestrian test scenarios in 2016 and pedestrian-AEB and cyclist-AEB test scenarios in 2018 (Euro NCAP, 2018). Recently, it has been recommended that an assessment of AEB effectiveness for motorcyclist safety be included in Euro NCAP 2020. Similarly, C-NCAP started a pedestrian-AEB assessment in 2018 (C-NCAP, 2018), and recently (August 2020) presented a TW-AEB assessment test scenario set which will be implemented in 2021 (C-NCAP, 2020). This scenario set contains three car-to-TW test configurations: a total of fourteen test scenarios, with variations in travelling speed of the car and the TW, are included in the assessment. The first test configuration represents a car going straight impacting a TW going straight which is travelling perpendicularly from the near side (right in China) of the car. The second test configuration is a mirror-image of the first: the TW is travelling perpendicularly from the far side (left in China) of the car. The third test configuration represents a longitudinal, same-direction crash: a car going straight impacts a TW going straight from the rear. All of the scenarios are set in daytime without visual obstruction (C-NCAP, 2020).

The selection of appropriate test scenarios is a key part of preparing an optimal consumer rating program to assess a system’s performance in standardised track tests (Nilsson et al., 2018). Test scenarios should represent real-world situations as accurately as possible and cover a variety of crash scenarios (Wisch et al., 2013; Stoll et al., 2016). The ultimate aim is, after all, to steer car manufacturers towards the design choices that save more lives and reduce the number of injuries in real-world crashes.

One approach to choosing appropriate crash scenarios for test-track testing is to organise crash data into homogenous groups based on expert knowledge and define a limited number of test scenarios for the most frequently occurring groups. Several European projects (e.g. AsPeCSS, PROSPECT and CATS) have adopted this approach to develop test scenarios for VRU-AEB assessment, thus providing reference information for the protocol of Euro NCAP tests. In the AsPeCSS project, for example, the seven most frequent car-to-pedestrian crash scenarios were first identified by analysing European national data; in-depth crash data from Germany and Great Britain were further investigated (Wische et al., 2013). A set of test scenarios was then developed, based on the identified crash scenarios and relevant parameters from additional in-depth accident data. Car-to-bicyclist test scenarios were developed using a similar approach in PROSPECT (Stoll et al., 2016). In the CATS project, instead of identifying the most common crash scenarios at the national level, researchers identified the three most common car-to-bicyclist crash scenarios based on in-depth crash databases (Uittenbogaard et al., 2016a, b). Typical car-to-bicyclist test scenarios were then developed, incorporating the key aspects of these original scenarios. At the end of the project, a test matrix consisting of four car-to-bicyclist scenarios was proposed, which became the foundation for the bicyclist-AEB test protocol in Euro NCAP (Uittenbogaard et al., 2016a, b).

However, large traffic crash databases are generally heterogeneous (Yau, 2004; Depaire et al., 2008; de Ona et al., 2013; Sasidharan et al., 2015; Nitsche et al., 2017; Nilsson et al., 2018), as crashes are complicated events, with many types of interactions between different road users and the environment (Yau, 2004; de Ona et al., 2013; Sasidharan et al., 2015; Nilsson et al., 2018; Nitsche et al., 2017). One main problem with heterogeneous data is that hidden relationships between factors within the data might be overlooked when analysing factors contributing to the crashes (Yau, 2004; Depaire et al., 2008; Sasidharan et al., 2015). That is, factors having a large influence on the outcome of some accidents might not be significant when the data sample is taken as a whole (Sasidharan et al., 2015). Meanwhile, the effects of different injury-contributing factors on the whole data sample might be misleading, as they vary under different conditions (de Ona et al., 2013; Sasidharan et al., 2015). Another problem when analysing crash-contributing factors on a whole data sample is that the effect level of crash-contributing factors is usually different for different groups of crashes (de Ona et al., 2013; Sasidharan et al., 2015). For example, a factor which increases the injury risk in one group might decrease the injury risk in another (Sasidharan et al., 2015).

One way to reduce the data heterogeneity in traffic databases is to segment data into separate homogeneous groups (Depaire et al., 2008; de Ona et al., 2013; Sasidharan et al., 2015; Sander and Lubbe, 2018). Existing ways to segment traffic data are based on expert domain experience, methodological considerations, or the study aim, and may consist of narrowing down the analysis to a specific vehicle type or crash type (Depaire et al., 2008; de Ona et al., 2013; Sasidharan et al., 2015). However, expert domain experience is not at all sufficient to guarantee a reduction in data heterogeneity (Depaire et al., 2008; de Ona et al., 2013;), because even an expert might miss some factors.

Data-driven cluster analysis is another, complementary, way to reduce data heterogeneity: cases are classified into clusters so that the homogeneity within and between clusters is maximised (Hair et al., 1998; Depaire et al., 2008; de Ona et al., 2013). Clustering is a common data mining technique for segmenting traffic data (Kim and Yamashita, 2007; Anderson, 2009; Kumar and Toshniwal, 2016) or discovering patterns (like typical crash scenarios) in underlying data. In fact, many studies have shown the benefits of cluster analysis for identifying relevant properties of crash scenarios based on a statistical method (Depaire et al., 2008; de Ona et al., 2013; Prato et al., 2012; Theofilatos and Efthymiou 2012; Kaplan and Prato, 2013; Sasidharan et al., 2015; Weiss et al., 2016; Nitsche et al., 2017; Sander and Lubbe, 2018; Nilsson et al., 2018).

Recently, cluster analysis has also been used to identify test scenarios efficiently (Lenard et al., 2014; Nitsche et al., 2017; Sander and Lubbe, 2018; Nilsson et al., 2018) for test-track tests (such as in the NCAP). One concern when developing test scenarios is whether they accurately represent the study population. Relevant, valid test scenarios applied in test-track tests have been shown to reflect the performance of the safety system in real-world traffic. Cluster analysis has been helpful for obtaining relevant test scenarios in the large, complicated sets of real-world crashes (Lenard et al., 2014; Nitsche et al., 2014; Nilsson et al., 2018). For example, cluster analysis was applied to two large British databases, STATS19 and the in-depth On-the-Spot (OTS) (Lenard et al., 2014). The goal was to develop relevant test scenarios by describing the typical circumstances of car-to-pedestrian accidents (Lenard et al., 2014). Nitsche et al. (2017) identified the critical pre-crash scenarios at T and four-way junctions through cluster analysis. The identified test scenarios provided a basis for testing the safety of automated driving systems. Additionally, Nilsson et al. (2018) used cluster analysis of GIDAS data to develop nine test scenarios depicting typical run-off-road crashes in Germany.

2.2.4. Driving simulator studies

When a driving simulator is used for safety system assessment, participants are asked to interact with a simulator in a “natural” way (Chrysler et al., 2015; Kovaceva et al., 2020). Typically, the performance of the system is then quantified by comparing the outcomes of trials with and without the safety system. However, there are several limitations to this method: a) many performance metrics are not obviously connected to safety (Chrysler et al., 2015), b) it is difficult to generalise the performance of the system to real-world traffic (Lee et al., 2002), and c) the testing situations are usually highly controlled (Lubbe and Davidsson, 2015).

2.2.5. Virtual simulation

In virtual simulations, all components of a real traffic situation, such as road users, vehicles (including vehicle dynamics, sensors and the system under assessment), and the environment, are modelled in a computer. This method is regarded as an efficient way to shorten development time and save test resources when estimating the benefit of protective and preventive safety systems (Leglatin et al., 2006; Lindman et al., 2010; Rosén 2013; Sander and Lubbe, 2016; Saadé et al., 2019).

Protective safety assessment

Virtual simulations with finite element (FE) and multibody systems (MBS) play important roles in the design of protective safety systems and car structures (Schmitt et al., 2014). Some well-known analysis programs, such as LS-DYNA and Madymo, have been developed to model vehicles, dummies, airbags, and restraint systems (Leglatin et al., 2006). With these models, the risk of fatal or severe injuries for different collision speeds can be derived based on the injury criteria of different body parts, such as the Head Injury Criterion (HIC), an outcome of LS-DYNA (Schmitt et al., 2014). Safety benefits of protective safety systems can then be estimated, shortening development time and cost compared to non-virtual tests.

Preventive safety assessment

In general, two simulation approaches are available for preventive safety assessments, depending on the data used: counterfactual simulations (“what-if simulations”) using time-series data from real traffic crashes and counterfactual simulations using artificially created crashes.

In counterfactual simulations, pre-crash time-series data from real traffic is re-analysed (Page et al., 2015; Bärgman et al., 2017; Sander, 2017). The potential safety benefit of a preventive safety system can be estimated for each event by running simulations with and without the system (Kusano and Gabler, 2012; McLaughlin et al., 2008; Page et al., 2015; Scanlon et al., 2016).

These simulations typically reconstruct the pre-crash kinematics of the road users involved in the crashes (e.g., Lindman et al., 2010; Rosén 2013; Sander and Lubbe, 2016; Saadé et al., 2019; Chajmowicz et al., 2019) or the EDR pre-crash data (e.g., Kusano and Gabler 2011; 2012; Zhao et al., 2019). Crash reconstruction is often only done on a subset of the crashes available in crash databases. For example, the Pre-Crash Matrices (PCM) database includes crash reconstructions based on a subset of the GIDAS data (Erbsmehl, 2009). It uses vehicle and environmental data from GIDAS itself, along with digital sketches of each crash and reconstruction files created by the reconstruction software: PC-Crash simulation (Erbsmehl, 2009). That is, it provides time-series information about the pre-crash phase of each crash, including trajectories and speeds of the crash participants. The position, speed, and acceleration for each involved road user are typically available in 10 msec time-steps (Jeppsson et al., 2018).

Virtual assessment of preventive safety systems is typically counterfactual. That is, the system under assessment is applied virtually to assess "what-if" that particular system would have been present in the "original" crash. However, for counterfactual simulations that use artificially created data, , instead of using real-world crashes, a set of crash events is generated by: a) using crash and near-crash data after the removal of the drivers' evasive manoeuvres, which may be replaced by driver response models (Bärgman et al., 2015; 2017); b) creating crashes based on distributions of crash-contributing factors from real-world, everyday driving scenarios (Woodrooffe et al., 2013; Yanagisawa et al., 2017), or c) creating crashes by running massive amounts of traffic simulations to generate crashes (Kitajima et al., 2019).

Kitajima et al. (2019) implemented different levels of automated driving technologies in the simulations, and the differences in the number (and severity) of crashes with and without the systems were compared. Bärgman et al. (2015) applied counterfactual simulations on artificial scenarios generated from rear-end critical events (crashes and near-crashes) from the SHRP II naturalistic driving project. A model of driver glance behaviour was used to define the probability of crash occurrence and injury severity.

Counterfactual simulations of preventive safety systems usually involve simplified models of the real safety system, including sensors, logic, and actuation. When the system requires driver action (e.g., the driver reacts to an FCW warning), driver models may be needed. On the other hand, when the system is completely automated (e.g., the AEB brakes automatically), they are not needed.

Most studies using counterfactual simulations have been based on data from European countries or the USA. Currently, the benefit of preventive safety systems such as AEB and FCW in China is not being investigated much, especially for crashes involving VRUs. Hence there is a clear need to understand the performance of these systems using Chinese data.

3. Aim

The overall aim of this Ph.D. work is to enhance the protection of TW riders in China—first by contributing to the development of preventive safety systems such as TW-AEB, and, in the future, completing the Ph.D. by studying the benefits of protective safety systems together with the TW-AEB.

To achieve this aim, the specific objectives covered in this thesis are:

- Define a set of TW-AEB test scenarios in China to be used as references in the C-NCAP consumer safety rating program.

- Investigate whether cars which demonstrate good performance in the C-NCAP testing of TW-AEB, or good performance in the proposed alternative reference test scenarios, are likely to perform equally well in the real world.

- Estimate the characteristics of the car-to-TW crashes which would still remain if TW-AEB systems were available in cars in China.

The thesis also provides an overview of the safety systems available for improving TW rider safety and the assessment methods available for validating these systems' safety performance.

4. Summary of papers

Paper I

Sui, B., Lubbe, N., & Bärgman, J. (2019). A clustering approach to developing car-to-two-wheeler test scenarios for the assessment of Automated Emergency Braking in China using in-depth Chinese crash data. *Accident Analysis and Prevention*, 132, 105242. https://doi.org/10.1016/j.aap.2019.07.018

Author's contribution: Main writer, performed most of the analyses, produced the figures and tables

Paper II

Sui, B., Lubbe, N., & Bärgman, J. (2020). Evaluating automated emergency braking performance in simulated car-to-two-wheeler crashes in China: A comparison between C-NCAP tests and in-depth crash data (submitted to Accident Analysis and Prevention)

Author's contribution: Main writer, ran the simulations and performed all the analysis, produced the figures and tables

Paper I: A clustering approach to developing car-to-two-wheeler test scenarios for the assessment of Automated Emergency Braking in China using in-depth Chinese crash data

Introduction: The number of TWs worldwide has been increasing rapidly in recent decades, creating crucial safety problems for TW riders, especially in developing countries like China. One safety system with the potential to improve the safety of TW riders is TW-AEB.

Aim: The aim of this study is to contribute to the development of TW-AEB testing in C-NCAP by describing typical car-to-TW crash scenarios in China.

Method: CIDAS data from 2011 to 2016 were used to develop car-to-TW test scenarios using cluster analysis. In total, 672 car-to-TW crashes were extracted. Accident scenarios were derived based on k-medoid clustering of five main crash characteristics. Furthermore, test scenarios were developed from descriptive frequency analysis of information on the road speed limit, the first contact points between the TW and the car for each test scenario.

