DESIGN OF THE DECISION LOGIC FOR A PTW INTEGRATED SAFETY SYSTEM

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ABSTRACT

The Powered Two Wheeler Integrated Safety (PISa) project is developing an integrated safety system for a range of powered two wheelers (PTWs). This system includes state of the art sensors, innovative warning devices and rider assistance systems.
This paper reports on the design of the decision logic for deploying autonomous braking (AB) and enhanced braking (EB) safety functions in the PISa system, for a PTW travelling towards leading obstacle, using on-board inertial measurement unit (IMU) and Laserscanner.
The decision logic deploys the AB and EB systems based on a theoretical kinematic parameter: the required deceleration to avoid a collision. The criterion for deployment is to trigger the AB and EB systems when the collision is physically unavoidable.
The decision logic is tested off-line for datasets acquired using the PTW integrated with the IMU and the Laserscanner.

INTRODUCTION

According to the European Road Safety Observatory (ERSO), in 2006 more than 24,000 road traffic fatalities were registered in the EU-14 (EU-15 without Germany). About 5,400 were PTW riders. During the period 2000 - 2006, the car fatalities decreased by 35%. During the same period moped fatalities also decreased by 30%, while motorcycle fatalities increased by 10%. The risk of fatality for PTWs (including mopeds and motorcycles) is 26 times higher per km travelled compared to passenger cars [1].
Within the European Commission's 6th Framework Program, the PISa project is developing an innovative approach for PTW safety to address the growing fatality rate. The aim of the PISa project is to develop and implement an integrated safety system for a range of PTWs, to contribute in the reduction of casualties by avoiding accidents and reducing injury severity.
In the PISa project, PTW accident analysis was performed using existing statistical data to identify important accident types and causation factors. Subsequently, a sample of existing in-depth motorcycle accident datasets were selected and predictive assessments were made regarding the ability of a range of safety systems to influence the accident outcome. This analysis was used to identify and prioritise the most effective safety functions to be implemented in the PISa system [2].
The following components of the PISa system were defined:

- sensors to obtain the state parameters to describe the relevant vehicle behaviour;
- human machine interfaces (HMIs) - a vibrating saddle to warn the rider;
- actuators - the braking assistance system and the semi-active suspension;
- decision logic to coordinate the activation or inhibition of the elements of the PISa system to appropriately deploy the selected safety functions.

Accidentology

A total of sixty in-depth real cases with relevance to the seven main accident scenarios identified in the Aprosys project [3] were extracted from COST 327, OTS and Fatal databases. The selected cases were analysed in detail to determine the characteristics of the accident, including relative vehicle behaviour (positions and speeds prior to collision), environmental and human contributing factors, casualties [4]. The outcome of the accident analysis led to the identification of the most frequent and severe PTW accident configurations (ACs) shown in Figure 1.

Safety Functions

A total of forty-five safety functions were identified based on the possibility to avoid the accidents or to reduce their outcomes at the different phases of the accident, i.e. pre-crash, crash, post-crash. These functions were prioritised by a group of experienced analysts of the PISa project, according to the effectiveness to influence the accident outcome for the sixty in-depth cases. The method to prioritise the safety functions was to rate each function in

each case from 0 to 5 (0 being no effect, 5 being most effective). For each function, the ratings in all the sixty cases were summed up to obtain the ranking for the safety functions in the order of effectiveness. In Table 1, the prioritised list of safety functions is shown, filtering out the least effective functions from the forty-five safety functions.

