MODELLING THE INFLUENCE OF DRIVING SAFETY AIDS ON THE INCIDENCE OF TRAFFIC ACCIDENTS

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Abstract Several thousand motorcyclists die in the EU every year. Despite the severe risk of death and injuries, there is relatively little research on motorcycle safety, and standard automobile safety features are not offered for most motorcycle models. More than a quarter of all traffic accidents represent rear-end collisions, with motorcycles at a higher risk due to poorer visibility and driver protection. In this paper we present an overview of literature on collision warning systems and their influence on traffic safety, and the current state of our research on the potential impact of introduction of a rear-end collision warning system in motorcycles in the EU and thus its potential contribution to the EU "Vision Zero" goal: reduce road deaths to almost zero by 2050. To this end we have developed a hybrid simulation model of rear-end collisions using multiple simulation methodologies, including System Dynamics (SD) and Agent Based Modelling (ABM).

Keywords: traffic safety, motorcycle accidents, braking aids, active safety, simulation modelling, Vision Zero.

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1 Introduction

Although the number of road traffic fatalities in the EU has decreased by 23% from 2010 to 2019, several thousand powered two-wheeler (PTW) i.e., motorcycle, moped and scooter drivers or passengers still die each year. They are involved in a disproportionately high percentage of fatal and serious accidents, most of which are in cities and are mostly caused by human error (European Commission, 2014). Two-wheelers are involved in up to 26% of all fatalities on the EU roads even though they represent only about 10% of all motor vehicles (European Commission, 2020). Globally, the risk of death for PTW users is 20 times that of car drivers or passengers (Organisation For Economic Co-Operation And Development (OECD) & Forum, 2015). PTWs are less stable, less visible and offer poorer driver and passenger protection than cars.

Along with the loss of life and injuries, traffic accidents incur high economic and social costs. Despite the high risks associated with motorcycle use, relatively little research on motorcycle safety aids (e.g., ESS, RECAS, AEB, FCW) has been carried out, and safety features that are standard in automobiles such as ABS, EBS, or even fog lights are not offered for most motorcycle models. According to NHTSA (NHTSA, 2007), rear-end crashes are the most frequently occurring type of collision, accounting for approximately 29% of all crashes, 7% of crashes with fatalities and resulting in a substantial number of injuries and fatalities each year. Rear-end collisions in which the lead vehicle is stopped or moving very slowly prior to the crash account for most of these crashes (NHTSA, 2007). Over the years several initiatives have addressed the problem of rear-end crashes, with limited success. For motorcycles, rear-end collisions may represent only 7% of all traffic accidents (NHTSA, 2021), however even a low speed rear-end collision into a motorcycle can result in disastrous consequences.

In previous research at the Faculty of Information Studies (Barbo & Rodič, 2021) we have developed MEBWS – motorcycle emergency braking warning system, a "warning system for rear-end collision prevention in motorcycles for the cases of emergency braking of motorcycle and excessively fast approach of following vehicles", a patented innovation which aims to increase the rear visibility of motorcyclists in critical situations and consequently reduce the number of rear-end collisions. MEBWS analyses motorcycle movement in real-time using an accelerometer and GPS and monitors the vehicles behind the motorcycle using a LIDAR. In case a potential rear-end collision is detected, MEBWS alerts the vehicles behind the motorcycle with an autonomous flashing LED light. Therefore, MEBWS represents a RECAS (Rear-end collision alert signal) type of safety aid for motorcycles.

The European Commission's long-term strategic goal is to get close to zero deaths and zero serious injuries on EU roads by 2050 (Vision Zero), and its medium-term goal is to reduce deaths and serious injuries by 50% by 2030 (European Parliament, 2021). Today, well-established safety measures such as wearing helmets and protective clothing have reduced the vulnerability of motorcyclists in traffic to a certain extent, but this is not enough. More active and passive safety mechanisms are needed to further increase the traffic safety of drivers of two-wheeled vehicles. For example, US data estimated that 80% of the deaths and injuries resulting from rear-end collisions could be prevented by collision avoidance technology (NTSB, 2015). With over 1 million new motorcycles and other PTWs sold annually in the EU (Motorcycles Data, 2021), the introduction of mandatory safety features has the potential to significantly improve EU traffic safety. To support the case for introduction of safety features such as MEBWS as standard equipment of motorcycles, we are conducting research on the influence of collision warning systems on traffic safety in the EU with the use of simulation modelling methodology. To this end we have developed a hybrid simulation model of rear-end collisions using multiple simulation methodologies, including System Dynamics (SD) and Agent Based Modelling (ABM) allowing heuristic verification of the influence of various technological, human, and environmental factors on the probability and consequences of traffic accidents. In our research we will examine the impact of varying levels of market penetration of MEBWS on road safety in different scenarios in which rear-end collisions may occur.