Results: Six car-to-TW crash scenarios typical of China were defined in this paper.

Discussion: Two of the scenarios were similar to those in Euro NCAP: in one, a TW moving straight ahead is hit by a car moving perpendicularly, and in another, the car hits a TW travelling in the same direction. However, the other scenarios defined in this paper include night-time scenarios and those in which the car or the TW is turning, which are not included in Euro NCAP. As a result, preventive safety systems (e.g. TW-AEB) designed to be rated highly by Euro NCAP might not do well in a rating program based on the scenarios defined, based on Chinese data, in this paper.

Conclusion: The scenarios obtained via cluster analysis depict the characteristics of six typical car-to-TW crashes in China. The scenarios can be used both to create safety system crash tests in consumer assessment programs and to assess a potential safety system’s ability to improve the traffic safety of TW riders.

Paper II: Evaluating automated emergency braking performance in simulated car-to-two-wheeler crashes in China: A comparison between C-NCAP tests and in-depth crash data

Introduction: Preventive safety systems such as AEB are effective at improving road safety. NCAPs, such as C-NCAP, have been striving to quantify AEB performance via test-track tests. One challenge with these tests is to predict whether the system's NCAP test performance represents the system's real-world performance.

Aim: The aim of the study is to assess whether the TW-AEB performance as rated in C-NCAP is likely to predict its real-world performance in terms of the crash avoidance rate and the characteristics of the remaining crashes.

Method: Counterfactual virtual simulations were applied to three car-to-TW pre-crash datasets: the C-NCAP scenario set to be introduced in 2021 (containing 14 cases), an alternative scenario set based on the results of Paper I (containing 151 cases), and reconstructed car-to-TW crashes from the SHUFO dataset (containing 113 crashes). The simulation results, comprising avoidance rate, impact speed after AEB application, and crash characteristics of the remaining crashes, were compared among these three datasets.

Results: With the same AEB system parameter settings, substantially more crashes were avoided in the C-NCAP scenario set than in the other two. In fact, with a FoV of 70°, an activation time of 1.1 s, and a braking deceleration of 8.82 m/s^2, all crashes in the C-NCAP scenario set were avoided; however, only 46% of the crashes in the alternative and 36% in the SHUFO crash set were avoided. The C-NCAP set also resulted in lower impact speeds for the remaining crashes than other two sets.

Discussion: Our results indicate that TW-AEB systems rated highly by C-NCAP might not perform correspondingly well on Chinese roads. The alternative scenario set (proposed in Paper I) produced results similar to those of the SHUFO crash set, indicating that the former accurately reflects real-world crashes in China.

Conclusion: The C-NCAP scenario set cannot cover all car-to-TW crashes in China; instead it should provide a set of representative scenarios. The current C-NCAP scenario set, to be implemented 2021, is not quite doing this—although it is a step in the right direction. Based on our results, we recommend the inclusion of two longitudinal same-direction scenarios (with either the car or TW turning) and perpendicular scenarios with the TW travelling at high speed in future C-NCAP releases to better represent real-world car-to-TW crashes in China.

5. Discussion

TW riders' safety in traffic is a major issue worldwide—especially in China, one of the largest markets for TWs. The development of safety systems that are suitable for the country/region where they are implemented is very important. This thesis addresses the initial steps toward improving TW traffic safety in China. First, it describes current car-to-TW crash characteristics by identifying car-to-TW crash scenarios typical of China. Second, it evaluates the benefit of the TW-AEB using real-world data. Third and finally, it characterises the remaining car-to-TW crashes to understand what protective safety systems can help save more TW riders' lives in China.

This chapter first explains why all types of TWs in China were combined into one group, instead of analysing each separately. The available crash data and the methods used to understand the TW traffic situation in China are then discussed. After that, the advantages and limitations of different available safety systems that may improve TW traffic safety are reviewed, particularly with respect to their application in China. In addition to selecting the safety system (TW-AEB), methods for assessing the benefit of the TW-AEB which are important to its design and development are explained further. The differences between car crashes with TWs in China and other countries are considered, along with their impact on the safety system design. Furthermore, the interactions between TWs and automated vehicles in the future are briefly discussed. The chapter concludes with a brief examination of the implications of my research for sustainable development, together with the future direction of this research.

5.1. Why analyse different two-wheeler types as one group?

In this thesis, different types of TWs, including traditional pedal bicycles, electric engine PTWs, and combustion engine PTWs, were grouped together for the assessment of TW riders' safety in China. In contrast, studies performed on data from North America and Europe typically separate the different types of TW. For example, Dozza and Piccinini (2014) analysed naturalistic cycling data from Sweden to examine the behaviour of traditional bicycle and electric engine PTW riders and found different exposures toward certain potential risk factors (e.g., intersections). Furthermore, in a later study, Dozza et al. (2016) analysed the differences in driving behaviour between users of electric engine PTWs and bicycles, based on the critical events (crashes and near-crashes) collected in an NDD; they recommended different safety systems for electric engine PTWs and bicycles. Other studies, such as those investigating the effectiveness of ABS on motorcycles (Rizzi et al. 2009, 2015, 2016; Teoh 2010), have grouped combustion engine PTWs separately. However, the primary reason for that no separation was made in Papers I and II was that the number of cases available in the bicycle group (in Paper I) was limited. In the total sample of TWs (n=672) in Paper I, only 69 (10%) were bicycles. Another reason is that no large differences were found in the distributions of the combination matrix of the key parameters (the relative moving direction between the car and the TW before the crash, the pre-crash driving behaviour of the car driver, and the pre-crash driving behaviour of TW rider) used to identify the typical car-to-TW scenarios in Paper I. Furthermore, in Paper I the biggest difference between the different types of TWs for the AEB assessment was found to be the travelling speed. Therefore, instead of specifying a specific speed in Paper I, a range of TW travelling speeds was provided for the test scenarios (covering the travelling speeds of the different TW types). These scenarios were then used in Paper II. In this way, we can provide a practical set of car-to-TW AEB test scenarios for C-NCAP across different TW types. A study by Wu et al. (2018) based on real-world crash data in China supports this merging approach, since they detected no significant differences in crash scenarios, injury severity, or impact location distributions across different types of TWs.

In summary, due to the low number of initial samples and similar speed distributions for each type of TW, we grouped the different types of TWs together in this thesis.

5.2. How can we understand the traffic situation of TWs in China better?

To improve road safety, a comprehensive understanding of traffic situations is important, so that safety systems can be developed with maximum performance in the real world. Traffic and road safety are complicated, involving interactions of risk factors, different road users and the environment; it is intuitively reasonable that traffic situations, and traffic conflicts, vary between countries, or even between areas within a country. To understand local traffic situations, representative and reliable real-world data are important (Isaksson-Hellman and Norin, 2005; Tivesten, 2014). Moreover, since crash occurrences are rare events, obtaining unbiased and relatively accurate information about crashes is costly—but necessary, in order to develop good safety systems (Isaksson-Hellman and Norin, 2005).

Several sources of real-world data are available for understanding the TW traffic situation in China. One is police-reported data, which is usually considered to be representative of national crash data. However, due to the underreporting issue in police-reported data (Hu et al., 2011; Huang et al., 2015; Huang et al., 2017), data collected by police may not reflect a genuine picture of the real-world traffic.

Since no real-world crash data that are representative and accurate on a macroscopic level can be currently obtained in China, microscopic real-world crash data was used in Papers I and II. One of the most detailed and representative crash databases in China, CIDAS, was used in Paper I to understand the typical car-to-TW crash scenarios in China. One reason for its selection was that it covers different types of geographical areas, such as plains, mountains, and coastlines (Chen and Dai, 2018). CIDAS consequently includes a variety of crashes, on urban and rural roads—as well as highways. Furthermore, CIDAS contains a wide range of detailed information about injuries, vehicle damage, and road and weather conditions, as well as to-scale accident sketches which illustrate the vehicle trajectories in both the pre-crash and post-crash phases. In Paper I, to understand the pre-crash driving behaviour of the car and TW, a case-by-case analysis was performed, using the variable UTYP (crash type, see CIDAS codebook, 2016) in CIDAS, driver interviews, and accident sketches. There are other crash databases available in China, including VRU-TRAVi (VRU TRaffic Accident database with Video; Han et al., 2018). In fact, Pan et al. (2020) used it to investigate the most common car-to-PTW crash scenarios in China. However, one limitation of this database is that only crash data from crashes with site-based video were collected. Since cameras in China are more likely to be positioned to monitor intersection traffic, the data in the Pan et al. study is biased towards intersection crashes. Another Chinese in-depth crash database is the National Automobile Accident In-depth Investigation System (NAIS). Cao et al. (2019) extracted car-to-TW crashes in China from NAIS. Like other databases, NAIS provides detailed crash characteristic information. However, it is more biased towards severe and fatal crashes than CIDAS, as the inclusion criteria are crashes with one or more fatality or an involved person injury of MAIS (Maximum Abbreviated Injury Scale, AAAM, 1985) level greater than equal to three (Cao et al., 2019).

In addition to the in-depth crash data, which can provide detailed crash information (as described in Sections 2.1.2 and 2.1.3), EDR and NDD can provide detailed information about the pre-crash phase—and maybe even about the post-crash phase. However, few cars in China have been equipped with EDR in a way that would allow data collection for research purposes. As for NDD, one inherent limitation is the rare occurrence of crashes in daily driving. There are no publicly available NDD in China that include a substantial amount of crashes.

Given the characteristics of the various databases, CIDAS was considered the most suitable for this research on TW crashes in China. Although CIDAS has the advantage of being the largest crash database in China and it covers a wide range of geographical areas, it, too, has some limitations.

One limitation is that CIDAS is biased towards severe crashes (albeit less so than NAIS), even though its inclusion criteria include crashes at all injury levels. I would argue that the reason for this bias is that for some minor crashes, without severe damage to the vehicle, the crash scene is not preserved for the investigation team. This is perhaps a characteristic unique to China. It is actually recommended by the traffic police that vehicles be moved away from the crash scene without waiting for a detailed investigation when the accident is minor, to reduce traffic congestion.

Another limitation of CIDAS is that no pre-crash kinematic database (such as the PCM in GIDAS) is available at present, so it is not possible to perform an assessment of the benefit of a preventive safety system through virtual simulation based on CIDAS. Further, the lack of a pre-crash database means that the travelling and impact speeds of the car and the TW are not directly available. As a result, in Paper I the road speed limit was used to indicate the car travelling speed and a range of TW speeds was noted—allowing our recommendations for C-NCAP test scenarios to apply to a variety of TW types.

In Paper II, to estimate the performance of AEB in the real world, the SHUFO database was used, which provides pre-crash reconstruction files from which a pre-crash database can be created. However, SHUFO is also (even more than CIDAS) biased towards severe crashes, because of the inclusion criteria. Another limitation of SHUFO is the small number of geographical areas covered, limiting its generalisability for China as a whole. Unfortunately, neither CIDAS nor SHUFO include any weighting factors to enable generalising to country-level impacts (Ding et al., 2016).

In summary, while CIDAS and SHUFO databases are limited, they provide the most detailed data available today for car-to-TW crash scenarios in China; they are able to offer a promising base for safety systems development.

5.3. How do we create representative car-to-TW test scenarios for consumer rating programs like C-NCAP?

In order to derive typical car-to-TW crash scenarios for specific preventive safety systems to address, reliable and correct data are not enough. Specific analysis techniques are needed to reduce the data's heterogeneity, a requirement that is often overlooked in traffic data analysis (Depaire et al., 2008; de Ona et al., 2013; Sasidharan et al., 2015; Nilsson et al., 2018).

The most common crash scenarios targeted in assessment programs are first derived from a descriptive frequency analysis of defined traffic conflicts based on real world crash data (Wische et al., 2013; Stoll et al., 2016; Uittenbogaard et al., 2016 a, b; Char and Serre, 2020). Test scenarios are then typically developed by complementing the derived crash scenarios with detailed pre-crash information, such as vehicle travelling speed, road layout and environment information. This approach has been used in the European projects AsPeCSS (Wisch et al., 2013), PROSPECT (Stoll et al., 2016), and CATS (Uittenbogaard et al., 2016 a, b). See Table 1 for an overview of the methods and variables used in different studies for the development of car-to-TW test scenarios.

One limitation of descriptive frequency analysis is that when it is used alone to segment the complicated traffic data, important information may be missed—due to data heterogeneity and hidden structures or patterns in the data (de Ona et al., 2013; Nilsson et al., 2018). As a result, incorrect conclusions may be drawn.

Cluster analysis address this issue to some extent, as it provides an efficient way to reduce data heterogeneity as much as possible and uncover hidden patterns in the data. In Paper I, cluster analysis was applied to obtain the typical car-to-TW crash scenarios in China. Six test scenarios were identified, including turning scenarios, scenarios with visual obstruction and night-time scenarios. Notably, a previous study of the most common car-to-TW crash scenarios in China applied frequency descriptive analysis to the same crash database (CIDAS); scenarios with visual obstruction were not identified as typical due to the low crash frequency. Another advantage of using cluster analysis is that it is an exploratory, data-driven method. Defining test scenarios calls for fewer subjective assumptions to be made about the structures of the data than in a description frequency approach. For example, for a descriptive frequency analysis, the number of typical crash scenarios needs to be selected subjectively by the researchers without quality metrics to refer to in the selection. In contrast, for cluster analysis, metrics such as the average silhouette width (ASW; Rousseeuw, 1987) and Bayesian information criterion (BIC; Cochran, 1952), which are further explained in the next paragraph, are applied to identify the optimum number of clusters.

