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# Analysis of the minimum swerving distance for the development of a motorcycle autonomous braking system

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ABSTRACT

In the recent years the *autonomous emergency brake* (AEB) was introduced in the automotive field to mitigate the injury severity in case of unavoidable collisions. A crucial element for the activation of the AEB is to establish when the obstacle is no longer avoidable by lateral evasive maneuvers (swerving). In the present paper a model to compute the minimum swerving distance needed by a *powered two-wheeler* (PTW) to avoid the collision against a fixed obstacle, named *last-second swerving* model ($L_{sw}$), is proposed. The effectiveness of the model was investigated by an experimental campaign involving 12 volunteers riding a scooter equipped with a prototype autonomous emergency braking, named *motorcycle autonomous emergency braking* system (MAEB). The tests showed the performance of the model in evasive trajectory computation for different riding styles and fixed obstacles.

## 1. Introduction

In the past ten years in the automotive field a number of primary safety systems were introduced on the market, e.g. *antilock braking system* (ABS) (Heißing and Ersoy, 2010; Evans, 1999), *adaptive cruise control* (ACC) (Lie et al., 2006; Erke, 2008), *electronic stability control* (ESC) (Schleicher and Gelau, 2011). More recently, high-end passenger cars started to be equipped with the *autonomous emergency brake* (AEB), which monitors the frontal environment of the vehicle and, in case of imminent collision, actuates the brakes without any input from the driver. The first applications of the AEB system addressed restricted scenarios and partial braking was allowed (Labayrade et al., 2007; Coelingh et al., 2007), whereas the actual AEB systems are capable of early and full automatic braking, with consequent improvement of the potential benefits (Coelingh et al., 2010).

As far as the motorcycle market concerns, the primary safety systems available for high-end models are the ABS, the *combined braking system* (CBS) and the *traction control* (TC). In the literature a number of studies were conducted to investigate the benefits coming from the aforementioned systems. Several authors evaluated the ABS effectiveness in real world crashes (Sporner and Kramlich, 2001; Elliott et al., 2003; Rizzi et al., 2009). In Roll and Hoffmann (2009) a comparison between the ABS and ABS plus integral brake was done. In the same article Roll et al. showed a possible improvement in terms of emergency braking distances adopting a brake-assist and an automatic pre-fill function linked to the braking system. A detailed study on emergency braking was conducted by the powered two-wheeler integrated safety (PISa) project[1] using a different approach. The PISa consortium carried out an analysis on powered two-wheeler (PTW) accident statistics and in-depth accident databases. As an outcome, the safety function of slowing down the PTW without explicit input from the rider (i.e. autonomous braking) was considered the highest priority among non-collaborative PTW safety systems (Grant et al., 2008). The autonomous braking named by the PISa consortium as *motorcycle autonomous emergency braking* (MAEB) is a novel system for PTWs. The MAEB was proved to be feasible and safe with tests under controlled laboratory conditions for the rider when traveling along a straight line and adopting mild decelerations (Symeonidis et al., 2011), with an experimental study conducted with a prototype scooter[2] (Savino et al., 2010) and a number of tests conducted in a virtual environment (Savino et al., 2013a,b).

The triggering criterion is a crucial aspect of any autonomous emergency braking system (AEB). It determines the early or late intervention thus influencing the potential benefits and it is responsible of possible false triggering. Once the collision is predicted, an

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[2] The PISa prototype vehicle is currently hosted at the University of Florence, Italy, for further development.

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early intervention produces a high reduction in the impact velocity or even the complete collision avoidance. As a drawback the early deployment increases the risk of undesired intervention (i.e. when the driver is still able to maneuver and avoid the crash) and false triggering cases. A solution proposed by Kaempchen et al. (2009) consists in deploying the AEB when the collision becomes physically unavoidable. In this manner the intervention of the AEB mitigates the impact consequences by reducing the impact velocity although the complete crash avoidance cannot be achieved.

In the case of an imminent accident the rider can try to avoid the collision by purely braking, purely swerving or by a combination of the two maneuvers, i.e. performing a turn while braking. Kaempchen et al. (2009) proposed a model to identify unavoidable collisions between two vehicles analyzing all the combinations of maneuvers conducted with maximum accelerations. This model considers the ratio between lateral and longitudinal acceleration as a constant value over the maneuver time. The experimental study conducted by Kaempchen in normal driving conditions showed that the triggering algorithm did not produce false activation signals for the autonomous brake, thus suggesting a good accordance between the avoidance prediction of the model and the real driver maneuvering.