In this paper we present an overview of existing literature on rear-end collisions and collision warning systems and the current state of our research on the influence of collision warning systems on traffic safety.

2 Previous research

The key study in the area of motorcycle traffic safety is MAIDS (Motorcycle Accident In Depth Study), conducted by ACEM (Association des Constructeurs Européens de Motocycles) and supported by the European Commission (ACEM, 2009; Grassi et al., 2018). The MAIDS study included 921 accidents of PTW vehicles, and within those accidents a second vehicle was present in 778 of the cases. In total, 11.2% of the PTW accidents resulted in fatalities. The study was carried out in the period of 1999–2000 in France, Germany, the Netherlands, Spain and Italy, with each accident recorded with a questionnaire containing 2000 variables. The MAIDS study forms the basis for much of further research in this field.

According to MAIDS results, pre-accident speeds for all PTW categories were relatively low, in most cases below 50 km/h. In only a few cases, speeding of one of the vehicles was a contributing factor to the accident. In 87.9% of cases, the human factor was the cause of the accident. The inattention of the OV (vehicle hitting the PTW) driver contributed to the traffic accident in 18.4% of the cases. In 36.6% of cases, the PTW driver was overlooked by the driver of OV due to a detection error or poor visibility of the PTW or its driver (ACEM, 2009), with the driver error recorded as:

- perception failure, e.g., lack of attention, temporary obstruction due to other vehicles or objects,
- comprehension failure, i.e., perceiving, but not understanding a dangerous situation,
- decision failure, e.g., ignoring the yellow or red light at a traffic light intersection and
- reaction failure, e.g., not reducing speed, although the condition of the road has critically deteriorated.

2.2 Rear-end collisions involving PTWs

The dynamic forces of the collision of a PTW with a car or truck are much higher than in the collision of two equivalent vehicles (Guderian, 2011, 2017). When a motorcyclist stands in front of an already standing car or truck, in the event of a collision all the kinetic energy of the pursuing vehicle is transferred directly to one point of the motorcycle and not to a large surface, as in the case of a car or truck (Guderian, 2011).

An important factor in traffic accidents involving motorcyclists remains the hindered perception by other drivers and their misjudgement about the motorcycle's position and speed (ITF & OECD, 2015). The motorcycle is smaller than other motor vehicles, and its silhouette at the 180° angle i.e., the viewing angle of the drivers of pursuing vehicles is the smallest, which is one of the reasons why drivers often do not notice that a motorcyclist in front has slowed down or stopped. From the point of view of a pursuing vehicle, a motorcycle covers about one quarter of the surface of a passenger car when viewed from the same distance (ITF & OECD, 2015; Tang et al., 2006).

2.4 Rear collision warning safety aids

To summarize the international regulations (Regulation No 48 of the Economic Commission for Europe of the United Nations (UNECE) — Uniform Provisions Concerning the Approval of Vehicles with Regard to the Installation of Lighting and Light-Signalling Devices [2019/57], 2019; European Commission Industry, Entrepreneurship and SMEs, 2016), the ESS (Emergency Stop Signal), also referred to as EBD (Emergency Braking Display) are lights that flash quickly when the driver brakes at full power (negative acceleration at least 6 m/s^2). Drivers driving behind a vehicle with an ESS aid are immediately warned that the vehicle in front of them is slowing down quickly and that they should react accordingly (GRE in (European Commission Industry, Entrepreneurship and SMEs, 2016), p. 8). ESS is currently offered by some car manufacturers but will become mandatory in new cars and trucks in the EU by 2024. ESS has proven to be a very effective safety aid, as it shortens the reaction time and consequently reduces the risk of accidents (European Commission Industry, Entrepreneurship and SMEs, 2016). A supplementary technology, the RECAS (Rear-End Collision Alert Signal) system uses ESS lights in the event of an impending collision with a pursuing vehicle. The system is activated at relative speed v_r greater than 30 km/h when the time to collision is ≤ 1.4 s, and at speeds up to 30 km/h when the time to collision is $\leq 1.4/30\ v_r$ (Regulation No 48 of the Economic Commission for Europe of the United Nations (UNECE) — Uniform Provisions Concerning the Approval of Vehicles with Regard to the Installation of Lighting and Light-Signalling Devices [2019/57], 2019). The operating parameters of the ESS emergency brake lights and the RECAS system are subject to international regulations (UN / ECE Regulation No. 48, Chapters 6.23 and 6.25, Regulation No. 13-H, Chapter 5.2.23 and Regulation No. 13, Chapter 5.2.1.31), which do not apply to motorcycles (*Regulation No 13-H of the Economic Commission for Europe of the United Nations (UN/ECE) — Uniform Provisions Concerning the Approval of Passenger Cars with Regard to Braking [2015/2364]*, 2015; *Regulation No 13 of the Economic Commission for Europe of the United Nations (UN/ECE) — Uniform Provisions Concerning the Approval of Vehicles of Categories M, N and O with Regard to Braking [2016/194]*, 2016; Regulation No 48 of the Economic Commission for Europe of the United Nations (UNECE) — Uniform Provisions Concerning the Approval of Vehicles with Regard to the Installation of Lighting and Light-Signalling Devices [2019/57], 2019). Projections also show that in Germany, the number of rear-end collisions would be reduced by 14% with 70% ESS penetration on the automotive market (Gail, Lorig, Gelau, Heuzeroth & Sievert in (*Report from the Commission to the European Parliament and the Council Saving Lives: Boosting Car Safety in the EU Reporting on the Monitoring and Assessment of Advanced Vehicle Safety Features, Their Cost Effectiveness and Feasibility for the Review of the Regulations on General Vehicle Safety and on the Protection of Pedestrians and Other Vulnerable Road Users*, 2016), p. 9).