Table 1.a.

Methods and variables used in different studies for crash scenario identification.

Study list	CATS	AsPeCSS	PROSPECT	Paper I
Data type	EU level crash data	EU level crash data	EU level crash data	In-depth crash data
Injury level	Killed and severely injured cyclist	All	All	All collected by CIDAS
Method	Descriptive frequency analysis	Descriptive frequency analysis	Descriptive frequency analysis	Cluster analysis
Orientation between car and object	✓	✓	✓	✓
Driving manoeuvre of car	✓	✓	✗	✓
Driving manoeuvre of TW	✓	✓	✗	✓
Light condition	✗	✓	✗	✓
Vision obstruction	✓	✓	✓	✓

Table 1. b

Methods and variables used in different studies for test scenario development (for NCAP tests) based on crash scenarios.

Study list	CATS	AsPeCSS	PROSPECT	Paper I
Data type	In-depth crash data	In-depth crash data	In-depth crash data	In-depth crash data
Injury level	Killed and severely injured cyclist	Killed and severely injured cyclist	Killed and severely injured cyclist	All collected by CIDAS
Method	Descriptive frequency analysis	Descriptive frequency analysis	Descriptive frequency analysis	Descriptive frequency analysis
Driving manoeuvre of car	-	-	✓	-
Driving manoeuvre of TW	-	-	✓	-
Weather and light condition	✓	✓	✓	-
Vision obstruction	✓	✓	✓	-
Road layout	✓	✓	✓	✗
Car & TW travelling speed	✓	✓	✓	✓
Collision point	✓	✓	✓	✓

While clustering is an established method that may be superior to descriptive frequency analysis, several aspects need to be considered in order to obtain optimal results. First, an appropriate clustering algorithm must be selected among many (such as K-mean, K-modes and Portioning Around Medoid: PAM), depending on the type of data to be analysed and the study aim (Nitsch et al., 2017; Sander and Lubbe, 2018). For example, in Paper I the data were categorical, so K-means, which deals only with numerical data, was not applicable. Further, PAM was more stable than the K-modes algorithm. Second, the variables used to develop test scenarios for cluster analysis need to be chosen carefully (Nilsson et al., 2018), usually after a literature review of relevant studies. In Paper I, five variables which were considered important for developing the TW-AEB test scenarios were identified beforehand: time of crash, existence of vision obstruction, pre-crash driving behaviour of the car, pre-crash driving behaviour of the TW and relative moving direction of the car and the TW before the crash. The time of crash and the existence of vision obstruction were added because the pedestrian-AEB test scenarios in Euro NCAP include night-time and visual obstruction testing scenarios (Euro NCAP 2018). In turn, Euro NCAP included these because higher-severity injuries have been identified in crashes occurring in darkness (Rosén, 2013; Chen et al., 2014; MacAlister, and Zuby, 2015; Uittenbogaard et al., 2016a). Third, the number of clusters needs to be defined subjectively (Kaufman and Rousseeuw, 2005). However, some objective assessment measures, such as ASW and BIC, are now available to guide the choice of the optimal number of clusters. Generally, the higher the values of ASW and BIC, the better the performance of the cluster analysis (Rousseeuw, 1987). In Paper I, ASW was used as an indication for the number of clusters. The number of clusters, six, was not optimal, as the value of ASW was 0.41, which indicated that a weak structure was found from cluster analysis. Higher values of ASW (0.61) could be found with a higher number of clusters (n=9). However, more clusters meant that some clusters had unreasonably small sample sizes, so a relatively low ASW value was accepted, instead of choosing a higher number of clusters with a higher ASW value.

In summary, cluster analysis, unlike descriptive frequency analysis, provides a way of defining typical crash scenarios that considers hidden structures or patterns in the data. Test scenarios derived from cluster analysis can support the development of effective countermeasures and provide a better understanding of real-world traffic situations.

5.4. How can we improve the safety of TW riders in traffic in China?

To address the critical safety issues of TWs, a variety of safety systems have been developed by car manufactures and automotive suppliers. As stated in Section 1.2, these safety systems include both protective safety systems (e.g., active pop-up hood and windshield airbags, inflatable jackets and TW airbags), and preventive safety systems (e.g., car-based FCW and AEB and TW-based ABS and AEB). Previously, many studies focussed on protective safety systems development, aiming to mitigate injury severity during the crash (Pastor, 2013; Ames and Martin, 2015; Shi et al., 2019). In the last few decades, to further improve road safety, car manufactures have shifted their efforts to advanced preventive safety systems aimed at avoiding the crash during the pre-crash phase, or mitigating injuries by, for example, braking (Coelingh et al., 2010; Kovaceva et al., 2020).

Car-based AEB has been regarded as the advanced preventive safety system with the most potential for avoiding crashes and mitigating injuries. This system reduces impact speed by applying braking automatically, removing the effect of any possible driver reaction limitations and distractions while optimising braking performance. Similarly, FCW can also reduce impact speed. However, unlike AEB, FCW relies on driver input since it only warns the driver of the imminent critical event. Consequently, the effectiveness of FCW depends on the drivers' reaction to the warning—and drivers' reactions to a signal can vary substantially depending on several factors, such as the driving environment and the driver's status (Warshawsky-Livne and Shinar, 2002). Late or wrong driver reactions, such as accelerating instead of braking, will actually increase the crash and injury risk for all involved. Hence, the application of FCW in the real world has many limitations. Another preventive safety system, ABS, has been proved to improve motorcycle braking stability and increases braking deceleration (Roll et al., 2009). So far, the system is almost exclusively available for motorcycles with high travelling speeds (Rizzi et al., 2009; Roll et al., 2009; Giovannini et al., 2013); it is rarely used in bicycles and electric engine PTWs. Furthermore, considering the cost of the AEB system, car-based AEB is more likely to be applicable to China in the near future than TW-based AEB.

Instead of applying only braking, theoretically, steering could help improve the AEB's performance, by providing another avoidance mechanism (Chajmowicz et al., 2019; Seacrist et al., 2020), especially when the car is travelling at high speed. With respect to manual driving, a study by Seacrist et al. (2020) showed that few drivers avoid crashes by steering. Furthermore, steering away to avoid a crash might lead to another critical situation with other road users (Sander, 2018; Robinson, 2020).

Automated emergency acceleration is another option with the potential to avoid a crash under specific circumstances (Sander, 2018). However, this possibility was not investigated in Paper II, since situations where steering would be efficient are rare and, using acceleration as an avoidance manoeuvre is controversial: accelerating a vehicle in a critical situation increases the kinetic energy, potentially making the situation even riskier.

Although car-based TW-AEB has shown great potential for improving TW traffic safety, one cannot expect it alone to solve all traffic problems: for one thing, although braking force is the most influential factor of AEB performance (Chajmowicz et al., 2019), only so much force can be exerted before the friction coefficient between the car tyre and road is exceeded. This limitation is one reason that, in Paper II, the maximum deceleration force was set to 8.82 m/s^2 (rather than the maximum possible under dry road conditions). One approach to increase the deceleration to above 9.8 m/s^2 is to use the Vacuum Emergency Brake (VEB), which can provide extra braking deceleration (Jeppsson et al., 2018; Jeppsson and Lubbe, 2020).

Furthermore, as the results from Paper II show, even though the car was equipped with an “ideal” AEB with perfect object detection and efficient braking, some crashes and injuries could not be avoided. This result demonstrates the limits of preventive safety systems for TW riders; it is necessary to provide them with protective safety systems as well. Safety countermeasures for TW riders, such as helmets and the active pop-up hood and windshield airbags are examples of systems that can help keep TW riders alive (Rizzi et al., 2011; Ohlin et al., 2017). Maximising TW traffic safety involves employing all effective systems, not just the single most beneficial one.

In summary, preventive safety systems, for example the TW-AEB, have been proven as an effective measure to save more lives by preventing the crash from happening and reducing injuries. However, depending on the specific scenarios and the complexities of traffic in the real world, preventive safety systems alone cannot eliminate road fatalities and severe injuries completely. Protective safety systems are still needed to reduce the number of TW death and suffering from traffic crashes.

5.5. How do we assess TW-AEB performance?

Assessing the performance of safety systems is essential for system development. As stated in Section 2, many stakeholders in the car industry can learn how effective a system is from the assessment. This information can then be the basis for further performance improvements. The ideal way to assess a safety system's performance is by comparing the crashes and injuries from real-world crashes with and without the safety system (i.e., studying events that actually happened), using the difference to quantify the system's performance. However, this retrospective method is not possible when the system has low market penetration (perhaps because the system has not been available for long, as is the case for TW-AEB) or when the system is not even yet available on the market.

There are several methods for assessing the benefit of preventive safety systems prospectively, before enough data is available to do a retrospective assessment. Such methods include in-depth case-by-case studies of manual "counterfactual" assessments, as in the work by Strandroth et al. (2012), who evaluated the future impact of vehicle safety technology in Sweden. Another example is "high-level filtering" of in-depth crash databases for factors that the safety system targets. Using this method, Lubbe et al. (2018) predicted future road traffic fatalities in Germany, assessing a variety of safety systems. Although these methods have their place, in this thesis the focus is on two other prospective methods: consumer rating (NCAPs) for safety assessment (Paper II; Euro NCAP, 2020; C-NCAP, 2018), and virtual safety assessment through counterfactual (what-if) simulations (Paper II; Lindman et al., 2010; Rosén 2013; Sander and Lubbe, 2016; Bärgman et al., 2017; Jeppsson et al., 2018; Zhao et al., 2019).

The Euro NCAP and C-NCAP programs assess the performance of new safety systems, with the goal of promoting the development of safer cars by the automotive industry (C-NCAP, 2018; Euro NCAP, 2020). To assess the performance of TW-AEB in particular, C-NCAP has included three test configurations, comprising 14 tests, which will be implemented in 2021 (C-NCAP, 2020). The tests are carried out in a test-track environment mimicking the real world, ensuring high physical fidelity in terms of the reproducibility of real-world situations (Boda, 2019). In fact, several studies have demonstrated that NCAPs are correlated with real-world traffic safety, indicating that they can be used for reliable assessment of safety system performance (Lie and Tingvall, 2000; Pastor, 2013; Strandroth et al., 2014). However, to the author's knowledge, no studies have been undertaken yet correlating NCAPs with real-world crashes to examine the impact of NCAPs on preventive safety systems like AEB. It is obvious that a preventive safety system which performs well in NCAP testing might not perform equally well in the real world, due to the limited number of tests scenarios available in NCAPs testing. Further, although not relevant for AEB assessment, one important factor in real-world performance of many preventive safety systems is driver behaviour, which is not taken into consideration in NCAP testing (Boda, 2019); or, at least, the variability of driver behaviour is not taken into account. There are, however, specified driver responses in some NCAP tests. For example, in Euro NCAP (2020) and C-NCAP (2018), a robot replicating a specific driver response is used for repeatability in the performance assessment of FCW. However, current NCAP processes do not actually evaluate the effect of the interaction between the safety systems and the driver. A further limitation of NCAP tests is that they are only available when the systems are already in production (or very close to being so). This means that the testing (which is expensive, as it includes physical tests) used when developing/ improving the functionality of systems that the NCAP targets is rarely used to develop new functionality. Consequently, less expensive testing methods are needed to assess systems for which NCAP tests are not yet available.

Virtual simulations can efficiently evaluate preventive safety systems benefit, performing a relatively large number of assessments in a short time. A computer and the relevant software suffice to run a large number of simulations at low cost; no test tracks or real vehicles are needed. Further, it is easy to vary parameter values, so sensitivity studies of main system parameters can be performed quickly, as was done in Paper II and in a range of other studies (Rosén, 2013; Edwards et al., 2015; Bärgman et al., 2015, 2017; Jeppsson et al., 2018; Cao et al., 2019; Jeppsson and Lubbe; 2020). Therefore, virtual simulations can quickly indicate both the safety performance of specific system designs and the potential impact on safety that the systems may have when brought to market. Another advantage of virtual simulations is that they can be used throughout the whole process of system development for a wide range of products other than NCAP tests. That is, unlike NCAPs, if all the components in the simulation are sufficiently good (validated), virtual simulations can assess the potential safety benefit of systems not yet on the market.

To be sure, virtual simulations for safety benefit assessment are not without their limitations. First, the simulations can only be as valid as their mathematical models (of the safety system, the driver, the vehicle and/or the environment). In contrast, NCAP testing uses—in addition to the actual safety system—real vehicles in a physical environment. Hence, model validation is an important part of preparing a simulation. Although the current research focusses on AEB, which does not require driver action, a simplified driver model was applied in Paper II as part of the AEB algorithms. However, detailed models of driver behaviour have been incorporated into virtual simulations to assess systems that include driver actions (Bi et al., 2014; Markkula, 2014; Bärgman et al., 2017; McDonald et al., 2019), as well as to assess driver behaviours, such as those associated with the introduction of new human-machine interfaces (Lee et al., 2002; Bärgman and Victor, 2019). In fact, all components in virtual simulations must be chosen carefully, due to the impact the choice may have. Another limitation of virtual simulations is that they require detailed time-series data of the pre-crash kinematics (Jeppsson et al., 2018; Sander, 2018), which are not often directly available in crash databases. Moreover, when the data are available, they are typically created from crash reconstructions and usually involve subjective assumptions about the pre-crash kinematic information.