For PTW applications, the autonomous emergency braking (AEB) should be inhibited as long as the collision is still avoidable either by braking or swerving. According to Corno et al. (2008) and Cossalter et al. (2004), to perform a braking maneuver in the best conditions it is necessary to achieve the motorcycle maximum deceleration. The optimal braking condition is achieved when the target deceleration is obtained using the same adherence on the front and rear wheel. In fact, this condition minimizes the adherence needed as well as the gap between the current condition and the limit condition (maximum coefficient of adherence). Concerning the capabilities of a two wheeled vehicle to avoid a collision by swerving, Schwab and Kooijman (2011) presented a review indicating the most relevant studies on this topic. A first one by Rice (1975) carried out a large experimental investigation on motorcycle lane-change manoeuvres focusing on the interaction rider-vehicle during the avoidance manoeuvre. Even though the accident avoidance capabilities of the motorcycles were not identified, the author found out the importance of motorcycle design and tire properties in motorcycle directional stability and control. A second one by Watanabe (1973) presented a comparison between car and motorcycle lateral avoidance manoeuvres. The paper highlighted the differences between four and two-wheeled vehicles, thus indicating the need for a specific investigation of the PTW minimum swerving distance. More recently, an investigation was conducted by Varat et al. (2004) carrying out an experimental investigation of normal lane change manoeuvres involving 53 test riders. The paper focussed on rider inputs and PTW state parameters during maneuvers, but the maximum avoidance performances of motorcycles were not analyzed.

The development of the *motorcycle autonomous emergency braking* system within the PISa project included a model to estimate the minimum swerving distance to avoid the collision, proposed by Savino et al. (2009), addressing the basic scenario where the PTW is proceeding along a straight trajectory towards a static obstacle, which is a fundamental subcase of Kaempchen's scenarios. In Savino's formulation the approach does not need a detailed vehicle characterization (e.g. tire parameters to define the friction conditions) thus reducing the computational load for minimum swerving distance estimation and enabling on-board real-time applications. Since the MAEB must be inhibited as long as the collision is still avoidable by swerving and it must avoid any unexpected activation of the autonomous brake, it is necessary to demonstrate that the minimum swerving distance, computed with the proposed model, represents the lower limit of the swerving performances of common riders in terms of swerving distances.

The present paper focuses on the validation of the model proposed by (Savino et al., 2012) for the minimum swerving distance estimation for PTW application. The validation process was performed with experimental tests, which involved 12 drivers performing the evasive maneuvers at different speeds and with different fixed obstacles. The last-second swerving model validation contributes to the development and optimization of the control logic of MAEB activation. The remainder of this paper is organized as follows. The model used to describe the swerving maneuver for PTWs is introduced in Section 2. In Section 3, the authors present the experimental activity conducted to validate the model for minimum swerving distance introduced in Section 2. Experimental tests result and data analysis are detailed in Sections 4 and 5. Finally conclusions are given in Section 6.

## 2. Models

The braking maneuver, swerving maneuver and a combination of them are the three actions to avoid the collision with an obstacle. The model adopted for braking distance computation within MAEB development is presented in detail by Savino et al. (2012). In the following paragraphs the model for minimum swerving distances computation will be described. The authors will show the influence of the PTW velocity and the obstacle dimensions on the swerving distance.

The evasive maneuver is described by several models assuming constant acceleration and constant turn radius (Coelingh et al., 2010; Kaempchen et al., 2009; Schmidt et al., 2006). The approaches of Kaempchen and Schmidt are based on *Kamm's circle* theory (Breuer and Bill, 2006) where each trajectory is a function of the angle $\phi$, the longitudinal acceleration $a_x$, the lateral acceleration $a_y$ and the initial velocity $V_0$. The angle $\phi$ is defined by the directions of vector $a_y$ and vector $a$ which is given by the sum of vectors $a_y$ and $a_x$. In addition, the theory of the *Kamm's circle* shows that the vectorial sum of the lateral and longitudinal acceleration cannot exceed the value $\mu \cdot g$ where $\mu$ is the maximum adherence and $g$ is the acceleration of gravity. In the case of dry surface the value for $\mu$ is approximately 1. Coelingh's approach to the collision risk calculation is based on the *time to collision* (TTC) both for braking and swerving (Coelingh et al., 2010). Another time-based model for the evasive maneuver for passenger cars is proposed by Ameling and Kirchner (2000). In the distance-based approach proposed by Savino et al. (2012) the distance $x_{obj}$ is compared with the minimum distance ($L_{sw}$) required to avoid the collision. $L_{sw}$ distance defines the lower limit beyond which an evasive maneuver cannot avoid the collision anymore. As long as the disequation Eq. (1) is satisfied the MAEB is inhibited because a swerving maneuver is still feasible to avoid the obstacle.

$$x_{obj} > L_{sw} \tag{1}$$

### 2.1. Last-second swerving distance computation

$L_{sw}$ distance is computed by schematizing the PTW behaviour while turning with a steady curve model which is a simplified version of Kaempchen's algorithm (Kaempchen et al., 2009). Kaempchen's model is based on the Kamm's circle algorithm and requires a complex analysis of the PTW lateral dynamics, whereas the *last-second swerving* model, defines a scheme for the geometry of the maneuver. Using the theoretical swerving model the minimum distance to avoid the collision by swerving is computed under the following hypotheses: