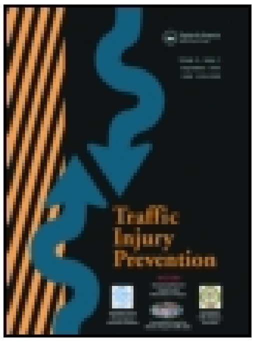

Traffic Injury Prevention

ISSN: 1538-9588 (Print) 1538-957X (Online) Journal homepage: https://www.tandfonline.com/loi/gcpi20

Active safety systems for powered two-wheelers: A systematic review

Giovanni Savino, Roberto Lot, Matteo Massaro, Matteo Rizzi, Ioannis Symeonidis, Sebastian Will & Julie Brown

To cite this article: Giovanni Savino, Roberto Lot, Matteo Massaro, Matteo Rizzi, Ioannis Symeonidis, Sebastian Will & Julie Brown (2020): Active safety systems for powered two-wheelers: A systematic review, Traffic Injury Prevention, DOI: 10.1080/15389588.2019.1700408

To link to this article: https://doi.org/10.1080/15389588.2019.1700408

TRAFFIC INJURY PREVENTION
https://doi.org/10.1080/15389588.2019.1700408

Taylor & Francis
Taylor & Francis Group

OPEN ACCESS   Check for updates

Active safety systems for powered two-wheelers: A systematic review

Giovanni Savino[a,b], Roberto Lot[c,d], Matteo Massaro[e], Matteo Rizzi[f], Ioannis Symeonidis[g], Sebastian Will[h], and Julie Brown[i,j]

[a]Department of Industrial Engineering (DIEF), University of Florence, Florence, Italy; [b]Accident Research Centre, Monash University, Melbourne, Australia; [c]University of Padua, Padua, Italy; [d]University of Southampton, Southampton, UK; [e]Department of Industrial Engineering, University of Padua, Padua, Italy; [f]Swedish Transport Administration, Stockholm, Sweden; [g]Centre for Research and Technology - Hellas, Thessaloniki, Greece; [h]Würzburg Institute for Traffic Sciences (WIVW), Würzburg, Germany; [i]The George Institute for Global Health, Sydney, Australia; [j]Neuroscience Research Australia, Sydney, Australia

ABSTRACT

Objective: Active safety systems, of which antilock braking is a prominent example, are going to play an important role to improve powered two-wheeler (PTW) safety. This paper presents a systematic review of the scientific literature on active safety for PTWs. The aim was to list all systems under development, identify knowledge gaps and recognize promising research areas that require further efforts.

Methods: A broad search using "safety" as the main keyword was performed on Scopus, Web of Science and Google Scholar, followed by manual screening to identify eligible papers that underwent a full-text review. Finally, the selected papers were grouped by general technology type and analyzed via structured form to identify the following: specific active safety system, study type, outcome type, population/sample where applicable, and overall findings.

Results: Of the 8,000 papers identified with the initial search, 85 were selected for full-text review and 62 were finally included in the study, of which 34 were journal papers. The general technology types identified included antilock braking system, autonomous emergency braking, collision avoidance, intersection support, intelligent transportation systems, curve warning, human machine interface systems, stability control, traction control, and vision assistance. Approximately one third of the studies considered the design and early stage testing of safety systems (n. 22); almost one fourth (n.15) included evaluations of system effectiveness.

Conclusions: Our systematic review shows that a multiplicity of active safety systems for PTWs were examined in the scientific literature, but the levels of development are diverse. A few systems are currently available in the series production, whereas other systems are still at the level of early-stage prototypes. Safety benefit assessments were conducted for single systems, however, organized comparisons between systems that may inform the prioritization of future research are lacking. Another area of future analysis is on the combined effects of different safety systems, that may be capitalized for better performance and to maximize the safety impact of new technologies.

ARTICLE HISTORY
Received 8 August 2019
Accepted 29 November 2019

KEYWORDS
Motorcycle; active safety; primary safety; systematic review

Introduction

Injury among motorcyclists is a global health problem. Worldwide, more than 300,000 people are killed annually using powered two-wheelers (PTW) (World Health Organisation 2015) and unless new effective solutions come in place, this figure is expected to grow. While the number of PTWs within the motor vehicle fleet of different countries varies, worldwide the absolute number of PTWs on the road has been steadily increasing (OECD/International Transport Forum 2015). In many countries within the European Union, in the United States, and in Australia, the growth of the PTW fleet over the last few decades has far surpassed the growth of the passenger car fleet (OECD/International Transport Forum 2015). In many Asian countries, PTWs continue to provide the primary means of transportation, with around 75% of the 300 million PTWs currently used on roads, being used in Asia (Rogers 2008). While there are a number of potential benefits to individuals and traffic systems in terms of mobility, cost-effective transport, and reduced congestion associated with increased use of PTWs, currently these may be offset by the increased risk of death and serious injury associated with the use of PTWs compared to other transport modes (OECD/International Transport Forum 2015). Previous research has shown that the fatality rates for motorcyclists are 20–40 times higher than for car occupants per distance traveled (Yannis et al. 2012; Blackman and Haworth 2013).

CONTACT Giovanni Savino giovanni.savino@unifi.it University of Florence, Florence, Italy.
Associate Editor H. Clay Gabler oversaw the review of this article.
Supplemental data for this article can be accessed on the publisher's website.

For other vehicle types, such as passenger cars, substantial investment in improved vehicle safety systems has resulted in significant reductions in death and injury. Recent estimates by the National Highway and Traffic Safety Administration (NHTSA) in the United States indicate more than 600,000 lives were saved from 1960 through 2012 in the United States alone due to enhanced vehicle safety technologies (Kahane 2015). Historically, many vehicle safety technologies applied to passenger vehicles have focused on injury prevention once a crash has happened, but more recently, many new technologies have focused on crash prevention. This includes technologies like electronic stability control, enhanced braking systems, and driver assist systems. These active safety systems have received much attention with respect to the potential benefit they are likely to impart to passenger vehicle drivers and occupants. Consumer information programs such as EuroNCAP have commenced assessing these types of systems and rewarding vehicle manufacturers for including these in new vehicle models (EuroNCAP 2015). Comparatively less attention has been given to the potential use and benefit of active safety systems for improving the safety of PTWs. This is despite the fact that many of the most common crash types among PTWs might be effectively mitigated through broader implementation of these types of safety systems. For example common PTW pre-crash scenarios identified through in-depth analysis include limited time for riders to take any evasive action, inadequate PTW braking, scan errors, low PTW conspicuity, and loss of control (Hurt et al. 1981; Sporner and Kramlich 2001; MAIDS 2004, 2009; Rizzi et al. 2009). PTW crashes also often occur at intersections. Given all these factors, potentially beneficial active safety systems for PTW include enhanced and assistive braking systems, collision warning, side view assist, enhanced stability systems, and intersection support systems.