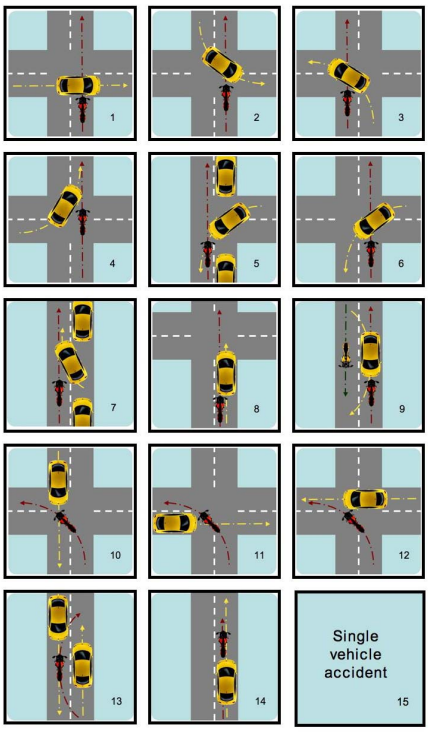

Figure 1. PISa accident configurations.

The most relevant safety functions based on the scope and the capability of the PISa Consortium were identified. In Table 1, the six selected functions are highlighted in bold. These functions will be implemented within the PISa project on two demonstrator PTWs. Taking into account the PISa project time scale, among the 15 accident configurations shown in Figure 1, two configurations (AC1 - cross intersection; AC8 - car following) were selected for implementation and validation of the safety system.

In the present work, the focus is on the development of the AB and EB functions for AC8, with two different states for the obstacle:

- PTW travelling towards a moving obstacle;
- PTW travelling towards a fixed obstacle.

The functionality of the AB is to automatically slow down with a precise deceleration, or eventually stop the PTW by braking without rider input. The intention is to reduce the PTW speed when the rider is unaware of a dangerous situation. This function is meant to warn the rider by braking at low deceleration value, anticipating the rider to react. If the rider does not react, the AB helps in reducing the consequences of the collision. If the rider reacts by braking, the EB will assist the rider in obtaining a predetermined deceleration of the PTW by amplifying the braking force during the emergency braking.

Table 1.
List of prioritised safety functions

n.	Prioritised function list
1	Warn other vehicle of PTW presence
2	Automatically slow/stop other vehicle without input from driver
3	**Amplify braking force – Enhanced braking system (EB)**
4	**Improve conspicuity – Special fairings/active lighting**
5	**Balance front to rear braking force – Combined braking system (CBS)**
6	**Detect and warn PTW that vehicle travelling from left, right or oncoming is crossing the PTW path – PTW to detect other vehicle and warn rider**
7	Avoid locking of wheels in straight line – Antilock Braking System (ABS)
8	**Automatically brake PTW without input from rider – Autonomous braking (AB)**
9	Communicate and warn PTW that vehicle travelling from left, right or oncoming is crossing PTW path
10	Restrict PTW to posted speed limit
11	**Reduce closing speed – Distance support system (DSS)**
12	Protect rider's legs
13	Advise rider of approaching permanent hazard (sharp bend, steep decline, fixed obstacles)
14	Help rider to maintain steering and prevent loss of control

Integrated Safety System

The safety functions are implemented in an integrated safety system, which is comprised of sensors, actuators and interfaces. The system is on board along with the decision logic on a PTW.

Sensors provide input to the safety system about the state of the PTW, the rider behaviour and the PTW surroundings.

The IMU provides the following information regarding the PTW:

- speed;
- acceleration;
- roll angle and roll rate;
- pitch angle and pitch rate.

Pressure sensors on the hydraulic braking system, an encoder mounted on the throttle and a load cell provide the following information about the rider behaviour:

- brake pressure applied on the front and rear wheels;
- throttle position;
- steering input.

A Laserscanner mounted in front of the PTW provides information about the surroundings. The objects in front of the PTW are detected, tracked and assigned with an ID. For each assigned object, the following data is computed:

- classification (PTW, passenger car, van, etc.);
- dimensions (width, length);

- relative position (longitudinal and transverse distance from the PTW);
- yaw angle (current direction of the object);
- both relative and absolute speed (longitudinal and transverse).