As for the system implementations, Paper II used simple models of the vehicle and the TW and, as previously stated, the driver (thus including the potential for braking and steering avoidance manoeuvres). Further, it was assumed that sensors and brake activation functioned ideally in the AEB algorithm, and that the TW-AEB detected TWs perfectly under all weather and lighting conditions. Also, no interactions between the car driver and the TW-AEB or any potential following rear-end crashes caused by sudden braking of the car were considered. These assumptions may have led to an overestimate of the TW-AEB's performance.

Many researchers have adopted the virtual approach for AEB performance assessment (Lindman et al., 2010; Rosén et al. 2010; Rosén 2013; Sander and Lubbe, 2016; Bärgman et al., 2017; Jeppsson et al., 2018; Zhao et al., 2019; Char and Serre, 2020). However, none of them have yet considered using it to compare the safety performance of NCAP test-track tests with real-world data; Paper II was designed to fill this knowledge gap.

The approach applied in Paper II provided an efficient way to evaluate the validity of NCAP tests in the real world. Usually it takes a long time to know if the safety system tested has the same effect in the real world (and, for example, to study the correlation between these results and NCAP testing procedures). However, this process can be shortened by performing virtual simulations using real-world crash data and the NCAP test-track test results to evaluate the system's performance before the actual system is on the market. Hence, virtual simulations can be a first (but only a first) step toward validating NCAP test scenarios. Virtual simulations can also be used for the future development and refinement of test scenarios. That is, this virtual cross-validation approach offers opportunities for NCAPs to update their testing programs. Car manufacturers and suppliers can also benefit from the approach's speed and economy throughout the development process (Page et al., 2015; Bärgman et al., 2015; 2017; Sander, 2017). Through key parameter sensitivity analysis, virtual simulations can tune safety system designs more easily than test-track tests (Rosén, 2013; Edwards et al., 2015; Bärgman et al., 2015; Bärgman et al., 2017; Jeppsson et al., 2018; Cao et al., 2019; Zhao et al., 2019).

In summary, virtual simulations can inexpensively and effectively assess the performance of TW-AEB in real world traffic and they can also be used as the first step in the validation of test-track tests (e.g., NCAP).

5.6. Differences in car-to-TW crash characteristics between China and other countries, and the implications for safety system development.

The design and development of safety systems should be based on an analysis of real-world crash characteristics from the area where the system aims to be deployed. Clearly, crashes in different regions may have different characteristics, leading to different system designs (Chen et al., 2014). Car-to-TW crash characteristics in China are quite different from those in other countries (Paper I; Rodon et al., 2013; Chen et al., 2014; Sui et al., 2017); thus, designing and developing safety systems specifically for the Chinese market, using Chinese real-world crash characteristics, is important.

One difference in car-to-TW crash characteristics between China and European countries is the TW travelling speeds. As stated in Section 1.1.1, the majority of the electric engine TWs in China are scooter-style, which can travel at higher speeds than the bicycle-style TWs common in European countries. Hence, in Paper II, the maximum TW travelling speed for the proposed test scenarios in C-NCAP was set to 45 km/h. Furthermore, combustion engine PTWs, a common mode of transportation in China, accelerate faster and achieve higher travelling speeds than other TWs. The higher the TWs' travelling speed, the shorter time the AEB system has to detect it, identify the imminent crash, take action and brake. Further optimisation of AEB systems for higher TW-speed crash scenarios would likely improve TW traffic safety in China substantially.

Another main issue threatening TW traffic safety in China is TWs' low conspicuity in traffic at night. Paper I indicates that night-time crashes are common in China: two night-time car-TW test scenarios are, in Paper I, recommended for the C-NCAP rating programs. Furthermore, Sui et al. (2017) found that 33% of car-to-TW accidents happen at night, based on CIDAS data. Similar findings, but with somewhat lower night-time crash rates, were observed in the European project CATS; 10%–25% of crashes with serious injuries and 25%–35% of fatal crashes occurred in low-light conditions (at dusk/dawn or at night; Op den Camp et al., 2017). Moreover, a study by AAA (2019) based on the evaluations of pedestrian detection systems found that AEB was relatively ineffective in low-light environments. These findings indicate that improving sensors' effectiveness in night-time conditions would probably substantially enhance the functionality of currently available AEB systems.

In addition to night-time crashes, the six scenarios proposed in Paper I include two scenarios with the car turning and one scenario with the TW turning, indicating the prevalence of turning scenarios in real-world traffic crashes in China. These scenarios require AEB systems to have a wider field of view and more complex algorithm to accurately identify the TW and predict an impact (Paper II). Nonetheless, even with an idealised AEB (360 degrees sensor FoV and no braking time delay), when the TW appears or changes direction suddenly, some collisions are simply unavoidable.

In summary, due to the different traffic situations between China and other countries, the development of TW-AEBs for China should be focussed on improving the sensors' detection capabilities (e.g., wider FoV and better night-time performance) and the decision algorithms (e.g., handling the higher speeds and wider FoV).

5.7. How will TW riders affect automated driving, and how will automated vehicles behave?

Because China is one of the largest potential markets for automated vehicles, the government has been investigating their development (Herskind et al., 2019). China has set a goal of achieving the mass production of intelligent vehicles with conditional self-driving capabilities by 2025 (National Development and Reform Commission, 2020). One critical issue with autonomous driving is that vehicles have to be able to deal with any sudden dangerous situation independently, a difficult challenge on Chinese roads where the traffic situation is quite complex. TWs are often involved in crashes on shared roadways where the riders engage in risky behaviours, including running red lights, excessive speeding, travelling in the opposite lane, illegal lane changing, and aggressive swerving (Wang et al., 2012; Wu et al., 2012; Bai et al., 2013; Guo et al., 2015; Guo et al., 2019). These risky manoeuvres lead to frequent near-miss events, increasing the challenges of automated vehicle development in China. As the TW-AEB is very likely to be an integral part of future automated vehicles, it is important to understand the typical car crashes with TWs (Paper I) and the potential benefit of TW-AEB in China (Paper II). TW-AEB algorithm design and development for Chinese traffic conditions will likely have substantial effect on the safety performance of automated vehicles of the future. Optimising automated vehicles' decision algorithms for Chinese traffic conditions is likely to require substantial effort due to the complicated real-world traffic situation in China. In addition to the issues/concerns above, developers will need to collect and input local traffic data to resolve the problem of unique and inconsistent road signage, for example. They will have to optimise motion planning through on-road testing, so the algorithms can deal with the risky driving behaviour of TW riders (Pizzuto et al., 2019). However, the overall technological solutions for autonomous driving in China will not differ much from those in other nations. Western cities, from downtown New York to Rome, have similarly dense populations and levels of mixed traffic (Pizzuto et al., 2019), although the specific conflict scenarios may vary, especially with respect to car-to-TW interactions.

In summary, given China's complex traffic environment, automated vehicles must adapt to local road conditions and the aggressive driving behaviours of TW riders, which could slow the adoption of automated vehicles in China. However, in the long run, with the advance of technology and a better understanding of local traffic situations, automated vehicles will likely succeed in working well with TW riders and other road users in China, even if it turns out to be a substantially more challenging task than, for example, in Sweden.

5.8. Sustainability development

Road transport is an essential, convenient way to carry people and goods from one place to another (UN, 2017). However, the cost of road transport is high, with severe health and socioeconomic consequences due to road traffic crashes. Safe, affordable, accessible, and sustainable transport systems for all road users are the key to the sustainable development of good health and well-being (UN, 2017). To improve road traffic safety worldwide, the UN has adopted some fatality reduction targets, like halving global deaths and injuries from road traffic crashes by 2020 (WHO, 2020). My research directly supports sustainable development through the vision of saving more lives globally.

First, my research is focussed on traffic safety improvement in China. While sustained political commitment and innovative strategies and technologies have been successfully applied in some developed countries, rates of road traffic injuries and deaths are still high in developing countries (WHO, 2020). As the country with the largest population in the world, China is particularly vulnerable to the impact of road traffic injuries (Huang et al., 2016). Hence, concerted efforts to improve road traffic safety in China can contribute to achieving sustainable development.

Second, the sustainable development aspect of my research targets TW riders' safety (in China). Traffic safety has been improving substantially during the past few years. However, traffic safety for VRUs has not improved at the same pace as for the occupants of cars. Measures to improve the traffic safety of TW riders can have a substantial impact on the sustainable development (saved lives) of road transport worldwide. That is, as TW riders are among the most vulnerable of road users (Haworth 2012), efforts to prevent TW crashes can produce substantial benefits (Yanagisawa et al., 2017). In my research, a benefit assessment of the AEB system was undertaken. One cannot expect that all crashes and injuries will be eliminated by these systems, as shown in the results of Paper II—at least in the short term. More advanced protective safety systems, working together with preventive safety systems, are needed to save more lives.

Overall, road safety improvement requires global action and collaboration across several areas, including stronger traffic safety laws and standards to enforce safe behaviour on the road. The research in this thesis supports the Chinese policymakers and the Chinese government as they propose to establish new regulations and create a roadmap to improve traffic safety in China.

5.9. Future work

The next step in my research will be to estimate the combined benefits of the protective and preventive safety systems in China which could save TW riders' lives and mitigate their injuries.

First, an average injury risk curve of TW riders based on Chinese crash data will be built, as Ding et al. (2018) did based on German crash data. The decrease in the number of injuries for the crashes remaining after TW-AEB application can be estimated based on this curve. The reduction in car-to-TW crash frequency can then be obtained from exposure data and the crash avoidance rate of preventive safety systems like TW-AEB and MAEB. Meanwhile, the effectiveness of protective safety systems such as active pop-up hoods, pedestrian protection airbags, helmets, PTW airbags, and inflatable jackets can be assessed based on existing tests or simulation results.

Second, I am to estimate the injury risk reduction of the integrated safety approach, through the application of knowledge about protective systems performance on the residual crashes after virtual simulations. For example, using the dose-response model, the total number of TW users' lives saved, and injuries reduced through a combination of preventive and protective safety systems can be estimated. Future work may also include modifying the protective safety systems to optimise TW rider protection, and virtually testing these systems with relevant scenarios.

6. Conclusions

Improving the safety of TW riders, who account for a large share of road traffic participants and fatalities in China, is the focus of this thesis. Cars are the most common partners in TW crashes, so developing automated emergency braking systems for cars encountering TWs (TW-AEB systems) has been proposed as a way to avoid or mitigate TW crashes and injuries. NCAPs, like C-NCAP, have been helping the automotive industry promote better safety systems (such as TW-AEB) by assessing and rating each safety system's performance using a set of test track tests. Clearly, these tests are supposed to represent real-world crashes as accurately as possible. In Paper I, cluster analysis was applied to the complex data in CIDAS, one of the most detailed crash datasets in China, to select typical scenarios that reflect the real-world traffic situation for TWs in China. Six car-to-TW crash scenarios were identified and proposed as reference TW-AEB test scenarios for C-NCAP.

Using virtual simulations, I compared the TW-AEB's performance with the scenarios from Paper I against its performance with real-world crash data (SHUFO). The findings show large similarities in the crash avoidance rate and remaining crash characteristics, validating the real-world representativity of the six proposed scenarios.

In August 2020, C-NCAP released its own TW-AEB test scenarios, which will be implemented in 2021. The scenarios are similar to those in the Euro NCAP (2020) TW-AEB assessment. However, some characteristics in the scenarios proposed in Paper I (car or TW turning, night-time, and visual obstructions) were not included in either of the NCAPs. Thus, in Paper II, the TW-AEB performance in the C-NCAP (2021) scenario set was studied to determine whether the C-NCAP scenarios can reflect real-world car-to-TW crashes in China. Counterfactual virtual simulations were run as they had been for the other two datasets. The results show much higher crash avoidance and lower remaining impact speeds for the C-NCAP scenario set compared to the results from the other two datasets, suggesting that the cars which have high ratings in C-NCAP (2021) might not perform as well as expected in the real world.

The differences in TW-AEB performance among these three datasets were investigated further. When a TW-AEB with a FoV of 70°, an activation time of 1.1 s, and a braking deceleration of 8.82 m/s2 was applied to all three scenario sets, all the crashes in the C-NCAP (2021) scenario set were avoided. However, more than half of the crashes in the SHUFO crash set and the proposed scenario set still occurred. Car or TW turning scenarios and perpendicular scenarios with high TW travelling speed accounted for a large share of the remaining crashes; importantly, these scenarios are not in the C-NCAP (2021) scenario set—although they are among the six proposed in Paper I. To address the scenarios with high TW travelling speed and longitudinal same-direction scenarios with car or TW turning, TW-AEBs with larger FoV are required. This makes it particularly important for C-NCAP to help promote the development of TW-AEB with FoV more than 70°. This can be done by including the missing scenarios in future C-NCAP releases. Furthermore, Paper II showed that, even though TW-AEBs can avoid many crashes, they do not seem able to avoid all crashes in scenarios like car or TW turning or those with high TW travelling speed. In the SHUFO and alternative scenario sets, approximately 20% of crashes had an impact speed above 40 km/h, after the application of TW-AEB. Even with an effective TW-AEB, protective safety systems are still needed to reduce TW fatalities and injuries sustained in these scenarios. Potential protective safety systems for TW riders were also reviewed in the thesis.

My work has resulted in concrete results which can be implemented to improve road traffic safety in China, as well as having the potential specifically to contribute to traffic fatality reduction, as targeted in the UN SDG 3.6. That is, by including the car-to-TW test scenarios that are missing in the current C-NCAP (2021) scenario, but are present in the scenario set proposed in Paper I, C-NCAP will help the automotive industry to develop and be able to sell TW-AEB systems that are likely to avoid crashes and mitigate injuries also in those scenarios. This, in turn, is likely to reduce the number of deaths and injuries on Chinese roads. In addition, this work has further shown that virtual simulations are an efficient way to prospectively assess safety system performance, as well as validate NCAP scenario sets.