Active safety technologies are being developed for PTWs and there have been some studies examining the potential effectiveness these might have in reducing PTW crashes. However, the literature reporting this work is scattered across a number of domains. A literature review on intelligent transport systems was performed by Barmpounakis et al. (2016), in which vehicle technologies and safety applications were briefly discussed together with several other topics related to PTWs. To date, there has been no attempt to systematically review work on PTW active safety technologies. Such a compilation is needed to provide researchers, industry, and government with an understanding of the current state of the art in this field, the current knowledge gaps and what technologies currently appear promising. This systematic review attempts to fill this space by synthesizing a broad spectrum of scientific literature reporting on phases of development, testing, and evaluation of active safety systems for PTWs.

Method

A systematic approach was used to collate data from published literature in the period from 1998 to 2018 using the academic datasets Scopus and Web of Science. In addition, Google Scholar search engine was used specifically to identify papers in English presented at the Enhanced Safety of Vehicles (ESV) conference and the International Motorcycle Conference organized by the Institut für Zweiradsicherheit (IFZ). The initial broad range search, performed on June 20th, 2018, used the following search string:

> (motorcycle OR "powered two wheeler" OR "powered two wheeled" OR moped OR "single track vehicle" AND safety).

The titles of selected records were then automatically screened for inclusion and exclusion using a-priori defined specific keywords (see supplementary Online Appendix for the complete list of keywords). To ensure consideration of the human factor, studies dealing with rider acceptability of safety systems were included in the review.

Two researchers (GS & RL) then manually screened the remaining titles for relevance, excluding those not related to active safety systems. Finally, abstracts of the remaining titles were manually reviewed by the same two researchers (GS & RL). At this point articles were excluded if there was no reference to PTWs, if the article focused on development of technologies with no direct implications on active safety, or if the study was incomplete or ongoing.

Full texts of the remaining records were accessed by the authors to extract information via a structured form. Data recorded included: article type (journal, conference, etc.), relevant safety system/technology (antilock braking system, curve warning, stability control, etc.), focus of the study (system development, field testing, evaluation, etc.), type of outcome (optimal intervention parameters, applicability, effectiveness, etc.), population/sample (if relevant), main findings.

The final reference list was then reviewed by all authors to identify any papers not identified in the search but known to be relevant. Once identified, these papers underwent a check by one researcher (GS) to ensure they met all inclusion criteria.

Data extracted from the final studies were thematically categorized by general technology type, i.e. antilock braking systems, autonomous emergency braking, collision avoidance, intersection support, intelligent transportation systems, curve warning, human machine interface, miscellanea, stability control, and vision assistance. The findings were then qualitatively summarized by type of system and type of study as shown in Table 1.

Reporting followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (http://www.prisma-statement.org) as closely as possible.

Results

Figure 1 presents a summary of the search process and results, and 62 articles underwent full review. These included 34 journal papers and 28 conference papers. Concerning the distribution in time, one paper was found in the period 2000–2005, 17 in the period 2006–2010, 27 in the period 2011–2015, and 17 in the remaining three years from 2016 to 2018. The studies can be classified in two main

Table 1. Summary of the systems and types of study included in the final list.

System	Number of papers*	Type of study
Antilock braking system	8 (5)	Experimental testing, computer simulations, evaluations of system effectiveness via retrospective crash data analysis
Autonomous emergency braking	10 (7)	Design and early stage testing, experimental testing, computer simulations, evaluations of system effectiveness via retrospective crash data analysis
Collision avoidance, intersection support, and intelligent transportation systems (ITS)	10 (5)	Design and early stage testing, field trials, computer simulations, riding simulator studies, evaluations of system effectiveness via retrospective crash data analysis
Curve warning	2 (2)	Design and early stage testing, field trials, riding simulator studies
Human machine interface and rider acceptability of assistance systems	12 (5)	Design and early stage testing, experimental testing, field trials, riding simulator studies, surveys
Miscellanea	5 (1)	Design and early stage testing, field trials, computer simulations
Stability control	6 (4)	Design and early stage testing, computer simulations, experimental testing, review
Traction control	5 (2)	Design and early stage testing, experimental testing, computer simulations, evaluations of system effectiveness via retrospective crash data analysis
Vision assistance	4 (3)	Design and early stage testing
Total	62 (34)	

*The number of peer-reviewed journal papers is provided in parentheses.

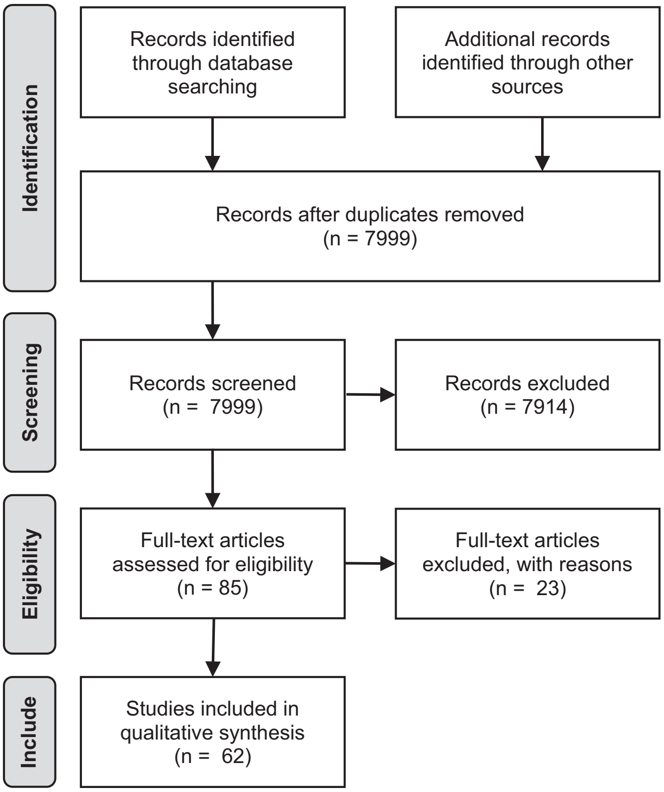

Figure 1. Search results as a PRISMA flow diagram.

groups: those which consider systems that influence the vehicle control and stability (such as antilock braking, autonomous braking, stability control, and traction control), and those dealing with the interaction between the rider and the vehicle, including systems that exchange information with the rider (collision avoidance, intersection support and intelligent transportation systems, curve warning, vision assistance, and more in general, human machine interfaces). The studies included design and early stage testing of safety systems (n.22), evaluations of system effectiveness via retrospective crash data analysis (n.15), experimental testing and field trials (n.13), riding simulator studies (n.5), computer simulations (n.15), and surveys (n.3).