Because the Laserscanner is mounted to the fixed frame of the PTW, detection of objects that are far away is sometimes not possible for high PTW roll angles. For this reason, it is convenient to work only on the configurations where PTW is travelling in a straight-line path. Nevertheless, to take into account of the curvature of the path even for small roll angles, a correction on the data coming from the Laserscanner is performed, based on the hypothesis of steady curve manoeuvre. In Table 2 the list of data acquired by the aforementioned sensors is shown.

Table 2:
Data acquired by the sensors

Element	Parameters
Host vehicle	Speed, acceleration
	Yaw and roll angles, roll rate
Rider	Throttle position
	Front/rear brake pressure
	Steering input
Surrounding object	Classification and dimensions
	Relative position from PTW
	Speed, acceleration

The actuators included in the integrated safety system are the braking assistance system with the AB and EB functionalities, and the vibrating seat to warn the rider. The development of the components will be finalised in the later stages of the PISa project.

DECISION LOGIC

The decision logic is the set of rules and algorithms that take care of the deployment of the AB and EB in a reliable manner, which means without false triggering. The AB and EB are implemented on a PTW for car following configuration, i.e., PTW following leading vehicle in straight path.

Deployment strategy

The AB and EB functions are deployed in emergency situation, without rider input, by performing an evaluation of the kinematic situation. The main criterion for deploying the functions is the risk for collision. The risk evaluates the possibility for a collision to occur and the severity of the outcomes associated with that event. Also the rider continuously performs risk evaluation and reacts accordingly, trying to keep the risk within a subjective reasonable level. A deployment of the AB or EB functions can be dangerous when the rider does not expect or even desire such a response. To overcome such a danger, the system will take the physical limits of the PTW into consideration to set the threshold for triggering. Accordingly, the system intervenes with the braking assistance only in case of an unavoidable collision against the leading vehicle. In such a situation, if the risk perceived by the rider is still within the personal safety limit it is probably due to rider misjudgement, distraction or physiological limitations. As a consequence, the system decision to deploy the braking assistance will be safer, no matter what the rider's intentions are.

Once the AB is triggered, the deployment is postponed by a delay time τ_{AB} to pre-warn the rider by the vibrating saddle, thus avoiding totally unexpected deceleration. The delay reduces the effects of the AB in terms of reduction of the impact speed, but it is fundamental to prepare the rider for the consequences of the deceleration.

Risk evaluation

A substantial amount of work has been done in defining the methods for risk evaluation to deploy safety functions in car following configuration. Zhang et al. [5] reviewed the different methodologies for computing a risk parameter based on kinematic quantities and proposed a new synthetic parameter for evaluating the threat. Among the different methodologies, focus must be laid in the required deceleration parameter. According to Kiefer et al. [6], the required deceleration measure is the constant deceleration level required for the driver to avoid colliding with the lead vehicle at manoeuvre onset. The assumption for this parameter is to consider constant deceleration of the leading vehicle. The inputs for evaluating the required deceleration (d_{req}) are PTW speed (v_{PTW}), lead vehicle speed (v_L), lead vehicle acceleration (a_L), relative distance between PTW and lead vehicle (L).

$$d_{req} = \frac{(v_{PTW} - v_L)^2}{L} - a_L$$

The importance of this parameter is the direct correlation with the kinematics of the situation associated with a low complexity. The risk parameter will be directly related to d_{req}. According to the research conducted by Kiefer et al. on passenger cars [7], it is not possible to establish a direct correlation between d_{req} and the driver perception of the threat. Therefore the deploying strategy based on d_{req} will be relied on the physics of the situation and not on the rider's evaluation.