In future work, I will assess the benefits of combining protective safety systems with TW-AEB, in terms of lives saved and injuries reduced. Overall, I argue that my work has the potential to save the lives of many TW riders, if the scenarios missing in the current C-NCAP are included in future C-NCAP releases, or manufacturers find other ways of bringing more complete TW-AEB systems (as identified in this thesis) to the market.

7. References

ADAC. (2020). *Airbag jackets for motorcyclists in the ADAC test.* https://presse.adac.de/meldungen/adac-ev/tests/airbag-jacken-fuer-motorradfahrer-im-adac-test.html. (accessed Nov. 2020)

Abay, K. A. (2015). Investigating the nature and impact of reporting bias in road crash data. *Transportation Research Part A: Policy & Practice*, 71, 31-45. https://doi.org/10.1016/j.tra.2014.11.002

Abbas, A. K., Hefny, A. F., & Abu-Zidan, F. M. (2012). Does wearing helmets reduce motorcycle-related death? A global evaluation. *Accident Analysis and Prevention*, 49, 249–252. https://doi.org/10.1016/j.aap.2011.09.033

AAA. (2019). *Automatic emergency braking with pedestrian detection.* American Automotive Association. https://www.aaa.com/AAA/common/aar/files/Research-Report-Pedestrian-Detection.pdf

Ames, E., & Martin, P. (2015). *Pop-up hood pedestrian protection.* In: Proceedings of the 24th International Technical Conference on the Enhanced Safety of Vehicles (ESV). Jun. 8-11, Gothenburg, Sweden. Paper Number 15-0111.

Aptel, I., Salmi, L. R., Masson, F., Bourdé, A., Henrion, G., & Erny, P. (1999). Road accident statistics: discrepancies between police and hospital data in a French island. *Accident Analysis and Prevention*, 31(1-2), 101-108. https://doi.org/10.1016/S0001-4575(98)00051-7

Association for the Advancement of Automotive Medicine (AAAM). (1985). *The Abbreviated Injury Scale, 1985 Revision.* Des Plaines IL, USA.

Aust, M. L., Engström, J., & Viström, M. (2013). Effects of forward collision warning and repeated event exposure on emergency braking. *Transportation Research Part F-traffic Psychology and Behaviour*, 18, 34-46. https://doi.org/10.1016/j.trf.2012.12.010

Bai, L., Liu, P., Chen, Y., Zhang, X., & Wang, W. (2013). Comparative analysis of the safety effects of electric bikes at signalized intersections. *Transportation Research Part D: Transport and Environment,* 20, 48–54. https://doi.org/10.1016/j.trd.2013.02.001

Benlagha, N., Charfeddine, L. (2020). Risk factors of road accident severity and the development of a new system for prevention: New insights from China. *Accident Analysis and Prevention*, 136, 105411. https://doi.org/10.1016/j.aap.2019.105411

Benmimoun, M., Pütz, A., Zlocki, A., & Eckstein, L. (2013). *euroFOT: Field Operational Test and Impact Assessment of Advanced Driver Assistance Systems: Final Results*. In: Proceedings of the FISITA 2012 World Automotive Congress. Nov. 27-30, Beijing, China.

Bi, L., Gan, G., & Liu, Y. (2014). Using Queuing Network and Logistic Regression to Model Driving with a Visual Distraction Task. *International Journal of Human–Computer Interaction*, 30(1), 32–39. https://doi.org/10.1080/10447318.2013.796442

Bovenkerk, J., Sahr, C., Zander, O., & Kalliske, I. (2009). *New modular assessment methods for pedestrian protection in the event of head impacts in the windscreen area*. In: Proceedings of the 21st International Technical Conference on the Enhanced Safety of Vehicles (ESV). Jun. 15-18, Stuttgart, Germany. Paper Number 09-0159.

Bull, J. P., Roberts, B. J. (1973). Road accident statistics--A comparison of police and hospital information. *Accident Analysis and Prevention*, 5(1), 45-53. https://doi.org/10.1016/0001-4575(73)90004-3

Bärgman, J. (2016). *Methods for analysis of naturalistic driving data in driver behavior research*. Ph.D. Thesis. Chalmers University of Technology, Gothenburg, Sweden.

Bärgman, J., Boda, C., & Dozza, M. (2017). Counterfactual simulations applied to SHRP2 crashes: The effect of driver behavior models on safety benefit estimations of intelligent safety systems. *Accident Analysis and Prevention*, 102, 165–180. https://doi.org/10.1016/j.aap.2017.03.003

Bärgman, J., Lisovskaja, V., Victor, T., Flannagan, C., & Dozza, M. (2015). How does glance behavior influence crash and injury risk? A "what-if" counterfactual simulation using crashes and near-crashes from SHRP2. *Transportation Research Part F: Traffic Psychology and Behaviour*, 35, 152–169. https://doi.org/10.1016/j.trf.2015.10.011

Bärgman, J., & Victor, T. (2019). Holistic assessment of driver assistance systems: how can systems be assessed with respect to how they impact glance behaviour and collision avoidance? *Intelligent Transport Systems,* 14(9), 1058-1067. https://doi.org/10.1049/iet-its.2018.5550

Cao, Y., Xiao, Y., Dong, H., Wang, Y., Wu, X., Li, P., & Qiu, Y. (2019). *Typical pre-crash scenarios reconstruction for two-wheelers and passenger vehicles and its application in parameter optimization of AEB system based on NAIS database.* In: Proceedings of the 26th International Technical Conference on the Enhanced Safety of Vehicles (ESV). Jun. 10-13, Eindhoven, Netherland. Paper Number 19-0272.

Capitani, R., Pellari, S. S., & Lavezzi, R. (2010). *Design and numerical evaluation of an airbag-jacket for motorcyclists.* In: Proceedings of the 4th International Conference on Expert Symposium on Accident Research (ESAR). Sep. 16-18, Hanover, Germany.

Cercarelli, L. R., Rosman, D. L., & Ryan, G. A. (1996). Comparison of accident and emergency with police road injury data. *The Journal of Trauma*, 40(5), 805–809. https://doi.org/10.1097/00005373-199605000-00021

Chajmowicz, H., Saadé, J., & Cuny, S. (2019). Prospective assessment of the effectiveness of autonomous emergency braking in car-to-cyclist accidents in France. *Traffic Injury Prevention*, 20. https://doi.org/10.1080/15389588.2019.1679797

Chang, F., Xu P., Zhou, H., Lee, J., & Huang, H. (2019). Identifying motorcycle high-risk traffic scenarios through interactive analysis of driver behavior and traffic characteristics. *Accident Analysis and Prevention*, 62, 844-854. https://doi.org/10.1016/j.trf.2019.03.010

Char. F., & Serre. T. (2020). Analysis of pre-crash characteristics of passenger car to cyclist accidents for the development of advanced drivers assistance systems. *Accident Analysis and Prevention*, 136, 105408. https://doi.org/10.1016/j.aap.2019.105408

Chen, Q., Chen, Y., Bostrom, O., & Ma, Y. (2014). *A Comparison Study of Car-to-Pedestrian and Car-to-E-Bike Accidents: Data Source: The China In-Depth Accident Study (CIDAS).* SAE Technical Paper 2014-01-0519. https://doi.org/10.4271/2014-01-0519

Chen, Q., & Dai, B. (2018). *Characteristics and Casualty Analysis of Two-Wheeler Accidents in China, Data Source: The China In-Depth Accident Study (CIDAS)*. SAE Technical Paper 2018-01-1052. https://doi.org/10.4271/2018-01-1052

Cherry, C. R, Weinert, J. X, & Yang, X. (2009). Comparative environmental impacts of electric bikes in China. UC Davis: Institute of Transportation Studies. *Transportation Research Part D: Transport and Environment*, 14, 281-290. https://doi.org/10.1016/j.trd.2008.11.003

Cherry, C., & Cervero, R. (2007). Use characteristics and mode choice behavior of electric bike users in China. *Transport Policy*, 14(3), 247–257. https://doi.org/10.1016/j.tranpol.2007.02.005

Cherry, C., & He, M. (2010). Alternative methods of measuring operating speed of electric and traditional bikes in China-implications for travel demand models. *Journal of the Eastern Asia Society for Transportation Studies*, 8, 1424–1436. https://doi.org/10.11175/easts.8.1424

Chrysler, S. T., Ahmad, O., & Schwarz, C. W. (2015). Creating pedestrian crash scenarios in a driving simulator environment. *Traffic Injury Prevention*, 16, S12–S17. https://doi.org/10.1080/15389588.2015.1015001

Cicchino, J. B. (2017). Effectiveness of forward collision warning and autonomous emergency braking systems in reducing front-to-rear crash rates. *Accident Analysis and Prevention*, 99, 142-152. https://doi.org/10.1016/j.aap.2016.11.009.

CIDAS. (2016). *China In-Depth Accident Study (CIDAS) codebook*. China Automotive Technology and Research Centre, Tianjin, China.

C-NCAP. (2018). *C-NCAP management regulation*. China Automotive Technology and Research Centre. http://www.c-ncap.org/cms/picture/284198871117160448.pdf

Cochran, W. G. (1952). The χ2 test of goodness of fit. *Annals of Mathematical Statistics*, 23, 315–345. https://doi.org/10.1214/aoms/1177729380

Coelingh, E., Eidehall, A., & Bengtsson, M. (2010). *Collision Warning with Full Auto Brake and Pedestrian Detection - a practical example of Automatic Emergency Braking*. In: Proceedings of the 13th International IEEE Conference on Intelligent Transportation Systems. Sep. 19-22, Madeira Island, Portugal.

Coelingh, E., Lind, H., Birk, W., & Wetterberg, D. (2006). *Collision Warning with Auto Brake*. In: Proceedings of FISITA World Congress, F2006V130, Yokohama Japan.

Cryer, P. C., Westrup, S., Cook, A. C., Ashwell, V., Bridger, B., & Clarke, C. (2001). Investigation of bias after data linkage of hospital admissions data to police road traffic crash reports. *Injury Prevention*, 7, 234–241. http://dx.doi.org/10.1136/ip.7.3.234

Dandona, R., Kumar, G. A., Ameer, M. A., Reddy, G. B., & Dandona, L. (2008). Under-reporting of road traffic injuries to the police: results from two data sources in urban India*. Injury Prevention*, 14(6), 360–365. https://doi.org/10.1136/ip.2008.019638

Daniels, S., Brijs, T., & Keunen, D. (2010). Official reporting and newspaper coverage of road crashes: A case study. *Safety Science*, 48(10), 1469-1476. Http://dx.doi.org/10.1016/j.ssci.2010.07.007

Davison, L., & Curl, A. (2014). A transport and health geography perspective on walking and cycling. *Journal of Transport and Health*, 1 (4), 341-345. https://doi.org/10.1016/j.jth.2014.09.001

Deng, B., Wang, H., Chen, J., Wang, X., & Chen, X. (2013). *Traffic accidents in shanghai – general statistics and in-depth analysis.* In: Proceedings of the 23rd International Technical Conference on the Enhanced Safety of Vehicles (ESV). May 27-30, Seoul, Korea. Paper Number 13-0182.

Depaire, B., Wets, G., & Vanhoof, K. (2008). Traffic accident segmentation by means of latent class clustering. *Accident Analysis and Prevention*, 40 (4), 1257–1266. https://doi.org/10.1016/j.aap.2008.01.007

Dobberstein, J., Bakker, J., Wang, L., Vogt, T., Düring, M., Stark, L., Gainey, J., Prahl, A., Müller, R., & Blondelle, G. (2017). *The Eclipse working group openPASS: an open source approach to safety impact assessment via simulation*. In: Proceedings of the 25th International Technical Conference on the Enhanced Safety of Vehicles (ESV). Jun. 5-8, Detroit Michigan, United States. Paper Number 17-0094.

Dozza, M. (2013). What factors influence drivers' response time for evasive maneuvers in real traffic? *Accident Analysis and Prevention*, 58, 299–308. https://doi.org/10.1016/j.aap.2012.06.003

Dozza, M., & González, N. (2013). Recognising safety critical events: can automatic video processing improve naturalistic data analyses? *Accident Analysis and Prevention*, 60, 298-304. https://doi.org/10.1016/j.aap.2013.02.014

Dozza, M., & Piccinini, G. F. B. (2014). *Do cyclists on e-bikes behave differently than cyclists on traditional bicycles?* In: Proceedings of the international cycling safety conference. Nov. 18-19, Gothenburg, Sweden.

Dozza, M., Piccinini, G. F. B., & Werneke, J. (2016). Using naturalistic data to assess e-cyclist behavior. *Transportation Research: Traffic Psychology and Behaviour*, 41, 217–226. http://dx.doi.org/10.1016/j.trf.2015.04.003

Duan, J., Li, R., Hou, L., Wang, W., Li, G., Li, S. E., Cheng, B., & Gao, H. (2017). Driver braking behavior analysis to improve autonomous emergency braking systems in typical Chinese vehicle-bicycle conflicts. *Accident Analysis and Prevention*, 108, 74–82. https://doi.org/10.1016/j.aap.2017.08.022

Eichberger, A., (2010). *Contributions to Primary, Secondary and Integrated Traffic Safety*. Verlag Holzhausen GmbH.

Erbsmehl, C. (2009). *Simulation of real crashes as a method for estimating the potential benefits of advanced safety technologies*. In: Proceedings of the 21st International Technical Conference on the Enhanced Safety of Vehicles (ESV), 2009-6-15 – 2009-6-18, Stuttgart, Germany. Paper Number 09-0162.