Antilock braking system

Antilock Braking Systems (ABS) for motorcycles were introduced in the late 1980s to reduce braking distance by maintaining wheel rotation during hard braking. Experimental trials have shown ABS to generally provide shorter stopping distances and increase braking stability preventing motorcyclists from falling to the ground (Gail et al. 2009; Teoh 2011; Lich et al. 2015).

Using a variety of police, hospital, and insurance data, a number of studies have demonstrated the real-world benefit of motorcycle ABS in reducing the number and severity of PTW crashes (Basch et al. 2015; Rizzi, Kullgren, et al. 2015; Rizzi, Strandroth, et al. 2015). There is also some limited evidence indicating ABS specifically reduces ‘sliding’ crashes, with in-depth investigations demonstrating riders who braked prior to a collision on ABS fitted PTWs were more likely to remain upright than those without ABS (Rizzi et al. 2016). Results from computer simulations suggest that the safety benefit of ABS can be maximized by implementing double-channel systems over single channel ABS systems (Ivanov et al. 2005).

Autonomous emergency braking

Autonomous Emergency Braking (AEB) is a last resort system that automatically performs a braking maneuver when the rider has no time to brake, or braking is delayed or absent due to distraction, perception failures or panic. While AEB is a mature technology that has been implemented in passenger cars for more than a decade and is now mandatory in Europe for trucks and buses, to date it has not yet been broadly implemented on PTWs. The literature is therefore limited to theoretical estimates of benefit, experimental examination of PTW stability under AEB and prototype system evaluation in rider trials.

Researchers examining the applicability of new safety technologies for PTWs by systematically analyzing the potential impact on in-depth crash investigation cases have reported AEB as a high priority system for PTWs (Grant et al. 2008), particularly when combined with ABS (Roll et al. 2009). There have been several studies using computer simulation to estimate potential benefits by reconstructing real-world cases from in-depth crash investigation with a hypothetical AEB system that deploys when an imminent collision becomes inevitable (approximately 0.5 s pre-crash). These studies have shown theoretical reductions of up to 10–14 km/h to PTW impact speed, depending on the crash scenario (Savino et al. 2013; 2014; 2015; Savino, Mackenzie, et al. 2016). To date there have been no objective estimates on potential benefits in terms of injury reduction.

Experimental trials have focused on the feasibility of automatic decelerations from the perspective of rider stability. These studies are few in number and have only examined the feasibility in limited conditions. Namely, with surrogate riders in crash tests with decelerations of up to 0.35 g (Symeonidis et al. 2012), with professional riders with expected decelerations of up to 0.8 g (Savino et al. 2012), and normal riders with unexpected mild deceleration events in straight line (mean 0.15 g) (Savino, Pierini, et al. 2016). While all have provided good support for feasibility in terms of rider stability and handling, there is a need to extend these studies to larger samples of riders, examine effects of genuine unexpected activations, and test the system in more realistic riding conditions. There is also a need to identify the threshold of safe interventions for different conditions, e.g. different levels of rider experience, type of vehicle, dynamic state, and road characteristics. Furthermore, technology development has been limited to setting up prototype systems and to the definition of triggering algorithms specific for single track vehicles (Savino, Giovannini, et al. 2016).

Collision avoidance, intersection support, and intelligent transportation systems

Current collision avoidance technology for PTW is limited to systems designed to scan the environment or monitor vehicle states to detect incipient conflict situations using a range of technologies including: video cameras (Fang et al. 2014; Gil et al. 2018), laser scanners (Roessler and Kauvo 2009), and vehicle to vehicle, or environment to vehicle communication (Berndt and Dietmayer 2008; Huth, Lot, et al. 2012; Miucic et al. 2015; Silla et al. 2018). Study outcomes presented in the literature include the assessment of timing of intervention (Berndt and Dietmayer 2008), detection accuracy (Roessler and Kauvo 2009), rider acceptance (Huth, Lot, et al. 2012), and safety impact (Berndt and Dietmayer 2008). In general, the technologies and systems described were in early stages of development, or involved early applications of existing automotive technologies to motorcycles. Study designs included computer simulation, early stage field tests of prototype systems, interaction with the rider, and expected benefits.

Studies examining collision warning systems reported high levels of detection accuracy (Fang et al. 2014; Gil et al. 2018) but noted limitations with existing technology in terms of real-time implementation (Fang et al. 2014) and timing (Berndt and Dietmayer 2008). Such functions appear viable when the opponent vehicle is coming from an opposite direction and turning in front of the host PTW. Tracking time of the obstacle detection system needs to be shorter than 0.5 s. The special PTW scenario of vehicle leaning was addressed by Roessler and Kauvo (2009) and Gil et al. (2018), demonstrating detection accuracy within certain boundaries of assessed lean angles.

Using real world data, Silla et al. (2018) examined the potential impact of intelligent transportation systems (ITS) that included a collaborative intersection system for improved PTW safety. The analysis showed that intersection support is beneficial for PTW riders, and assuming full penetration, such system may reduce the yearly number of rider fatalities in Europe by approximately 6%. However, computer simulation and simulator studies investigating intersection support systems have not as yet demonstrated the same potential global benefit. Berndt and Dietmayer (2008) reported that intersection support systems are more likely to contribute when the PTW is traveling at around 50 km/h compared to lower or higher speeds, and that automatic interventions on the brake system may be beneficial, particularly at T-junctions when violations of right-of-way could occur. However, Huth, Lot, et al. (2012) found no significant differences in the number of critical situations recorded in a simulator when participants were exposed to no intersection support compared to when they were provided with collision warnings via force feedback throttle or haptic glove. These results suggest that overall the support system did not modify riding behavior in test conditions. Hans et al. (2016) modeled one single case example to illustrate a proposed control approach based on the prediction of critical conditions for the PTW, including forward collision detection. This prediction model used computation of a reference swerve avoidance maneuver to elaborate real-time avoidance maneuvers after predicting possible collision in a time frame of a few seconds.