Triggering

The required deceleration is a theoretical parameter with a practical significance related to the possibility of avoiding the collision by braking. The deceleration of the PTW is obtained by the longitudinal forces between the tyres and the road and by the aerodynamic forces. The latter is a function of the

speed and depends on the geometry and the mass of the PTW including riders, while the former is limited by the friction coefficient between tyre and asphalt. Below 20 m/s the aerodynamic forces are negligible, so the maximum deceleration mainly depends on the maximum friction coefficient μ_p (traction coefficient). Under these assumptions, the maximum deceleration is $\mu_p g$. For this reason, the braking assistance will not be activated until d_{req} is less than $\mu_p g$, since the collision is theoretically avoidable by braking. When the d_{req} overcomes $\mu_p g$, the system will trigger the brake assistance to contribute in the reduction of the impact speed because the collision is reasonably inevitable.

Since the braking traction coefficient is difficult to be measured locally with precision, the triggering deceleration (d_{trigg}) is set to 10 m/s^2, estimated when μ_p=1, which is the maximum value for common road conditions with dry surface. If locally $\mu_p < 1$, e.g. on wet surface, the triggering limit of 10 m/s^2 is still fail-safe because the maximum braking deceleration that the PTW can feasibly achieve is $\mu_p g <$ 10 m/s^2, so the system still deploys when d_{req} is beyond the physical limits.

In principle, in normal road conditions (μ_p=1), the triggering threshold identified referring to the physical possibilities of the PTW with maximum traction coefficient could be reduced to the actual possibilities of each rider with a specific PTW. Nevertheless the present work refers to a generic rider and PTW. Winkelbauer et al. [8] showed that on a population of riders with various levels of riding experience, comprehensive of novices, on different PTW equipped with ABS, the braking performances after a short training were so high that to include the 90% of them in the deploying criterion of the maximum feasible performances, d_{trigg} must be higher than 9.5 m/s^2. Considering that the EB function is not allowed without being associated to ABS, d_{trigg} cannot be reduced because of the real performances of the riders.

Inhibition

Triggering is inhibited in cases where system activation might cause dangerous consequences. Two parameters are taken into account before deploying the braking assistance system.

Firstly, if roll angle and roll rate are not close to zero, the PTW is not in the proper conditions for the deployment of the braking assistance, as the AB or EB deployment would lead to a destabilisation of the PTW and dangerous outcomes. If roll angle or roll rate are greater (in modulus) than a threshold, the system will inhibit the deployment of the braking assistance.

Secondly, before triggering the braking assistance system, it is important to assess that collision avoidance against the lead vehicle is no longer feasible by swerving. It is assessed by measuring the relative distance between the PTW and lead vehicle (L) and comparing it with the minimum distance required to avoid the collision by swerving (L_{swerve}), which is calculated using the speed of the PTW and lead vehicle and by defining a maximum value for the roll angle. Until L is higher than the feasible limit L_{swerve}, the AB is inhibited. The minimum distance to avoid the collision by curving is computed under the following hypotheses:

• v_{PTW} and v_L are constants;

• radius of the path R suddenly changes from infinite (straight path) to a constant value R_{min}:

$$R_{\min} = \frac{v_{PTW}^{\ 2}}{g \cdot \tan\varphi_{\max}}$$

where φ_{max} is the maximum feasible roll angle for the PTW during emergency curving.

$$L_{swerve} = \sqrt{2 \cdot k \cdot v_{PTW}^{\ 2} \cdot s + s^2} + k \cdot v_{PTW} \cdot v_L \cdot \arccos\left(\frac{k \cdot v_{PTW}^{\ 2}}{k \cdot v_{PTW}^{\ 2} + s}\right)$$

where $k = \dfrac{1}{\tan\varphi \cdot g}$ and s is the tolerated distance between the centres of gravity of the PTW and the obstacle.

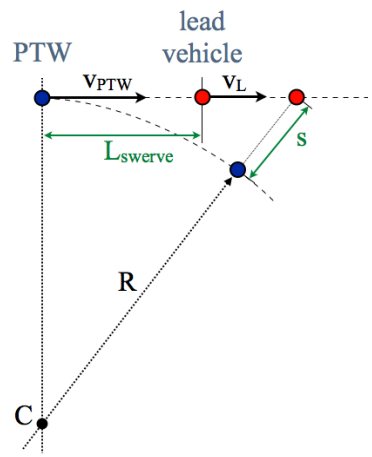

Figure 2. Kinematic representation to calculate L_{swerve}.