Teoh, E. R. (2011). Effectiveness of Antilock Braking Systems in Reducing PTW Fatal Crash Rates. *Traffic Injury Prevention*, 12(2), 169-173. https://doi.org/10.1080/15389588.2010.541308

ESCAP. (2013). *Combatting Congestion.* https://www.unescap.org/sites/default/files/bulletin82_Fulltext.pdf.

Euro NCAP. (2018a). *Euro NCAP rating review 2018*. https://cdn.euroncap.com/media/41777/ratings-group-report-2018-version-11-with-appendices.201811121629591429.pdf (accessed Nov. 2020).

Euro NCAP. (2018b). *European new car assessment programme-test protocol.* https://cdn.euroncap.com/media/32279/euro-ncap-aeb-vru-test-protocol-v202.pdf (accessed Nov 2020).

Euro NCAP. (2020). *European New Car Assessment Programme-assessment protocol.* https://cdn.euroncap.com/media/58228/euro-ncap-assessment-protocol-overall-rating-v901.pdf (accessed Nov. 2020).

Evans, L. (1999). Antilock Brake Systems and risk of different types of crashes in traffic. *Journal of Crash Prevention and Injury Control*, 1(1), 5-23. https://doi.org/10.1080/10286589908915737

Fernandes, F. A., & Sousa, R. J. (2013). Motorcycle helmets-a state of the art review. *Accident Analysis and Prevention*, 56, 1-21. https://doi.org/10.1016/j.aap.2013.03.011

Fishman, E., & Cherry, C. (2016). E-bikes in the mainstream: Reviewing a decade of research. *Transport Reviews*, 36(1), 72–91. http://dx.doi.org/10.1080/01441647.2015.1069907

Fitch, G. M., Rakha, H. A., Arafeh, M., Blanco, M., Gupta, S. K., Zimmermann, R. P., & Hanowski, R. J. (2008). *Safety Benefit Evaluation of a Forward Collision Warning System.* https://one.nhtsa.gov/DOT/NHTSA/NRD/Multimedia/PDFs/Crash%20Avoidance/2008/DOT-HS-810-910.pdf (accessed Nov. 2020).

Fredriksson, R., Bylund, P. O., & Oman, M. (2012). Fatal Vehicle-to-Bicyclist Crashes in Sweden - an In-Depth Study of injuries and vehicle sources. Annals of advances in automotive medicine. *Association for the Advancement of Automotive Medicine. Annual Scientific Conference*, 56, 25–30. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3503412/pdf/file003final.pdf

Fredriksson, R., & Rosén, E. (2012a). Integrated pedestrian countermeasures – Potential of head injury reduction combining passive and active countermeasures. *Safety Science*, 50(3), 400-407. https://doi.org/10.1016/j.ssci.2011.09.019

Fredriksson, R., & Rosén, E. (2012b). *Priorities for Bicyclist Protection in Car Impacts – a Real life Study of Severe Injuries and Car Sources*. In: Proceedings of the 2012 International Research Council On the Biomechanics of Impact Conference (IRCOBI). Sep. 12-14, Dublin, Ireland.

Fredriksson, R., Rosén, E., & Kullgren, A. (2010). Priorities of pedestrian protection--a real-life study of severe injuries and car sources. *Accident Analysis and Prevention*, 42(6), 1672–1681. https://doi.org/10.1016/j.aap.2010.04.006

Fredriksson, R., Shin, J., & Untaroiu, C. D. (2011). Potential of pedestrian protection systems--a parameter study using finite element models of pedestrian dummy and generic passenger vehicles. *Traffic injury prevention*, 12(4), 398–411. https://doi.org/10.1080/15389588.2011.566655

Fredriksson, R., Zhang, L., Boström, O., & Yang, K. (2007). Influence of impact speed on head and brain injury outcome in vulnerable road user impacts to the car hood. *Stapp Car Crash Journal*, 51, 155–167. https://doi.org/10.4271/2007-22-0007

Gavanas, G. (2019). Autonomous Road Vehicles: Challenges for Urban Planning in European Cities. *Urban Science*, 3(2), 61. https://doi.org/10.3390/urbansci3020061

General Technical Standards of E-Bike (GB17761-1999). *National E-bike Compelling Standards*. Chinese Standards Publisher, Beijing, China.

Grant, R., Frampton, R., Savino, G., & Pierini, M. (2008). *PISa—Powered Two-Wheeler Integrated Safety. Project objectives, achievements and remaining activities.* In: Proceedings of the 7th International PTW Conference. Oct.6-7, Cologne, Germany.

Guillen, P. P., Gohl, I. (2019). Forward collision warning based on a driver model to increase drivers' acceptance. *Traffic Injury Prevention*, 20(1), S21-S26. https://doi.org/10.1080/15389588.2019.1623397

Guo, Y., Liu, P., Bai, L., Xu, C., & Chen, J. (2014). Red-light running behaviors of electric bicycles at signalized intersections in China. *Transportation Research Record*, 2468, 28–37. https://doi.org/10.3141/2468-04

Guo, Y., Osama, A., & Sayed, T. (2018). A cross-comparison of different techniques for modelling macro-level cyclist crashes. *Accident Analysis and Prevention*, 113, 38–46. https://doi.org/10.1016/j.aap.2018.01.015

Guo, Y., Sayed, T., & Zaki, M. (2017). Automated analysis of pedestrian walking behaviour at a signalised intersection in China. *Intelligent Transport Systems*, 11(1), 28–36. http://dx.doi.org/10.1049/iet-its.2016.0090

Habibović, A. (2012). *Analyzing real-world data to promote development of active safety systems that reduce car-to-vulnerable road user accidents*. Ph.D. Thesis. Chalmers University of Technology, Gothenburg, Sweden.

Hair, J. F. Jr., Anderson, R. E., Tatham, R. L., & Black, W. C. (1998). *Multivariate Data Analysis*. Pearson Education Limited.UK.

Han, Y., Li, Q., Qian, Y., Zhou, D., & Svensson, M. Y. (2018). Comparison of the landing kinematics of pedestrians and cyclists during ground impact determined from vehicle collision video records. *International Journal of Vehicle Safety*, 10, 212-234. https://doi.org/10.1504/IJVS.2018.097708

Hautzinger, H., Pastor, C., Pfeiffer, M., & Schmidt, J. (2007). *Analysis methods for accident and injury risk studies.* Deliverable from the TRACE project. Brussels, Belgium.

Hautzinger, H., Pfeiffer, M., & Schmidt, J. (2004). *Expansion of GIDAS sample data to the regional level: statistical methodology and practical experiences*. In: Proceedings of the 4th International Conference on Expert Symposium on Accident Research (ESAR). Sep. 16-18, Hanover, Germany.

Haworth, N. L., & Schulze M. T. (1996). *Motorcycle crash countermeasures: Literature review and implementation workshop.* Retrieved from https://www.monash.edu/__data/assets/pdf_file/0017/217241/muarc087.pdf (accessed Jun. 2020).

Haworth, N. L. (2012). Powered two wheelers in a changing world-challenges and opportunities. *Accident Analysis and Prevention*, 44(1), 12-18. https://doi.org/10.1016/j.aap.2010.10.031

Johannsen, H., Krettek, C., Hannawald, L., & Schaser, K. (2017). *Consideration of Accident Avoidance Technology Within GIDAS*. In: Proceedings of the 25th International Technical Conference on the Enhanced Safety of Vehicles (ESV). Jun. 5-8, Detroit Michigan, United States. Paper Number 17-0397.

Helmer, T., Kühbeck, T., Gruber, C., & Kate, S. R. (2013). *Development of an Integrated Test Bed and Virtual Laboratory for Safety Performance Prediction in Active Safety Systems.* In: Proceedings of the FISITA 2012 World Automotive Congress. Nov. 27-30, Beijing, China. https://doi.org/10.1007/978-3-642-33805-2_34

Herskind, N. C., Lim, C., Holst, S. (2019). *How China will shape the future of autonomous vehicles*. https://qvartz.com/business/news/how-china-will-shape-the-future-of-autonomous-vehicles/ (accessed Nov. 2020).

Hu, G., Baker, T., & Baker, S. P. (2011). *Comparing road traffic mortality rates from police-reported data and death registration data in China*. Bulletin of the World Health Organization, 89(1), 41–45. https://doi.org/10.2471/BLT.10.080317

Huang, H., Chang, F., Schwebel, D. C., Ning, P., Cheng, P., & Hu, G. (2018). Improve traffic death statistics in China. *Science*, 362(6415), 650 LP –650. https://doi.org/10.1126/science.aav5117

Huang, H., Yin, Q., Schwebel, D. C., Ning, P., & Hu, G. (2017). Availability and consistency of health and non-health data for road traffic fatality: Analysis of data from 195 countries, 1985-2013. *Accident Analysis and Prevention*, 108, 220–226. https://doi.org/10.1016/j.aap.2017.08.033

Huang, S., & Yang, J. (2010). Optimization of a reversible hood for protecting a pedestrian’s head during car collisions. *Accident Analysis and Prevention*, 42 (4), 1136–1143. https://doi.org/10.1016/j.aap.2009.12.028

Hutchingson, T. P. (1987). *Road accident statistics*. Rumsby Scientific Publishing. Adelaide, Australia.

Jaensch, M., Otte, D., Pund, B., Chiellino, U., & Hoppe, M. (2009). *Implementation of ACASS (accident causation analysis with seven steps) in in-depth accident study GIDAS.* Retrieved from https://bast.opus.hbz-nrw.de/opus45-bast/frontdoor/deliver/index/docId/473/file/Implementation_of_ACASS_Accident_Causation_Analysis_with_Seven_Steps.pdf (Accessed Nov. 2020)

Jaensch, M., Otte, D., Pund, B., Chiellino, U., & Hoppe, M. (2009). *Implementation of ACASS (accident causation analysis with seven steps) in in-depth accident study GIDAS.* In: Proceedings of the 3rd International Conference on Expert Symposium on Accident Research (ESAR). Sep. 5-6, Hanover, Germany.

Jakobsson, L., Lindman, M., Svanberg, B., & Carlsson, H. (2010). Real world data driven evolution of volvo cars' side impact protection systems and their effectiveness. Annals of advances in automotive medicine. Association for the Advancement of Automotive Medicine. *Scientific Conference*, 54, 127-136.

Jamson, A., Lai, F., & Carsten, O. (2008). Potential benefits of an adaptive forward collision warning system. *Transportation Research Part C*, 16(4), 471–484. https://doi.org/10.1016/j.trc.2007.09.003

Jeong, E., & Oh, C. (2017). Evaluating the effectiveness of active vehicle safety systems. *Accident Analysis and Prevention*, 100, 85-96. https://doi.org/10.1016/j.aap.2017.01.015

Jeppsson, H., Östling, M., & Lubbe, N. (2018). Real life safety benefits of increasing brake deceleration in car-to-pedestrian accidents: Simulation of Vacuum Emergency Braking. *Accident Analysis and Prevention*, 111, 311–320. https://doi.org/10.1016/j.aap.2017.12.001

Kaplan, S., & Prato, C. G. (2013). Cyclist-motorist crash patterns in Denmark: a latent class clustering approach. *Traffic Injury Prevention*, 14(7), 725–733. https://doi.org/10.1080/15389588.2012.759654

Kaufman, L., & Rousseeuw, P. J. (2005). Finding groups in data: an introduction to cluster analysis. *Wiley-Interscience*, 33 (1), 368. http://dx.doi.org/10.1007/s00134-006-0431-z

Korner, J. (1989). *A method for evaluating occupant protection by correlating accident data with laboratory test data*. SAE Technical Paper 890747. https://doi.org/10.4271/890747

Kovaceva, J., Bálint, A., Schindler, R., & Schneider, A. (2020). Safety benefit assessment of autonomous emergency braking and steering systems for the protection of cyclists and pedestrians based on a combination of computer simulation and real-world test results. *Accident Analysis and Prevention*, 136, 105352. https://doi.org/10.1016/j.aap.2019.105352

Krantz K. P. (1985). Head and neck injuries to motorcycle and moped riders--with special regard to the effect of protective helmets. *Injury*, 16(4), 253–258. https://doi.org/10.1016/s0020-1383(85)80014-0

Krenn, M., Mlekusch, B., Wilfling, C., Dobida, F., & Deutscher, E. (2003). *Development and evaluation of a kinematic hood for pedestrian protection*. SAE Technical Paper 01-0897, 2003, https://doi.org/10.4271/2003-01-0897

Kuroe, T., Namiki, H., & Iijima, S. (2005). *Exploratory study of an airbag concept for a large touring PTW: further research second report*. In: Proceedings of the 19th

International Technical Conference on the Enhanced Safety of Vehicles (ESV), Jun. 6-9, Detroit Michigan, United States. Paper Number 05-0316.

Kusano, K. D, & Gabler, H. C. (2011). Method for estimating time to collision at braking in real-world, lead vehicle stopped rear-end crashes for use in pre-crash system design. *SAE International*, 4(1), 435-443. https://doi.org/10.4271/2011-01-0576

Kusano, K. D., & Gabler, H. C. (2012). Safety benefits of forward collision warning, brake assist, and autonomous braking systems in rear-end collisions. *IEEE Transactions on Intelligent Transportation Systems*, 13, 1546-1555. https://doi.org/10.1109/TITS.2012.2191542

Larsen, L. (2004). Methods of multidisciplinary in-depth analyses of road traffic accidents. *Journal of Hazardous Materials*, 111(1–3), 115-122. http://dx.doi.org/10.1016/j.jhazmat.2004.02.019

Lee, J. D., McGehee, D. V., Brown, T. L., & Reyes, M. L. (2002). Collision warning timing, driver distraction, and driver response to imminent rear-end collisions in a high-fidelity driving simulator. *Human Factors*, 44(2), 314–334. https://doi.org/10.1518/0018720024497844

Leglatin, N., Blundell, M., & Blount, G. N. (2006). The simulation of pedestrian impact with a combined multibody finite elements system model. *Journal of Engineering Design*, 17, 463 - 477. https://doi.org/10.1080/09544820600664622.