Collision warning may also be implemented via vehicle to vehicle communication. Miucic et al. (2015) performed an experimental test in highway settings and found that in both static and dynamic tests the quality of the communication was fair in a 40 m range. However, they also found that lateral positioning classification was not precise due to inaccurate GPS localization. Other researchers developed and tested low-cost collision detection systems using cameras (Muzammel, Yusoff, Meriaudeau 2017) and microphones (Muzammel, Yusoff, Malik, et al. 2017) for application in low- and middle-income countries. In both cases, the early stage low-cost solutions achieved an accuracy greater than 90%.

Santa et al. (2017) provided a technical description of cooperative ITS. The proposed device for Cooperative Intelligent Transport Systems (C-ITS) based on vehicular wireless communication and consisting in a cooperative awareness messaging system managed by on-board middleware, has an architecture suitable for installation on bikes.

Sundharam et al. (2016) developed a prototype ITS suitable for PTWs that identifies safety related parameters such as vehicle speed and blood alcohol concentration (BAC), and transmits these data over the Internet for monitoring purposes. The system can also display information sent by the central monitoring server, including safety-related messages.

Curve warning

Vehicle monitoring and warning systems can identify curve hazards. In Huth, Biral, et al. (2012) the authors reported that curve warnings delivered with haptic glove were effective in decreasing the number of hazard events, with small effects on rider workload in simulator trials. Biral et al. (2014) presented a pilot study on curve warning conducted on public roads, involving 10 participants. Objective analysis of experimental data showed that curve warning can provide the rider with correct and effective warnings, although in some cases the warning was issued too late.

Human machine interface and rider acceptability of assistance systems

The Human-Machine Interface (HMI) on a PTW typically describes all motorcycle-fixed devices that display information to the rider, such as the dashboard, and controls that are used to modify information displayed or change settings, such as switches on the handlebar. With a recent rapid increase in the number of functions available on PTWs, and the emergence of active safety systems for PTWs, there is an increasing need to ensure hazard free interactions with the HMI. Reflecting this, only a few HMI related papers were identified in this review and most of these were published during the last decade. The majority of the papers identified also focused on rider acceptance of HMI. This seems appropriate given the work by Huth and Gelau (2013) who used a theoretical model to predict the acceptance of rider assistance systems and found that social norms and interface design may be the strongest predictors of whether such systems are accepted with level of perceived safety being less relevant.

Almost all PTW HMI research conducted to date have been studies using some form of PTW simulator. Pieve et al. (2009) examined auditory & visual vs. auditory warnings in hazardous situations using a PTW desktop simulator. They found auditory & visual warnings have the highest detection rate and resulted in the best understanding of the warning content (urgency and direction of threat). This reflects the findings of other PTW simulator studies that examined combinations of sensory cues to issue a warning. In general, these studies report that multi-sensory warnings have the highest acceptance and result in objectively better rider performance in terms of reaction time (Valtolina et al. 2011). One study examined the effectiveness of different types of auditory warning in a simulator setting and reported that warnings that use non-emotional sounds improved performance in hazard situations and led to speed reduction and to a safer gaze behavior (Di Stasi et al. 2010).

Eight studies dealt specifically with the use and specification of haptic cues using a mix of simulator and riding trial designs. Baldanzini et al. (2011) evaluated a prototype handle for haptic HMI based on pressure cues and found the best compromise between perceptibility and acceptability was obtained with 1.5 Hz pressure stimuli. Regardless of the study design, the literature indicates that haptic cues achieve high acceptance. However, it is commonly noted that vibration patterns presented in a simulator setting need further investigation regarding recognizability and acceptability in a real riding setting when there are more disturbances from engine vibration or wind pressure (Diederichs et al. 2010).

A number of studies have examined different helmet-based HMI solutions. In on-road experiments, Song et al. (2017) found in-helmet crash warning systems achieved highest levels of acceptance. Touliou et al. (2012) found haptic feedback given as vibration signals within the helmet outperformed audio feedback from in-helmet stereo loudspeakers and visual information in the dashboard in terms of usability and acceptance. Two further studies dealt with placement and quantity of information presented in a Head-up Display (Ito et al. 2015; Jenkins and Young 2016) and found that generally riders prefer having a lot of information presented with icons or short words.

More generally, Beanland et al. (2013) conducted a large survey to investigate rider acceptability to a set of 18 assistance systems. Results showed that systems that reduce or limit rider control of the vehicle may suffer lower acceptability. Two important characteristics for rider acceptability are system reliability and affordability.

Miscellaneous systems

Other papers presented vehicle diagnostics (Manzoni et al. 2010; Bansal et al. 2016), active seat for improved handling (Goodarzi and Armion 2010), and anti-glare systems (Motoki et al. 2009).

Stability control

Stability control systems aim to enhance vehicle stability by controlling or preventing roll and yaw instabilities and by reducing related vibrations. Roll angle estimation is essential for such systems. The first commercial stability control for motorcycles appeared on the market in 2013 (Lich et al. 2016). Current generation technology combines ABS, traction control (TC), and combined braking (CB) technologies and extends their capabilities to cornering, through a roll angle estimation. This technology works by preventing the wheels from locking during braking (cornering ABS), preventing the drive wheel from spinning in acceleration (cornering TC), and ensure optimum distribution of brake force between both wheels (CB systems).

The current literature is limited to few studies and primarily focuses on stability control system design, with numerical assessment of proposed design solutions. The focus has been on specific scenarios where enhanced stability may be beneficial; e.g. tandem riding (Koizumi et al. 2008), corner braking (Tanelli, Corno, et al. 2009; Baumann et al. 2016), friction jump while cornering, and excessive lateral acceleration (De Filippi et al. 2014). Focus was also on the type of modulated variable, e.g. steering torque, wheel torque, braking distribution, velocity of stabilizing gyroscope, and suspension force. Outcomes are presented in terms of performance, e.g. reduction of brake-steer-torque (Baumann et al. 2016), reduction of roll rate vibrations (De Filippi et al. 2014), and reduction of skidding (Tanelli, Corno, et al. 2009). With the exception of (Lich et al. 2016), none of the studies included experimental data.