Theoretical benefits

The AB and EB are meant to reduce the consequences of inevitable collision principally by decreasing the impact speeds. The theoretical performances depend on the following intervention parameters for triggering:

- required deceleration for triggering (d_{req});
- reference deceleration for the AB (d_{AB});
- reference deceleration for the EB (d_{EB});
- delay-time for deploying the AB (τ_{AB}).

The reference deceleration for the AB must be small enough to avoid the rider falling off the PTW,

since the rider may not be aware about the deployment of the AB. Specific tests will be required to identify the maximum acceptable deceleration for the AB.
For the EB, since the braking assistance is deployed when the rider is already braking, a high value of deceleration could be acceptable, as the rider is aware of the emergency situation. Further investigation will be necessary to assess the deceleration value for the EB.
Table 3 shows the values for the assumed intervention parameters.

Table 3.
Intervention parameters

Parameter	Value
d_{trigg}	10 m/s^2
d_{AB}	4 m/s^2
d_{EB}	8 m/s^2
τ_{AB}	0.1 s

The impact speed reduction is a function of Δv and does not depend on v_{PTW} itself. For the assumed values of the intervention parameters, in Table 4 the reduction of impact speed and energy when the rider performs no braking manoeuvre are shown.

Table 4.
Relative impact speed reduction
(only AB, no reaction from the rider)

Δv [m/s]	5	10	15	20	25
Impact speed reduction (%)	12	17	19	20	21
Impact energy reduction (%)	23	32	35	36	37

In theory, when the AB triggers, the rider is expected to start braking. In that case the system will switch from the AB to the EB. Hypothetically, if the delay-time between the instant when the AB actually deploys and the rider brakes is $\tau_{EB} = 0.2$ s, the final impact speed reduction is still a function of Δv. Under these assumptions, the theoretical benefits are not negligible, as shown in Table 5.

Table 5.
Relative impact speed reduction
(AB followed by EB)

Δv [m/s]	5	10	15	20	25
Impact speed reduction (%)	12	24	34	39	42
Impact energy reduction (%)	23	43	56	63	66

PRELIMINARY TESTS

Tests were conducted to validate the triggering strategy in real conditions in terms of reaction time to trigger and false triggering. This will form the basis for a future evaluation of the theoretical benefits of the AB and EB.

For evaluating the triggering, the deployment of the braking actuators is not necessary. Hence the tests are conducted off-line, by elaborating the datasets acquired on a PTW.

Test preparation

The PTW, a 500cc Malaguti SpiderMAX scooter, is integrated with the Laserscanner (Ibeo LUX) manufactured by Ibeo Automobile Sensor GmbH to monitor the surrounding and the IMU (MTi-G, Xsens) to acquire the information about the state of the PTW.
The Laserscanner is utilised with the following characteristics:

- scan frequency: 12.5 Hz;
- field of view (horizontal): 100°;
- range: 0.3 m to 200m.

In Figure 3 the Ibeo Laserscanner mounted in front of the PTW is shown.
The characteristics of IMU are the following:

- maximum update frequency: 120 Hz;
- heading estimation (dynamic accuracy): 2° RMS;
- speed estimation.

Figure 3. Ibeo Laserscanner mounted on board the PTW.

Table 6.
Processed variables acquired for the tests

n.	Variable
1	time
2	speed of the PTW
3	obstacle id
4	relative x distance of the obstacle
5	relative y distance of the obstacle
6	relative x speed of the obstacle
7	relative y speed of the obstacle
8	absolute x speed of the obstacle
9	absolute y speed of the obstacle

The raw scan data and the state of the PTW acquired respectively from the Laserscanner and the IMU are processed together using an application software developed by Ibeo. An object tracking and classification are performed, providing the information shown in Table 6.
The software runs on an electronic control unit (ECU) connected to a hard drive to store the data. Both the ECU and the hard drive are mounted on-

board the PTW. Then the processed data stored in the hard drive is utilised to perform an off-line elaboration. Figure 4 shows the acquisition system set up on board the PTW.