Lenard, J., Badea-Romero, A., & Danton, R. (2014). Typical pedestrian accident scenarios for the development of autonomous emergency braking test protocols. *Accident Analysis and Prevention*, 73, 73–80. http://dx.doi.org/10.1016/j.aap.2014.08.012

Li, G., Yang, Y., & Qu, X., (2020). Deep learning approaches on pedestrian detection in hazy weather. *IEEE Transactions on Industrial Electronics*, 67(10), 8889-8899. https://doi.org/10.1016/j. jsr.2019.09.012

Li, L. P., Li, G. L., Cai, Q. E., Zhang, A. L., & Lo, S. K. (2008). Improper motorcycle helmet use in provincial areas of a developing country. *Accident Analysis and Prevention*, 40(6), 1937–1942. https://doi.org/10.1016/j.aap.2008.06.019

Lim, J. H., Park, J. S., Yun, Y. W., Jeong, S. B., & Park, G. J. (2015). Design of an airbag system of a mid-sized automobile for pedestrian protection. *Journal of Automobile Engineering*, 229(5), 656–669. https://doi.org/10.1177/0954407014551186

Lindman, M., Oedblom, A., Bergvall, E., Eidehall, A., Svanberg, B., & Lukaszewicz, T. (2010). *Benefit estimation model for pedestrian auto brake functionality*. In: Proceedings of the 4th International Conference on Expert Symposium on Accident Research (ESAR). Sep. 16-18, Hanover, Germany.

Liu, B. C., Ivers, R., Norton, R., Boufous, S., Blows, S., & Lo, S. K. (2008). Helmets for preventing injury in motorcycle riders. *The Cochrane Database of Systematic Reviews*, (1), CD004333. https://doi.org/10.1002/14651858.CD004333.pub3

Ljung Aust, M., Benmimoun, M., Regan, M. (2011). *Disentangling the effects of advanced driver assistance system functions in field operational tests: recommendations from the European "EURO FOTt" project*. Retrieved from https://eurofot-ip.eu/download/papersandpresentations/its_european_congress/iffstar.pdf. (Accessed Nov. 2020).

Lubbe, N., Jeppsson, H. Ranjbar, A., Fredriksson, J. Bärgman, J. & Östling M. (2018) *Predicted road traffic fatalities in Germany: The potential and limitations of vehicle safety technologies from passive safety to highly automated driving*. In: Proceedings of the 2018 International Research Council On the Biomechanics of Impact Conference (IRCOBI). Sep. 12-14, Athens, Greece.

Lubbe, N., Davidsson, J. (2015). Drivers' comfort boundaries in pedestrian crossings: a study in driver braking characteristics as a function of pedestrian walking speed. *Safety Science*, 75, 100–106. https://doi.org/10.1016/j.ssci.2015.01.019

MacAlister, A., & Zuby, S. D. (2015). *Cyclist crash scenarios and factors relevant to the design of cyclist detection systems*. In: Proceedings of the 2015 International Research Council On the Biomechanics of Impact Conference (IRCOBI). Sep. 9-11, Lyon, France.

McDonald, A. D., Alambeigi, H., Engström, J., Markkula, G., Vogelpohl, T., Dunne, J., & Yuma, N. (2019). Toward computational simulations of behavior during automated driving takeovers: a review of the empirical and modeling literatures. Human Factors, 61(4), 642–688. https://doi.org/10.1177/0018720819829572

MacLeod, J. B., Digiacomo, J. C., & Tinkoff, G. (2010). An evidence-based review: helmet efficacy to reduce head injury and mortality in motorcycle crashes: EAST practice management guidelines. *The Journal of Trauma*, 69(5), 1101–1111. https://doi.org/10.1097/TA.0b013e3181f8a9cc

Markkula, G. (2014). Modeling driver control behavior in both routine and near-accident driving. *The Human Factors and Ergonomics Society Annual Meeting*, 58(1), 879–883. https://doi.org/10.1177/1541931214581185

Maki, T., Kajzer, J., Mizuno, K., & Sekine, Y. (2003). Comparative analysis of vehicle-bicyclist and vehicle-pedestrian accidents in Japan. *Accident Analysis and Prevention*, 35(6), 927-940. https://doi.org/10.1177/0954411917723674

Mathers, C. D., Lopez, A. D., Murray, C. J. L., Ezzati, M., & Jamison, D. T. (2006). *The burden of disease and mortality by condition: data, methods and results for 2001.* Oxford University Press. New York, USA.

Ministry of Industry and Information Technology of the People's Republic of China. (2018). *GB 17761-2018-Safety technical specification for electric bicycle.* https://www.miit.gov.cn/cms_files/filemanager/oldfile/miit/n1146285/n1146352/n3054355/n3057497/n3057502/c6176772/part/6176777.pdf. (Accessed Nov. 2020).

Moran, D., Bose, D., & Bhalla, K. (2017). Impact of improving vehicle front design on the burden of pedestrian injuries in Germany, the United States, and India*, Traffic Injury Prevention*, 18(8), 832-838. https://doi.org/10.1080/15389588.2017.1324200

Najm, W. G., Smith, J. D., & Yanagisawa, M. (2007). *Pre-Crash scenario typology for crash avoidance research*. Retrieved from https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/pre-crash_scenario_typology-final_pdf_version_5-2-07.pdf (Accessed Nov. 2020).

NASS. *National Automotive Sampling System – Crashworthiness Data System 2015 Analytical User's Manual.* Retrieved from https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812321 in May 2020.

National Bureau of Statistics of China. (2018). *China statistical year book 2018*. http://www.stats.gov.cn/tjsj/ndsj/2017/indexeh.htmhttp://data.stats.gov.cn/easyquery.htm?cn=C01andzb=A0S0D02andsj=2018. Accessed in May, 2020.

National Development and Reform Commission. 2020. *关于印发《智能汽车创新发展战略》的通知*. https://www.ndrc.gov.cn/xxgk/zcfb/tz/202002/t20200224_1221077.html. Accessed in May 2020.

NHTSA. (2008). *Traffic safety facts, Data: Motorcycles*. https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/811159. (Accessed Nov. 2020)

NHTSA. (2010). *Evaluating the Relationship Between Near-Crashes and Crashes: Can Near-Crashes Serve as a Surrogate Safety Metric for Crashes?* https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/documents/dot_hs_811_382.pdf

NHTSA. (2020). *Overview of the Crashworthiness Data System*. https://www.nhtsa.gov/national-automotive-sampling-system-nass/crashworthiness-data-system. (Accessed Aug. 2020).

NHTSA. (2020). *Event Data Recorder*. https://www.nhtsa.gov/research-data/event-data-recorder#overview-10516. (Accessed Aug. 2020).

Nilsson, D., Lindman, M., Victor, T., & Dozza, M. (2018). Definition of run-off-road crash clusters-For safety benefit estimation and driver assistance development. *Accident Analysis and Prevention*, 113, 97–105. https://doi.org/10.1016/j.aap.2018.01.011

Nitsche, P., Thomas, P., Stuetz, R., & Welsh, R. (2017). Pre-crash scenarios at road junctions: a clustering method for car crash data. *Accident Analysis and Prevention*, 107, 137–151. https://doi.org/10.1016/j.aap.2017.07.011

Noy, I. Y., Shinar, D., & Horrey, W. J. (2018). Automated driving: Safety blind spots. *Safety Science*, 102, 68–78. https://doi.org/10.1016/j.ssci.2017.07.018

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. https://doi.org/10.1016/j.ssci.2016.05.007

Oke, O., Bhalla, K., Love, D. C., & Siddiqui, S. (2018). Spatial associations in global household bicycle ownership. *Annals of Operations Research*, 263, 529-549. https://doi-org.proxy.lib.chalmers.se/10.1007/s10479-016-2358-2

Op den Camp, O., van Montfort, S., Uittenbogaard, J., & Welten, J. (2017). Cyclist target and test setup for evaluation of cyclist-autonomous emergency braking. International Journal of Automotive Technology, 18, 1085–1097. https://doi.org/10.1007/s12239-017-0106-5

Östling, M., Jeppsson, H., & Lubbe, N. (2019). *Predicting crash configurations in passenger car to passenger car crashes to guide the development of future* *passenger car safety.* In: Proceedings of the 2019 International Research Council On the Biomechanics of Impact Conference (IRCOBI). Sept. 11 - 13, Florence, Italy.

Otte, D., Krettek, C., Brunner, H., & Zwipp, H (2003). *Scientific approach and methodology of a new in-depth-investigation study in Germany so called GIDAS*. In: Proceedings of the 18th International Technical Conference on the Enhanced Safety of Vehicles (ESV). May 19-22, Nagoya, Japan.

Ouellet, J.V. (1990). *Appropriate and inappropriate strategies for injury reduction in motorcycle accidents*. SAE Technical Paper 900747, https://doi.org/10.4271/900747

Page, Y., Fahrenkrog, F., Fiorentino, A., Gwehenberger, J., Helmer, T., Lindman, M., Op den Camp, O., van Rooij, L., Puch, S., Fränzle, M., Sander, U., & Wimmer, P. (2015). *A comprehensive and harmonized method for assessing the effectiveness of advanced driver Assistance Systems by virtual simulation: The P.E.A.R.S. initiative*. in: Proceedings of the 24th International Technical Conference on the Enhanced Safety of Vehicles (ESV). Jun. 8-11, Gothenburg, Sweden. Paper Number 15-0370.

Pan, D., Han, Y., Jin, Q., & Huang, H. (2020). *A preliminary analysis of vehicle-to-powered two-wheeler accident scenarios based on the VRU-TRAVi database.* In: Proceedings of the 2020 International Research Council On the Biomechanics of Impact (IRCOBI) Asia Conference. Jun. 1-2, Beijing, China.

Pastor, C. (2013). *Correlation between pedestrian injury severity in real-life crashes and Euro NCAP pedestrian test results*. In: Proceedings of the 23rd International Technical Conference on the Enhanced Safety of Vehicles (ESV). May 27-30, Seoul, Korea. Paper Number 13-0308.

Pizzuto, L., Thomas, C., Wang, A., & Wu, T. (2019*). How China will help fuel the revolution in autonomous vehicles. https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/how-china-will-help-fuel-the-revolution-in-autonomous-vehicles#:~:text=DOWNLOADS&text=Self%2Ddriving%20cars%20could%20steer,the%20automotive%20and%20mobility%20industries*. (Accessed in Nov. 2020).

Pizzuto, L., Thomas, C., Wang, A., & Wu, T. (2020). *How China will help fuel the revolution in autonomous vehicles.* Retrieved from https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/how-china-will-help-fuel-the-revolution-in-autonomous-vehicles (Accessed Nov. 2020).

Puthan, P., Thalya, P., & Lubbe, N. (2018). *Active and passive safety passenger car technologies: potentials to save lives in India*. In: Proceedings of the 2018

International Research Council on the Biomechanics of Impact (IRCOBI) Asia Conference. Apr. 25-27, Lonavala, India.

Rao, R. M. (2017). *Using Event Data Recorder (EDR) data to perform What-if simulations for safety benefit analysis by reconstructing real traffic kinematics and driver behaviors.* Master Thesis. Chalmers University of Technology, Gothenburg, Sweden.

Rizzi, M. (2011). *The potential of AEB in fatal PTW crashes.* Paper presented at: the 55th AAAM Student Research Symposium, Oct. 2, Paris, France.

Rizzi, M., Kullgren, A., & Tingvall, C. (2016). The combined benefits of motorcycle antilock braking systems (ABS) in preventing crashes and reducing crash severity. *Traffic Injury Prevention*, 17(3), 297–303. https://doi.org/10.1080/15389588.2015.1061660

Rizzi, M., Kullgren, A., & Tingvall, C. (2016). The combined benefits of motorcycle antilock braking systems (ABS) in preventing crashes and reducing crash severity. *Traffic Injury Prevention*, 17(3), 297–303. https://doi.org/10.1080/15389588.2015.1061660

Rizzi, M., Strandroth, J., & Tingvall, C. (2009). The effectiveness of antilock brake systems on motorcycles in reducing real-life crashes and injuries. *Traffic Injury Prevention*, 10(5), 479–487. https://doi.org/10.1080/15389580903149292

Rizzi, M., Strandroth, J., Johansson, R., & Lie, A. (2017). *The potential of different countermeasures in reducing ptw fatal crashes: what in-depth studies tell us*. In: Proceedings of the 25th International Technical Conference on the Enhanced Safety of Vehicles (ESV). Jun. 5-8, Detroit Michigan, United States. Paper Number 17- 0191.

Rizzi, M., Strandroth, J., Kullgren, A., Tingvall, C., & Fildes, B. (2015). Effectiveness of motorcycle antilock braking systems (ABS) in reducing crashes, the first cross-national study. *Traffic Injury Prevention*, 16(2), 177–183. https://doi.org/10.1080/15389588.2014.927575

Roll, G., Hoffmann, O. (2009). *Effectiveness evaluation of antilock brake system (ABS) for motorcycles in real-word accident scenarios*. In: Proceedings of 21st International Technical Conference on the Enhanced Safety of Vehicles (ESV). Jun. 15-18, Stuttgart, Germany. Paper Number 09-0254.