3 Methodology: rear-end collision simulation modelling

The main research questions are:

1. How would the application of MEBWS affect the outcome (i.e., the severity of injuries) of traffic accidents in selected rear-end collision scenarios due to shortened driver reaction time and thus a lower probability of collision or reduced kinetic energy at impact?
2. What is the potential impact of varying levels of motorcycle market penetration of MEBWS on overall road safety in different scenarios in which rear-end collisions may occur due to reducing the number of accidents and the severity of their consequences?

We have not found any previous research results on the road safety effects of safety aids for PTW vehicles integrating the same functionalities as MEBWS, which is not surprising due to unavailability of such devices either as factory installed or as aftermarket products (i.e., combining the functionalities of ESS emergency brake lights and detection of vehicles behind a motorcycle and warning of the possibility of a collision into a RECAS system).

Because field research using experiments is not feasible without significant financial and technological resources, the methodology of our research is based on the use of modelling and simulation methods which allow experiments in a computer model of a road transport system. While analytical methods can be used to calculate the reduction of reaction time and thus reduced speed at impact of vehicles in a general scenario, the accuracy of results and adaptability of the solution would be limited. The outcome of a rear-end collision depends on many factors, from road conditions, visibility to human factors, which are stochastic in nature. Heuristic methods such as simulation modelling are better suited for analysis of complex, nonlinear systems containing stochastic variables.

The road transport system simulation model presented here is a hybrid i.e., a multimethod model: the roadway, vehicles, their dynamics, and the driver's reaction are modelled by a combination of ABM (Agent-Based Modelling) and System Dynamics (SD) methods. The model variables and parameter values are based on data from MAIDS (ACEM, 2009; Grassi et al., 2018) and other previous research projects cited in this paper. As the main purpose of the model is simulation of rear-end collisions, the model contains a single road section. To ensure the validity of the simulation results for the overall traffic safety in the EU, we will develop simulation scenarios in which the distribution of situations with different vehicle speeds and traffic density of individual vehicle categories will correspond to Eurostat and other publicly available statistical data on road infrastructure, amount and type of road traffic and road traffic accidents in the European Union (European Commission, 2021).

3.1 System Dynamics modelling

In our previous paper (Barbo & Rodič, 2021) we have presented the use of a SD model for high abstraction level modelling of the impact of traffic safety parameters on daily number of traffic accidents in the EU. This SD model (shown in (Barbo & Rodič, 2021)) works as standalone and allows us to verify and calibrate the influence of a diverse set of parameters, based on the results of the seminal MAIDS study (ACEM, 2009; Grassi et al., 2018). In addition, this SD model also has a didactic function, as it serves as a presentation of the mutual influence of various factors on the occurrence of traffic accidents e.g., weather related visibility and road conditions, level of maintenance of vehicles, road maintenance, etc. The basic calibration of this model has been performed using Eurostat statistical data on traffic accidents for year 2020 (European Commission, 2021). Neutral values of parameters (i.e., multiplier of 1) represent the average values of parameters such as motorcyclist visibility and driver reaction time among the EU population of drivers.