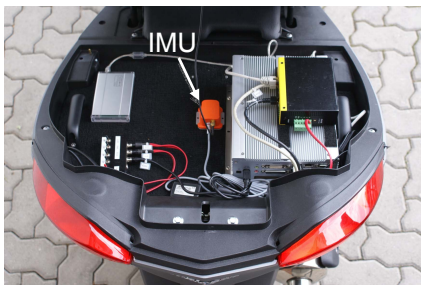

Figure 4. Acquisition system on board the PTW.

Test description

A total of ten tests were conducted for AC8 with both moving and fixed obstacle, while PTW travelling towards it. Six tests were conducted for the PTW travelling on a straight path towards a leading car proceeding at different speeds. These tests were performed on a straight road in real traffic conditions. In all the cases the car was approaching an intersection and slowed or stopped, with the PTW following. The PTW rider was aware of the situation and braked with an appropriate deceleration, thus avoiding the collision.

Figure 5. PTW travelling towards a fixed obstacle.

Four tests were conducted with the PTW travelling on a straight path towards fixed foam as obstacle in a parking lot along with other fixed objects (Figure 5). The tests were performed simulating different rider behaviours in terms of awareness of the imminent collision:

- no awareness – proceeding with constant speed against the obstacle;
- late reaction – proceeding with constant speed before braking too late, thus colliding with the obstacle;
- full braking – proceeding with constant speed before hard braking, thus avoiding the collision;
- complete awareness – proceeding with constant speed before braking on time to avoid the collision.

Elaborations

For each test, the Laserscanner identifies several objects with the related information about the state. In principle, for each object it is possible to calculate the risk for collision. On-line elaborations will be performed alternatively by computing the information of all the detected objects simultaneously or by utilising a specific algorithm to automatically identify and compute only the information related to the principal object. Since in the present work the elaborations are conducted off-line, the principal object is selected manually and the information is obtained about it. For each test, the outcome of the elaboration is the trend as a function of time for the following parameters:

- d_{req};
- L_{swerve};
- trigger for the AB.

For these preliminary tests, the throttle position and the braking forces are not measured.

Results

The results of the evaluation are shown in a graphical manner. These graphs are divided into two groups, the first representing d_{req} and the trigger. On the x-axis the time duration of the test is shown. On the left y-axis, the distance between the PTW and the obstacle (black line) is shown together with the v_{PTW} (green dotted line), on the same scale. On the right y-axis d_{req} (red line) is shown. The trigger is represented as a step function (zero means no triggering).

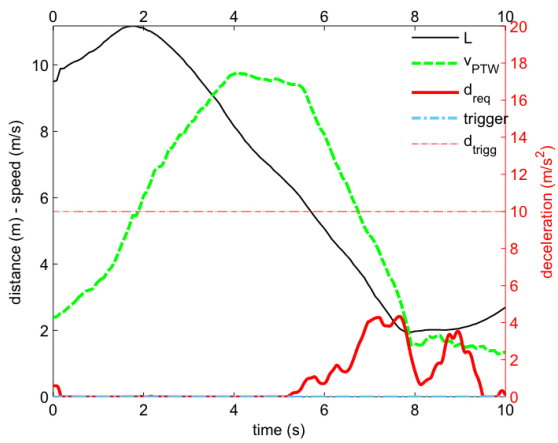

Figure 6. Risk evaluation for a specific PTW following a car.

<u>**Moving obstacle**</u> - For the PTW following a leading car, six tests were conducted when the rider was completely aware of the situation, hence there was no necessity to trigger the AB. In fact, in all these cases the rider reacted on time by braking to avoid the collision. In Figure 6, risk evaluation for a specific PTW following a leading car is shown. It is representative of all the six cases for car following, as they were similar. During these preliminary tests

conducted in real traffic conditions with an attentive rider, d_{req} is always less than or equal to 5 m/s^2, which is far below the defined threshold for triggering.

Fixed obstacle - As expected, for the three different rider behaviours, while travelling towards a fixed obstacle, the deployment algorithm computes different responses. Figure 7 represents the PTW travelling towards a fixed obstacle without performing any collision avoidance manoeuvres, to simulate the rider behaviour with no awareness of the imminent collision. The result of this elaboration shows that while the PTW is approaching the obstacle, d_{req} increases and exceeds the triggering threshold limit. The triggering deploys 0.7 s prior to the collision, coherent with theoretical estimation.

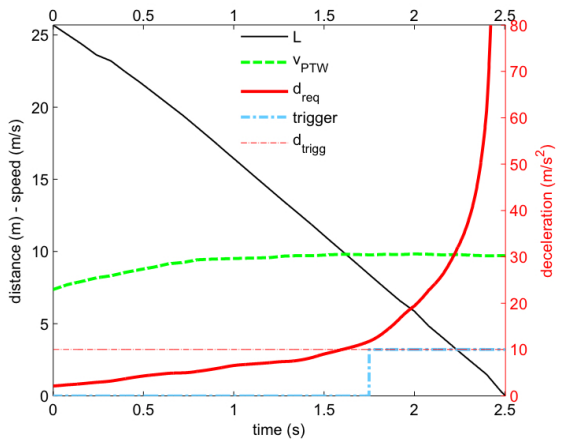

Figure 7. Risk evaluation for a specific PTW travelling towards fixed obstacle with no awareness.

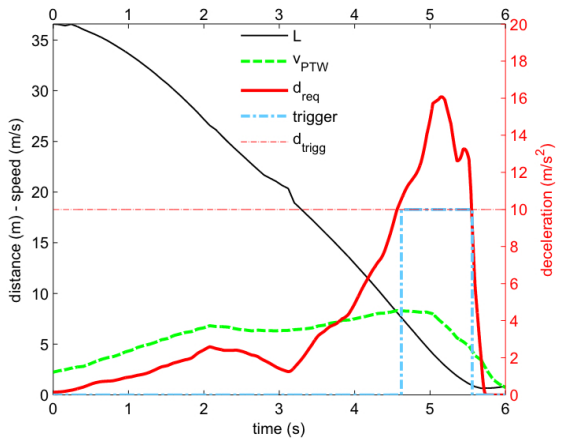

Figure 8. Risk evaluation for a specific PTW travelling towards fixed obstacle and reacting too late.

Figure 8 represents the PTW travelling towards a fixed obstacle with the rider performing the braking manoeuvre too late to avoid the collision, thus simulating the rider behaviour of late reaction. The result of this elaboration shows that also in this case d_{req} exceeds the triggering threshold limit. The triggering is 0.2 s prior to the full braking applied by the rider.

Figure 9 represents the PTW travelling towards a fixed obstacle when the rider reacts to the emergency situation with a last second braking, thus representing a full braking manoeuvre with no collision. In this case the global maximum of d_{req} is below the threshold limit, in fact the rider was able to avoid the collision.

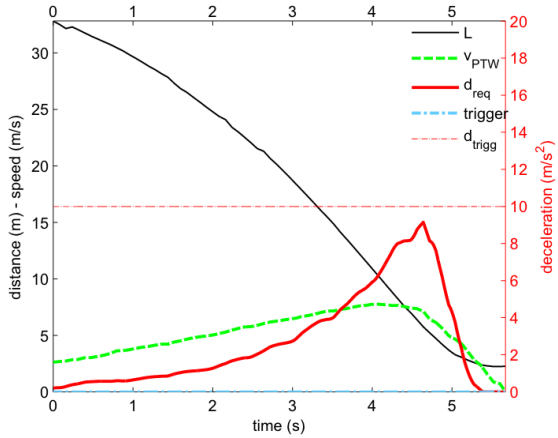

Figure 9. Risk evaluation for a specific PTW travelling towards fixed obstacle with full braking.