Rose, G. (2012). E-Bikes and urban transportation: Emerging issues and unresolved Questions. *Transportation*, 39(1), 81–96. https://doi.org/10.1007/s11116-011-9328-y

Rosén, E. (2013). *Autonomous emergency braking for vulnerable road users*. In: Proceedings of the 2013 International Research Council On the Biomechanics of Impact Conference (IRCOBI) Conference. Sep.11-13, Gothenburg, Sweden.

Rosén, E., Källhammer, J. E., Eriksson, D., Nentwich, M., Fredriksson, R., & Smith, K. (2010). Pedestrian injury mitigation by autonomous braking. *Accident Analysis and Prevention*, 42 (6), 1949–1957. http://dx.doi.org/10.1016/j.aap.2010.05.018

Rousseeuw, P. J. (1987). Silhouettes: a graphical aid to the interpretation and validation of cluster analysis. *Journal of Computational and Applied Mathematics*, 20, 53–65. https://doi.org/10.1016/0377-0427(87)90125-7

Saadé, J. (2017). *Autonomous Emergency Braking AEB (pedestrians and cyclists). H2020 project Safety Cube*. https://www.roadsafety-dss.eu/assets/data/pdf/synopses/Autonomous_Emergency_Braking_AEB_pedestrians_cyclists_20112017.pdf. (Accessed Nov. 2020).

Saadé, J., Chajmowicz, H., & Cuny, S. (2019). Prospective Evaluation of the Effectiveness of Autonomous Emergency Braking Systems in Increasing Pedestrian Road Safety in France. *Traffic Injury Prevention*, 20, S20-S25. https://doi.org/10.1080/15389588.2019.1679797

Sander, U. (2017). Opportunities and limitations for intersection collision intervention-A study of real world 'left turn across path' accidents. *Accident Analysis and Prevention*, 99, 342-355. https://doi.org/10.1016/j.aap.2016.12.011

Sander, U. (2018a). *Predicting safety benefits of automated emergency braking at intersections - virtual simulations based on real-world accident data*. Ph.D. Thesis. Chalmers University of Technology, Gothenburg, Sweden.

Sander, U., & Lubbe, N. (2016). *Prediction of accident evolution by diversification of influence factors in computer simulation: opportunities for driver warnings in intersection accidents*. In: Proceedings of Methodenentwicklung für Aktive Sicherheit und Automatisiertes Fahren, Oct. 26-27 Essen, Germany.

Sander, U., & Lubbe, N. (2018). The potential of clustering methods to define intersection test scenarios: Assessing real-life performance of AEB. *Accident Analysis and Prevention*, 113, 1-11. https://doi.org/10.1016/j.aap.2018.01.010

Sasidharan, L., Wu, K. F., & Menendez, M. (2015). Exploring the application of latent class cluster analysis for investigating pedestrian crash injury severities in Switzerland. *Accident and Analysis Prevention*, 85, 219–228. http://dx.doi.org/10.1016/j.aap.2015.09.020

Savino, G., Giovannini, F., Baldanzini, N., Pierini, M., & Rizzi, M. (2013). Assessing the potential benefits of the motorcycle autonomous emergency braking using detailed crash reconstructions. *Traffic Injury Prevention*, 14, S40–S49. https://doi.org/10.1080/15389588.2013.803280

Savino, G., Pierini, M., Rizzi, M., & Frampton, R. (2013). Evaluation of an autonomous braking system in real world PTW crashes. *Traffic Injury Prevention*. 14(5), 532–543. https://doi.org/10.1080/15389588.2012.725878

Scanlon, J. M., Page, K., Sherony, R., & Gabler, H. C. (2016). *Using event data recorders from real-world crashes to investigate the earliest detection opportunity for an intersection advanced driver assistance system.* SAE Technical Paper 2016-01-1457. https://doi.org/10.4271/2016-01-1457

Schmitt, U., Niederer, P. F., Cronin, D. S., Muser, M. H., & Walz, F. (2014). *Trauma Biomechanics: An Introduction to Injury Biomechanics. Forth Edition.* Springer International Publishing.

Seller, P., Song, B., & Hedrick, J.K. (1998). Development of a collision avoidance system. *Automotive Engineering International*, 109, 24–28. https://doi.org/10.4271/980853

Shinar, D., Treat, J. R., & Mcdonald, S. T. (1983). The validity of police reported accident data. *Accident Analysis and Prevention*, 15 (3), 175-191. https://doi.org/10.1016/0001-4575(83)90018-0

Sina Car. (2019). *两轮电动车市场规模将达千亿*. http://k.sina.com.cn/article_6587629867_188a7412b00100kf3d.html. (Accessed Sep. 2020).

Stoll, J., Schneider, A., Wisch, M., Seiniger, P., & Schaller, T. (2016). *The Addressed VRU Scenarios Within PROSPECT and Associated Test Catalogue, PROSPECT Deliverable D3.1.* Retrieved from https://www.researchgate.net/publication/330675531_Deliverable_D31_The_addressed_VRU_scenarios_within_PROSPECT_and_associated_test_catalogue. (Accessed May 2020.

Strandroth, J., Rizzi, M., Sternlund, S., Lie, A., & Tingvall, C. (2011). The correlation between pedestrian injury severity in real-life crashes and Euro NCAP pedestrian test results. *Traffic Injury Prevention*, 12(6), 604–613. https://doi.org/10.1080/15389588.2011.607198

Strandroth, J., Sternlund, S., Lie, A., Tingvall, C., Rizzi, M., Kullgren, A., Ohlin, M., & Fredriksson, R. (2014). Correlation Between Euro NCAP Pedestrian Test Results and Injury Severity in Injury Crashes with Pedestrians and Bicyclists in Sweden. *Stapp Car Crash Journal*, 58, 213-231. https://doi.org/10.4271/2014-22-0009

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 Journal*, 56, 497–509. https://doi.org/10.4271/2012-22-0015

Sui, B., Lubbe, N., & Bärgman, J. (2019). A clustering approach to developing car-to-two-wheeler test scenarios for the assessment of Automated Emergency Braking in China using in-depth Chinese crash data. *Accident Analysis and Prevention*, 132, 105242. https://doi.org/10.1016/j.aap.2019.07.018

Sui, B., Zhou, S., Zhao, X., & Lubbe, N. (2017). *An overview of car-to-two-wheeler accidents in China: Guidance for AEB assessment*. In: Proceedings of the 25th International Technical Conference on the Enhanced Safety of Vehicles (ESV). Jun. 5-8, Detroit Michigan, United States. Paper Number 17-0204.

Sunnevång, C., Rosén, E., & Bostrom, O. (2009). Real-life fatal outcome in car-to-car near-side impacts—implications for improved protection considering age and crash severity. *Traffic Injury Prevention*, 10, 194 - 203. https://doi.org/10.1080/15389580802594127

TechSci Research (2019). *China Two Wheeler Market By Vehicle Type (PTW, Scooter/Moped and Electric Two Wheelers), By Engine/Battery Capacity, By Type of Sales (Individual vs Institutional), By Region, Forecast and Opportunities*, 2024. https://www.techsciresearch.com/report/china-two-wheeler-market/3195.html. (Accessed Oct. 2020).

Theofilatos, A., & Efthymiou, D. (2012). Investigation of pedestrians' accident patterns in Greater Athens area. *Procedia Social and Behavioral Sciences*, 48, 1897–1906. https://doi.org/10.1016/j.sbspro.2012.06.1164

Tivesten, E. (2014). *Understanding and prioritizing crash contributing factors*. Ph.D. Thesis. Chalmers University of Technology, Gothenburg, Sweden.

Uittenbogaard, J., Op den Camp, O., & van Montfort, S. (2016b). *CATS car-to-cyclist accident parameters and test scenarios.* TNO 2014 R11705. http://publications.tno.nl/publication/34622251/lXpquB/TNO-2014-R11705.pdf. (Accessed Oct. 2020).

Uittenbogaard, J., Rodarius, C., & Op den Camp, O. (2016a). *CATS car-to-cyclist accident scenarios.* TNO 2014 R11594*.* http://resolver.tudelft.nl/uuid:2ff8352c-5caf-4b77-9dff-97164121c31a. (Accessed Oct. 2020).

Wang, J., & Wei, H. (1993). *Traffic Segregation on Spatial and Temporal Bases: The experience of Bicycle Traffic Operations in China*. http://onlinepubs.trb.org/Onlinepubs/trr/1993/1396/1396-003.pdf. (Accessed Nov. 2020).

Wang, X., Xu, Y., & Tremont, P. (2012). Moped rider violation behavior and moped safety at intersections in China. *Transportation Research Record*, 2281(1), 83–91. https://doi.org/10.3141/2281-11

Warshawsky-Livne, L., & Shinar, D. (2002). Effects of uncertainty, transmission type, driver age and gender on brake reaction and movement time. *Journal of Safety Research*, 33(1), 117–128. https://doi.org/10.1016/s0022-4375(02)00006-3

Weinert, J. X, Ma, C., & Cherry, C. (2006). *The transition to electric bikes in china: history and key reasons for rapid growth.* Retrieved from https://escholarship.org/uc/item/00m5410t. (Accessed Nov. 2020).

Weinert, J. X., Ma, C., Yang, X., & Cherry, C. R. (2007). Electric two-wheelers in china: effect on travel behavior, mode shift, and user safety perceptions in a medium-sized city. *Transportation Research Record*, 2038(1), 62–68. https://doi.org/10.3141/2038-08

Weiss, H. B., Kaplan, S., & Prato, C. G. (2016). Fatal and serious road crashes involving young New Zealand drivers: a latent class clustering approach. *International Journal of Injury Control and Safety Promotion*, 23(4), 427–443. https://doi.org/10.1080/17457300.2015.1056807

WHO, (2018). *Global Status Report on Road Safety 2018*. https://www.who.int/violence_injury_prevention/road_safety_status/2018/English-Summary-GSRRS2018.pdf?ua=1. (Accessed Oct. 2020).

Wisch, M., Lerner, M., Kovaceva, J., Bálint, A., Gohl, I., Schneider, A., Juhász, J., & Lindman, M. (2017). *Car-to-Cyclist Crashes in Europe and Derivation of Use Cases as Basis for Test Scenarios of Next Generation Advanced Driver Assistance Systems - Results From PROSPECT*. In: Proceedings of the 25th International Technical Conference on the Enhanced Safety of Vehicles (ESV). Jun. 5-8, Detroit Michigan, United States. Paper Number 17-0396.

Wisch, M., Seiniger, P., Edwards, M., Schaller, T., Pla, M. B., Aparicio, A. F., Géronimi, S., & Lubbe, N. (2013). *European project AsPeCSS - interim result: development of test scenarios based on identified accident scenarios*. In: Proceedings of the 23rd International Technical Conference on the Enhanced Safety of Vehicles (ESV. May 27-30, Seoul, Korea. Paper Number 13-0405.

Woodrooffe, J., Blower, D., Flannagan, C., Bogard, S. & Bao, S. (2013)., *Effectiveness of a Current Commercial Vehicle Forward Collision Avoidance and Mitigation Systems.* SAE Technical Paper 2013-01-2394. https://doi.org/10.4271/2013-01-2394

Wu, C., Yao, L., & Zhang, K. (2012). The red-light running behavior of electric bike riders and cyclists at urban intersections in China: An observational study. *Accident Analysis and Prevention*, 49(0), 186–192. https://doi.org/10.1016/j.aap.2011.06.001

Yamazaki, T., Iijima S, & Yamamoto, T. (2001). *Exploratory Study of an Airbag concept for a large touring motorcycle: further research*. In: Proceedings of the 17th International Technical Conference on the Enhanced Safety of Vehicles (ESV). Jun. 4-7, Amersterdam, Netherlands. Paper Number 01-S9-O-240.

Yanagisawa, M., Swanson, E., Azeredo, P., & Najm, W. G. (2017). *Estimation of potential safety benefits for pedestrian crash avoidance/mitigation systems*. (Report No. DOT HS 812 400). US Department of Transportation. https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/documents/812400_pcambenefitsreport.pdf. (Accessed Nov. 2020).

Yau, K. K. W. (2004). Risk factors affecting the severity of single vehicle traffic accidents in Hong Kong. *Accident Analysis and Prevention*, 36 (3), 333–340. https://doi.org/10.1016/S0001-4575(03)00012-5

Yu, X. Q., Ke, L., Ivers, R., Du, W., & Senserrick, T. (2011). Prevalence rates of helmet use among motorcycle riders in a developed region in China*. Accident Analysis and Prevention*, 43(1), 214–219. https://doi.org/10.1016/j.aap.2010.08.012

Zander, O., & Hamacher, M. (2017). *Revision of passive pedestrian test and assessment procedures to implement head protection of cyclists*. In: Proceedings of the 25th International Technical Conference on the Enhanced Safety of Vehicles (ESV). Jun. 5-8, Detroit Michigan, United States. Paper Number 17-0376.

Zhang, J., Zhuo, J., & Chen, N. A. (2004). A study of PTW helmet use in Guangxi. *Chinese Journal of Disease Control and Prevention*, 8 (6), 512–515.

Zhao, Y., Ito, D., & Mizuno, K. (2019). AEB effectiveness evaluation based on car-to-cyclist accident reconstructions using video of drive recorder. *Traffic Injury Prevention*, 20(1), 100–106. https://doi.org/10.1080/15389588.2018.1533247