Only one study examined the potential benefit of vehicle stability control (VSC) systems for motorcycles using real world data. Gail et al. (2009) used in-depth crash data to identify crash types potentially prevented with VSC, identifying crashes involving unbraked cornering and a step friction and those exceeding maximum lateral acceleration as preventable scenarios. From population-level databases, they estimated that 4–8% of high-risk motorcycle accidents might be ameliorated with VSC. Overall, the authors reported that the potential of VSC is likely to be low when compared to ABS.

A later paper by Seiniger et al. (2012) argued that, as of 2012, full stabilization of a motorcycle with sliding wheels was not possible and not theoretically possible in the future. Roll stabilization by gyroscope is not practical, roll stabilization by normal load control cannot be achieved and yaw stabilization, although technically feasible, would have a relatively low impact on accidents figures. Braking with the front wheel in a turn leads to brake-steer-torque, which can make it difficult to control the vehicle. This could possibly be mitigated by reducing the front brake force, by reducing the offset between steering axis and tire contact patch, by adaptive steer damper, or by active steer torque.

Traction control

Traction Control (TC) aims to prevent the rear wheel from skidding during accelerations. TC first appeared in production motorcycles in the early 1990s and was originally marketed as a safety device especially useful on slippery surfaces. More recently (late 2000s), TC reappeared as a performance-oriented device, intended to enhance acceleration performance. Early versions of TC design worked for straight motion only, but more recent versions also apply in cambered conditions. Many PTW brands offer their own TC system.

Despite the relatively long history of this technology and current application, relatively few papers were identified in our literature review. These were limited to engineering studies focusing on system development, with numerical or experimental assessment of TC performance. The main outcomes were the type of modulated variable (spark control vs throttle control), type of controlled variable (wheel acceleration vs tyre slip) and controller architecture (proportional-integral, sliding, heuristic). TC effects were typically presented in terms of enhanced acceleration performance (in straight and while cornering), and reduction of the risk of sliding and falling due to excessive tyre engagement.

Studies in the literature focus on two main modulating approaches: spark-control and throttle control (Cardinale et al. 2008; Tanelli, Vecchio, et al. 2009). Engine torque modulation by throttle is in general slower when compared to spark-control, however the spark-control has limitations related to engine temperature and combustion dynamics. Throttle control approaches therefore seem preferable as they do not interfere with combustion dynamics. As for the ABS, either wheel-acceleration based or tire-slip based controls are possible. Reports in the literature have examined systems for regulating and optimizing both (Vetr et al. 2009; Urda et al. 2016). Tire-slip controls seem preferable as they rely on variables related to tire force generation. However, slip estimation may be difficult at low speed and hard acceleration, depending on how the system is employed. While some throttle-based TC aimed at regulating wheel slip require identification of road type, most slip-based systems do not require estimation of actual road friction, but accurate roll estimation is necessary. Overall, the literature suggests TC can potentially increase both the safety and the performance of PTWs during accelerations. However, rigorous studies attempting to quantify such effects are lacking. In one study, real world data were used to assess the safety potential of this system, showing that TC could have avoided 9% of fatal crashes in Sweden (Rizzi et al. 2011).

Vision assistance

Concerning vision assistance, the two environmental situations addressed in the literature are nighttime vision, and blind-spot assistance. However, the related studies are limited to technical description and no studies have examined safety benefit. Varlakati et al. (2013) presented analytical methods and two mechanisms for improving road visibility at night with adaptive headlights. Nakano et al. (2006) presented the design of adaptive front light system (AFS), Night Vision (NV) and Head up display (HUD). Functionality tests confirmed that AFS enhances visibility during cornering; NV can help detecting pedestrians in the dark; HUD provides support to NV and can be used to present image processing for enhanced pedestrian detection.

For blind spot monitoring, Kirjanov et al. (2017) provided a technical description of a camera-based side view assistance system to support lane changes. Shiao et al. (2013) presented a technical description of an actuated mirror that aimed to reduce the blind spot.

Discussion

For our literature review we used a very broad approach not to miss any relevant study, however we did take a rigorous systematic approach. While the systematic approach is a strength, work not meeting our inclusion criteria such as work published in languages other than English may have been missed. Similarly, other relevant work may have been missed due to faulty keywords or unusual keywords.

Our literature review identified a set of active safety systems for PTWs at various stages of development. While this development is positive for improved PTW safety, there are many significant research and knowledge gaps concerning how to optimally implement these systems and fully understand the potential benefit and limitations of the different systems.

The review identified systems designed to influence the riding task by warning the rider (e.g. intersection support, collision warning, curve warning, and lane change warning) or via direct control actions (e.g. ABS, AEB, and TC). Warning systems require hazard identification and information delivery to the rider. As for passenger car applications, the definition of warning thresholds discriminating safe riding from critical situations is still challenging. Early warnings can disturb the driving or riding task and are not accepted either by drivers nor riders. However, postponed warnings may not allow correct responses by the rider. Besides warning time, the way in which warnings are delivered is very important. As shown in this review, results from both simulator and field experiments suggest that suboptimal warning delivery methods are likely to compromise the effectiveness of the warning itself. There is a significant research gap in this area and further work is warranted to consolidate the safety potential of rider warning systems.

Safety systems operating through control actions typically assist the riding task (ABS, TC), but in at least one example, they may operate independently from the rider's action, namely in AEB. Further work is required to ensure full benefit and limitations of these types of systems are understood. AEB provides an important example, as this system is designed to influence longitudinal dynamics and as such could have adverse effects. These potential adverse effects need to be fully understood and mitigated before wide spread implementation. Rider acceptance, particular to systems that interfere with or are perceived to lessen rider control is also of utmost importance. Further work examining how such systems can be implemented in a manner acceptable to riders is needed.

One clear limitation among active safety technologies currently implemented or under development for PTWs is that many address only specific riding scenarios or maneuvers, and there has been little work examining the potential of combined technologies. For example, ABS has shown to be effective in critical situations involving a braking action of the rider, but ABS does not assist when the rider does not apply any braking. Research examining the potential of combining technologies into integrated systems where single solutions can collectively be exploited may be worthwhile. However, the downside of an integrated approach is a remarkable increase in the complexity of ensuring system reliability. Safety critical elements need to be tested in a large number of use cases, both one-by-one and also in every possible combination. This was recently well explained with reference to the case of passenger cars, when several automated functions are made available and their correct interaction needs to be validated (Liersch 2017).