The SD model is deceptively simple, as it includes a single level (stock) element (Total number of rear accidents) and a flow element (Daily occurrences of accidents) and contains no feedback loops. The number of model parameters and their interplay however makes the model calibration and experimentation complex. However, we can set the values of parameters outside of research scope to neutral values. As the main goal of our research is to verify the influence of varying levels of market penetration of MEBWS (RECAS for motorcycles) on road safety, we have focused on the influence of MEBWS on driver reaction time and its influence on rear-end accident probability. We have thus calibrated the relevant parameters as well as validated the model using previous research on the effectiveness of rear-end collision warning aids (Cicchino, 2017; Kusano & Gabler, 2012; Li et al., 2014; NTSB, 2015).

While the high abstraction level SD model would allow us to model the potential impact of MEBWS on traffic safety on the macro level of the EU's road transport system, the results would be at best approximate. Furthermore, in order to model the influence of MEBWS on the outcomes of rear-end traffic accidents (i.e., the probability of collision and severity of injuries), we needed to build a micro (low abstraction level) simulation model, which allows us to model individual incidents.

3.2 System Dynamics model integration in the hybrid model

Adaptation of the high abstraction level SD model for integration in the hybrid model required the removal of the stock and flow elements representing the daily number and cumulative number of accidents, as the micro model allows the simulation of individual traffic incidents, with "accident" as one of the possible outcomes. The number of accidents per day on micro level is therefore a statistic from a number of simulation runs.

The system dynamics (SD) model is located in the centre of the hybrid model interface shown in Figure 1. The SD model allows testing the impact of individual traffic safety parameters such as presence of safety mechanisms, weather conditions, technical condition of vehicles, etc. on the probability of traffic accidents via their influence on driver reaction time, braking distance etc. The parameter of motorcycle visibility (Visibility of PTW), which depends on the presence of a MEBWS safety aid, is used to calculate the time to collision variable (TTC) (translatable to vehicle distance) when the driver of the pursuing vehicle notices the motorcycle. This value is the SD model's input into the other hybrid model components.

Other MAIDS (ACEM, 2009; Grassi et al., 2018) based parameters include the vehicle condition, general roadway surface condition, weather influence on visibility and roadway surface and driver fitness, which should allow us (and other users) to adapt the model to the characteristics of different road transport systems in the future.

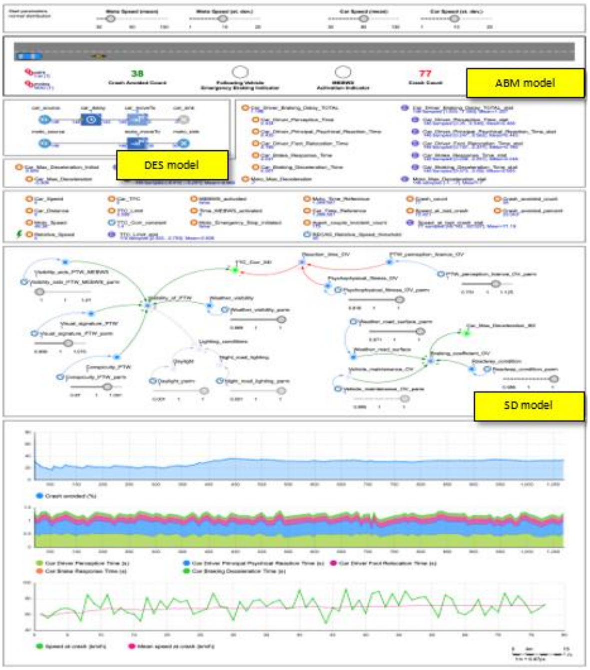

Figure 1: Hybrid simulation model of rear-end collisions

Source: authors

3.3 Discrete Event Simulation modelling

The DES (discrete event simulation) component of the model is a simple process model, used to generate the arrivals of vehicle (car and motorcycle), model their movement on the road and model a part of their behaviour (i.e., pursuit of the motorcycle by the car). While these functionalities can also be modelled using ABM (Siebers et al., 2010), the DES process diagram improves model clarity.

3.4 Agent based modelling

The ABM part of the model (see e.g. (Bonabeau, 2002; Gilbert, 2007; Ligmann-Zielinska, 2010) for introduction to agent based modelling) represents a section of a road with two vehicles, allowing us to model typical rear-end collision scenarios. The car driver behaviour is modelled using the state chart (Figure 2), which is based on research presented in (Markkula et al., 2012). In complex scenarios such as a traffic accident, ABM can effectively simulate human perception and decision making and consequently help understand and improve transport systems (Alqurashi & Altman, 2019; Tchappi Haman et al., 2017).