One key element for the development of vehicular safety systems is the assessments of the safety impact. Examples of this type of evaluation were identified for some of the systems, including ABS, AEB, collision avoidance systems, and TC. However, our review shows that standardized methodologies for structured analysis of the safety impact represent a clear research need for motorcycle active safety. Also, structured comparisons of the estimated safety impact of the systems as single solutions or in combinations are lacking in the literature. These types of studies are strongly warranted in future research, given the wide range of systems to be further investigated, the high complexity of the development process, and the limited resources available in the PTW domain.

Funding

This work has been supported by the COST action TU1407 "Scientific and technical innovations for safer Powered Two Wheelers" (www.cost.eu/COST_Actions/tud/TU1407).

ORCID

Giovanni Savino http://orcid.org/0000-0003-0949-0811
Roberto Lot http://orcid.org/0000-0001-5022-5724
Matteo Massaro http://orcid.org/0000-0001-6256-3384
Sebastian Will http://orcid.org/0000-0003-0098-6212
Julie Brown http://orcid.org/0000-0002-7284-0127

References

Baldanzini N, Bencini G, Pierini M. 2011. Design and preliminary testing of an haptic handle for powered two wheelers. Eur Transp Res Rev. 3(1):1–9. doi:10.1007/s12544-010-0044-z

Bansal A, Jain A, Srivastava P, Tiwary AK, Dear RK. 2016. Significance of tire pressure monitoring system in motorcycle. SAE Technical Papers. 2016-04-05.

Barmpounakis EN, Vlahogianni EI, Golias JC. 2016. Intelligent transportation systems and powered two wheelers traffic. IEEE Trans Intell Transport Syst. 17(4):908–916. doi:10.1109/TITS.2015.2497406

Basch N, Moore M, Hellinga L. 2015. Evaluation of motorcycle antilock braking systems. Paper presented at: 24th International Technical Conference on the Enhanced Safety of Vehicles (ESV); Gothenburg, Sweden.

Baumann M, Bächle T, Buchholz M, Dietmayer K. 2016. Model-based corner braking control for electric motorcycles. IFAC-PapersOnLine. 49(11):291–296. doi:10.1016/j.ifacol.2016.08.044

Beanland V, Lenné MG, Fuessl E, Oberlader M, Joshi S, Bellet T, Banet A, Rößger L, Leden L, Spyropoulou I, et al. 2013. Acceptability of rider assistive systems for powered two-wheelers. Transp Res Part F Traffic Psychol Behav. 19:63–76. doi:10.1016/j.trf.2013.03.003

Berndt H, Dietmayer K. 2008. Timing analysis for motorcycle intersection assistance systems. Paper presented at: 15th World Congress on Intelligent Transport Systems and ITS America Annual Meeting; Ulm, Germany.

Biral F, Bosetti P, Lot R. 2014. Experimental evaluation of a system for assisting motorcyclists to safely ride road bends. Eur Transp Res Rev. 6(4):411–423. doi:10.1007/s12544-014-0140-6

Blackman RA, Haworth NL. 2013. Comparison of moped, scooter and motorcycle crash risk and crash severity. Accid Anal Prev. 57:1–9. doi:10.1016/j.aap.2013.03.026

Cardinale P, D'Angelo C, Conti M. 2008. A traction control system for motocross and supermotard. Paper presented at: 6th Workshop on Intelligent Solutions in Embedded Systems, WISES'08; Ancona, Italy.

De Filippi P, Tanelli M, Corno M, Savaresi SM, Santucci MD. 2014. Electronic stability control for powered two-wheelers. IEEE Trans Contr Syst Technol. 22(1):265–272. doi:10.1109/TCST.2013.2238541

Di Stasi LL, Contreras D, Cañas JJ, Cándido A, Maldonado A, Catena A. 2010. The consequences of unexpected emotional sounds on driving behaviour in risky situations. Safety Sci. 48(10):1463–1468. doi:10.1016/j.ssci.2010.07.006

Diederichs JPF, Ganzhorn M, Widlroither H, Bekiaris E, Nikolaou S, Montanari R, Spadoni A, Fontana M, Bencini G, Baldanzini N, et al. 2010. Saferider, HMI strategies for motorcycles' ARAS and OBIS. Paper presented at: 17th ITS World Congress; Tokyo, Japan.

EuroNCAP. 2015. 2020 Roadmap, European new car assessment programme, Revision 1 [Technical Paper]. [accessed 2019 Nov 27]. https://cdn.euroncap.com/media/16472/euro-ncap-2020-roadmap-rev1-march-2015.pdf.

Fang C-Y, Hsu W-H, Ma C-W, Chen S-W. 2014. A vision-based safety driver assistance system for motorcycles on a smartphone. Paper presented at: 17th IEEE International Conference on Intelligent Transportation Systems, ITSC 2014; Taiwan.

Gail J, Funke J, Seiniger P, Westerkamp U. 2009. Anti lock braking and vehicle stabilty control for motorcycles - why or why not. Paper presented at: 21st International Conference on the Enhanced Safety of Vehicles (ESV); Stuttgart, Germany.

Gil G, Savino G, Piantini S, Pierini M. 2018. Motorcycle that see: multifocal stereo vision sensor for advanced safety systems in tilting vehicles. Sensors. 18(2):295. doi:10.3390/s18010295

Goodarzi A, Armion A. 2010. Integrated fuzzy-optimal motorcycle dynamic control. Veh Syst Dyn. 48(sup1):505–524. doi:10.1080/00423114.2010.502942

Grant R, Frampton R, Peldschus S, Schuller E, Stclair V, Mccarthy M, Babu R, Pierini M, Savino G. 2008. Pisa – powered two-wheeler integrated safety. Project objectives, achievements and remaining activities. Paper presented at: IFZ International Motorcycle Conference; Cologne, Germany.

Hans S, Krehel M, Köbe M, Prokop G. 2016. A cascaded model-predictive approach to motorcycle safety. Paper presented at: 13th International Symposium on Advanced Vehicle Control AVEC16; Munich, Germany.

Hurt H, Ouellet J, Thom D. 1981. Motorcycle accident cause factors and identification of countermeasures Volume I: Technical report. Traffic Safety Center, University of Southern California; Research Report DOT HS-5-01160.

Huth V, Biral F, Martín O, Lot R. 2012. Comparison of two warning concepts of an intelligent curve warning system for motorcyclists in a simulator study. Accid Anal Prev. 44(1):118–125. doi:10.1016/j.aap.2011.04.023

Huth V, Gelau C. 2013. Predicting the acceptance of advanced rider assistance systems. Accid Anal Prev. 50:51–58. doi:10.1016/j.aap.2012.03.010

Huth V, Lot R, Biral F, Rota S. 2012. Intelligent intersection support for powered two-wheeled riders: a human factors perspective. IET Intell Transp Syst. 6(2):107–114. doi:10.1049/iet-its.2011.0130

Ito K, Nishimura H, Ogi T. 2015. Head-up display for motorcycle navigation. Paper presented at: SIGGRAPH Asia 2015 Head-Up Displays and their Applications; Kobe, Japan.

Ivanov V, Mikhaltsevich M, Kliausovich S, Shyrokau B. 2005. Virtual testing of active safety control for two-wheeled vehicles at braking mode. Paper presented at: 19th International Technical Conference on the Enhanced Safety of Vehicles (ESV); Washington, DC, USA.

Jenkins MP, Young D. 2016. BARRACUDA: An augmented reality display for increased motorcyclist en route hazard awareness. Paper presented at: IEEE International Multi-Disciplinary Conference on Cognitive Methods in Situation Awareness and Decision Support (CogSIMA); San Diego, CA, USA.

Kahane CJ. 2015. Lives saved by vehicle safety technologies and associated Federal Motor Vehicle Safety Standards, 1960 to 2012–passenger cars and LTVs. Paper presented at: 24th International Technical Conference on the Enhanced Safety of Vehicles (ESV); Gothenburg, Sweden.

Kirjanov M, Grzyb P, Hoffmann J, Osman A. 2017. Advanced Driver Assistance Systems for motorcycles: Concept of a lane change assist. Paper presented at: 25th International Technical Conference on the Enhanced Safety of Vehicles (ESV); Detroit, MI, USA.

Koizumi T, Tsujiuchi N, Ezaki Y. 2008. Disturbance rejection control in motorcycle that considers cooperativeness with the rider's driving operation. SAE Technical Papers. 2008-32-0055.

Lich T, Block WG, Prashanth S, Heiler B. 2016. Motorcycle stability control-the next generation of motorcycle safety and riding dynamics. SAE Int J Engines. 9(1):491–498.

Lich T, Kumaresh G, Moennich J. 2015. Benefit estimation of anti-lock braking system for powered two wheeler on Indian highways. SAE Technical Papers. 2015-26-0167.

Liersch C. 2017. Automated vehicles supporting "Towards Zero" initiative. J Australas Coll Road Saf. 28(1):49–53.

MAIDS. 2004. In-depth investigation of accidents involving PTW - Final report 1.3. European Association of Motorcycle Manufacturers.

MAIDS. 2009. MAIDS: In-depth investigations of accidents involving powered two wheelers. European Association of Motorcycle Manufacturers.

Manzoni V, Corti A, Spelta C, Savaresi SM. 2010. A driver-to-infrastructure interaction system for motorcycles based on smartphone. Paper presented at: IEEE Conference on Intelligent Transportation Systems; Milan, Italy.

Miucic R, Rajab S, Bai S, Sayer J, Funkhouser D. 2015. Improving motorcycle safety through DSRC motorcycle-to-vehicle communication. SAE Technical Papers. 2015-01-0291.

Motoki M, Hashimoto H, Hirao T. 2009. Study on visibility and discomfort glare of adaptive frontal lighting system (AFS) for motorcycle. Paper presented at: 21st International Technical Conference on the Enhanced Safety of Vehicles (ESV); Stuttgart, Germany.

Muzammel M, Yusoff MZ, Malik AS, Saad MNM, Meriaudeau F. 2017. Motorcyclists safety system to avoid rear end collisions based on acoustic signatures. Paper presented at: 13th International Conference on Quality Control by Artificial Vision; Tokyo, Japan.

Muzammel M, Yusoff MZ, Meriaudeau F. 2017. Rear-end vision-based collision detection system for motorcyclists. J Electron Imaging. 26(3):033002. doi:10.1117/1.JEI.26.3.033002

Nakano S, Shimada T, Nakaya A, Dohmoto M, Nagata K. 2006. Development of Advanced Safety Motorcycle. SAE Technical Paper. 2006-32-0112.

OECD/International Transport Forum. 2015. Improving safety for motorcycle, scooter and moped riders. ITF Research Reports. [accessed 2019 Nov 27]. https://www.oecd-ilibrary.org/docserver/9789282107942-en.pdf?expires=1574844676&id=id&accname=oid009417&checksum=B4DD27302525E51C4192B087947A8BFA.

Pieve M, Tesauri F, Spadoni A. 2009. Mitigation accident risk in powered two wheelers domain: Improving effectiveness of human machine interface collision avoidance system in two wheelers. Presented at: 2nd Conference on Human System Interactions HSI'09; Catania, Italy.

Rizzi M, Kullgren A, Tingvall C. 2015. The combined benefits of motorcycle antilock braking systems (ABS) in preventing crashes and reducing crash severity. Traffic Inj Prev. 17(3):297–303. doi:10.1080/15389588.2015.1061660

Rizzi M, Strandroth J, Johannson R, Lie A. 2011. The potential of different countermeasures in reducing motorcycle fatal crashes: What in-depth studies tell us. Presented at: 22nd International Technical Conference on the Enhanced Safety of Vehicles (ESV); Washington, DC, USA.

Rizzi M, Strandroth J, Holst J, Tingvall C. 2016. Does the improved stability offered by motorcycle antilock brakes (ABS) make sliding crashes less common? In-depth analysis of fatal crashes involving motorcycles fitted with abs. Traffic Inj Prev. 17(6):625–632. doi:10.1080/15389588.2015.1134794

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 Inj Prev. 16(2):177–183. doi:10.1080/15389588.2014.927575

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

Roessler B, Kauvo K. 2009. Laserscanner based adas for motorcycle safety. In: Meyer G, Valldorf J, Gessner W, editors. Advanced microsystems for automotive applications 2009. VDI-Buch. Berlin, Heidelberg: Springer. p. 245–253.

Rogers N. 2008. Trends in motorcycles fleet worldwide. Presented at: joint OECD/ITF Transport Research Committee workshop on motorcycling safety; Lillehammer, Norway.