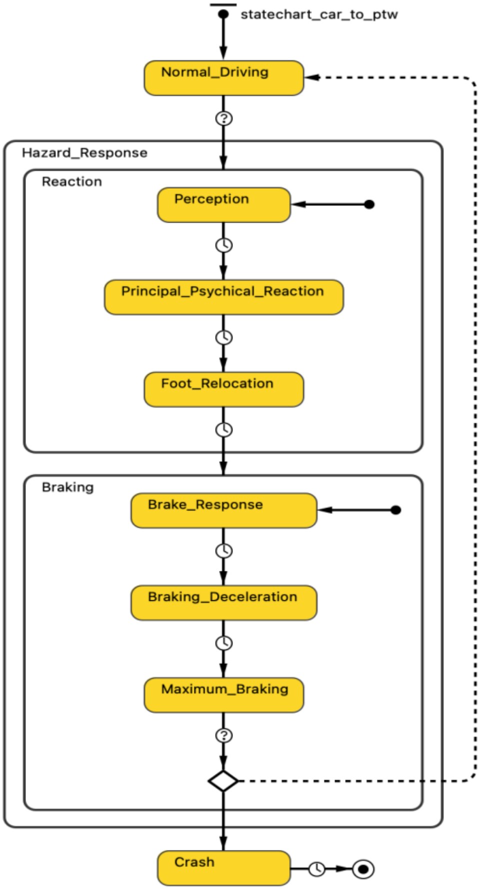

Figure 2: Driver behaviour state chart
Source: authors

The states are grouped into "normal driving" which represents driving with a constant speed while no motorcycle is present (or detected), "hazard response", which represents the phases between first detection of the motorcycle and its "perception" as a potential road hazard (something that the car can collide with) and the "relocation" of car driver's foot to the brake pedal. The next group of states is "braking" and models the phases from the initial "brake response" to the "maximum braking" (we are assuming the driver eventually elicits maximum braking force). In case of vehicle contact, a collision and relative speed at collision are recorded, updating the statistics and graphs in the bottom of Figure 1, otherwise "normal driving" state is resumed, and another scenario is generated (road is cleared, a new car and motorcycle agents are introduced). Most of the transitions between states (shown as clock symbol in Figure 2) are modelled as timeouts e.g., with PERT/Gamma distribution, based on research in (Karwowska & Simiński, 2015) and (Reński in (Karwowska & Simiński, 2015), 2015, p. 60–62).

3 Results and conclusion

After simulating 697 emergency braking of the OV agent, we found that an accident occurs in 17.96% of cases (125 collisions) if the agent brakes with an average deceleration of -6.979 m/s^2 (coefficient of friction 0.71). The minimum, maximum and average speed at collision were 1.296 km/h, 53.545 km/h and 14.750 km/h, respectively. The average sum of the reaction times of the car driver agent and their response times were 1.215 s, while the average TTC_Limit (the time before impact when the car needs to apply maximum braking force to barely avoid a collision) was 2.615 s. The car driver agent starts braking when a potential collision is noticed, but usually just in time to avoid a collision. We found that TTC_Limit of 1.4 s (as found in regulations (Regulation No 48 of the Economic Commission for Europe of the United Nations (UNECE) — Uniform Provisions Concerning the Approval of Vehicles with Regard to the Installation of Lighting and Light-Signalling Devices [2019/57], 2019)) is usually not enough to successfully stop the vehicle, as the sum of the individual reaction times is on average 1.2 s before braking with maximum deceleration even begins. The result was somewhat surprising, given that this value appears in the literature as the activation parameter of the RECAS system, which is supposed to provoke visual perception and immediate braking. It takes about 1 s for the driver to respond, which means that the vehicle should stop in about 0.4 s, which is unrealistic.

Limitations of the current version of the model include the focus on rear-end collisions and the modelling of the road transport system as a set of scenarios using a distribution of vehicle speeds, traffic density and road sections based on publicly available statistical data on road infrastructure, amount and type of road traffic. Both limitations are the results of a conscious choice. Finding the right level of abstraction is one of the key decisions in modelling. While a high level of abstraction (e.g. SD model in section 3.1) loses out on details, too many details can also be problematic. The modelling of other types of accidents (head on, lateral etc.) would require significant additional time and effort, without contributing to our research goal, while the development of a low abstraction model, i.e., a Geographic Information System (GIS) model of the entire EU-wide road transport system (with over 6 million km of roads) would not be feasible within our project. Development of such a model would require very significant data and computing resources, resulting in a highly complex model, which would be difficult to calibrate and adapt to changes in EU road network or regulations or adapt for other road transport systems. We believe that the selected level of abstraction will yield sufficiently precise results while being feasible.

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