Roll G, Hoffmann O, König J. 2009. Effectiveness evaluation of antilock brake systems (ABS) for motorcycles in real-world accident scenarios. Presented at: 21st International Technical Conference on the Enhanced Safety of Vehicles (ESV); Stuttgart, Germany.

Santa J, Fernández PJ, Zamora MA. 2017. Cooperative ITS for two-wheel vehicles to improve safety on roads. IEEE Vehicular Networking Conference, VNC; San Javier (Murcia), Spain.

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 Inj Prev. 14(sup1):S40–S49. doi:10.1080/15389588.2013.803280

Savino G, Giovannini F, Fitzharris M, Pierini M. 2016. Inevitable collision states for motorcycle-to-car collision scenarios. IEEE Trans Intell Transport Syst. 17(9):2563–2573. doi:10.1109/TITS.2016.2520084

Savino G, Giovannini F, Piantini S, Baldanzini N, Pierini M. 2015. Autonomous emergency braking for cornering motorcycle. Paper presented at: 24th International Technical Conference on the Enhanced Safety of Vehicles (ESV); Gothenburg, Sweden.

Savino G, Mackenzie J, Allen T, Baldock M, Brown J, Fitzharris M. 2016. A robust estimation of the effects of motorcycle autonomous emergency braking (MAEB) based on in-depth crashes in Australia. Traffic Inj Prev. 17(sup1):66–72. Sdoi:10.1080/15389588.2016.1193171

Savino G, Pierini M, Baldanzini N. 2012. Decision logic of an active braking system for powered two wheelers. Proc Inst Mech Eng D: J Autom Eng. 226(8):1026–1036. doi:10.1177/0954407011434445

Savino G, Pierini M, Thompson J, Fitzharris M, Lenné MG. 2016. Exploratory field trial of motorcycle autonomous emergency braking (MAEB): considerations on the acceptability of unexpected automatic decelerations. Traffic Inj Prev. 17(8):855–862. doi:10.1080/15389588.2016.1155210

Savino G, Rizzi M, Brown J, Piantini S, Meredith L, Albanese B, Pierini M, Fitzharris M. 2014. Further development of motorcycle autonomous emergency braking (MAEB), What can in-depth studies tell us? A multinational study. Traffic Inj Prev. 15(Sup1):S165–S172. doi:10.1080/15389588.2014.926009

Seiniger P, Schroter K, Gail J. 2012. Perspectives for motorcycle stability control systems. Accid Anal Prev. 44(1):74–81. doi:10.1016/j.aap.2010.11.018

Shiao Y, Nguyen Q-A, Hou C-F. 2013. Actuation of adaptive rearview system for motorcycles. AMM. 284-287:587–591. doi:10.4028/www.scientific.net/AMM.284-287.587

Silla A, Leden L, Rämä P, Scholliers J, Van Noort M, Morris A, Hancox G, Bell D. 2018. A headway to improve PTW rider safety within the EU through three types of ITS. Eur Transp Res Rev. 10(2):18. doi:10.1186/s12544-018-0289-5

Song M, Mclaughlin S, Doerzaph Z. 2017. An on-road evaluation of connected motorcycle crash warning interface with different motorcycle types. Transport Res Part C: Emer Technol. 74:34–50. doi:10.1016/j.trc.2016.11.005

Sporner A, Kramlich T. 2001. Motorcycle braking and its influence on severity of injury. Paper presented at: 17th International Technical Conference on the Enhanced Safety of Vehicles (ESV); Amsterdam, The Netherlands.

Sundharam SM, Fejoz L, Navet N. 2016. Connected motorized riders - A smart mobility system to connect two and three-wheelers. Paper presented at: 6th International Symposium on Embedded Computing and System Design, ISED 2016; Patna, India.

Symeonidis I, Kavadarli G, Erich S, Graw M, Peldschus S. 2012. Analysis of the stability of ptw riders in autonomous braking scenarios. Accid Anal Prev. 49:212–222. doi:10.1016/j.aap.2011.07.007

Tanelli M, Corno M, Boniolo I, Savaresi SM. 2009. Active braking control of two-wheeled vehicles on curves. IJVAS. 7(3/4):243–269. doi:10.1504/IJVAS.2009.033263

Tanelli M, Vecchio C, Corno M, Ferrara A, Savaresi SM. 2009. Traction control for ride-by-wire sport motorcycles: A second-order sliding mode approach. IEEE Trans Ind Electron. 56(9):3347–3356. doi:10.1109/TIE.2009.2018430

Teoh ER. 2011. Effectiveness of antilock braking systems in reducing motorcycle fatal crash rates. Traffic Inj Prev. 12(2):169–173. doi:10.1080/15389588.2010.541308

Touliou K, Margaritis D, Spanidis P, Nikolaou S, Bekiaris E. 2012. Evaluation of rider's support systems in power two wheelers (PTWs). Procedia Soc Behav Sci. 48:632–641. doi:10.1016/j.sbspro.2012.06.1041

Urda P, Cabrera JA, Castillo JJ, Guerra AJ. 2016. An intelligent traction control for motorcycles. In: Rosenberger M, Plöchl M, Six K, Edelmann J, editors. The dynamics of vehicles on roads and tracks. 1st ed. Amazon Digital Services; p. 809–819.

Valtolina S, Vanzi S, Montanari R, Minin L, Marzani S. 2011. Design of warning delivery strategies in advanced rider assistance systems. Paper presented at: ASME 2011 World Conference on Innovative Virtual Reality, WINVR 2011; Milano, Italy.

Varlakati SS, Yogaraja V, Sudharsan S. 2013. Self adaptive front lighting mechanism for the fixed headlamp mounted two wheelers. SAE Technical Papers. 2013-01-09.

Vetr M, Hirsch M. Del Re L 2009. Curve safe traction control for racing motorcycles. SAE Technical Papers. 2009-04-20.

World Health Organisation. 2015. Global status report on road safety 2015 [Report]. [accessed 2019 Nov 27]. http://apps.who.int/iris/bitstream/10665/189242/1/9789241565066_eng.pdf.

Yannis G, Evgenikos P, Papantoniou P, Broughton J, Brandstatter C, Candappa N, Christoph M, Van Duijvenvoorde K, Vis M. 2012. Basic fact sheet "motorcycles and mopeds. EC FP7 project DACOTA; Deliverable D3.9.