The second group of graphs (Figure 10 and Figure 11) shows d_{req} (red line) and the distance to avoid collision (dotted blue line) together with the distance between the PTW and the obstacle (black line). They represent the cases in which the activation occurred, to highlight the influence of the distance to avoid collision by swerving on the triggering. On the x-axis, the time duration of the test is shown. On the left y-axis both the distances are shown, while on the right y-axis d_{req} is shown.

To compute L_{swerve}, the values assumed are shown in Table 7.

Table 7.
Intervention parameters

Parameter	Value
s	3 m
φ_{max}	30°

In Figure 10, d_{req} exceeds the threshold (point A). At this point, the rider cannot avoid the collision by braking, but still has the possibility to avoid the collision by swerving, as L_{swerve} is lower than L. Hence there is no trigger. When L becomes lower than L_{swerve} (point B), the collision avoidance is no longer possible neither by swerving and therefore the trigger is activated.

In both Figure 10 and Figure 11, for the PTW speeds less than or equal to 10 m/s, approximately at the same time d_{req} exceeds the threshold for trig-

gering and L becomes lower than L_{swerve}. For this reason, even with a lower value of d_{trigg} there will be no anticipation in the triggering, because of the inhibition produced by L_{swerve}.

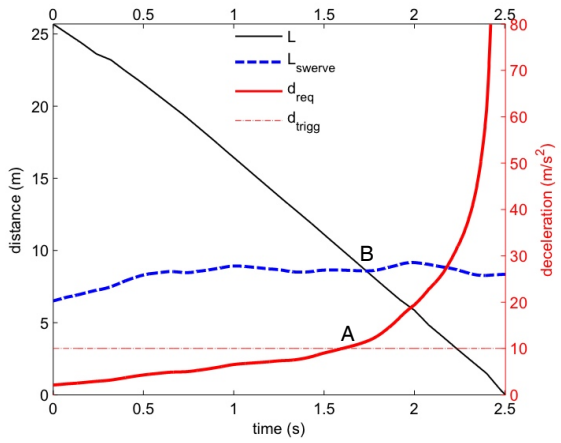

Figure 10. Triggering activation/inhibition parameters for no awareness case.

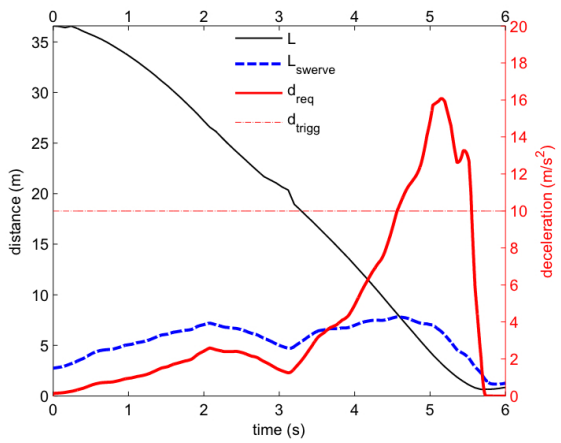

Figure 11. Triggering activation/inhibition parameters for late reaction case.

CONCLUSIONS

The decision logic described in the paper defines the deployment criteria for the AB and EB of a PTW integrated safety system in order to reduce the casualties in car following configuration.

The criterion is to deploy the braking assistance functions only when the collision has become physically unavoidable, since a prior deployment is potentially dangerous for the rider. The collision is considered unavoidable based on two parameters:

- required deceleration to avoid the collision (d_{req});
- distance to avoid the collision by swerving (L_{swerve}).

When d_{req} is higher than d_{trigg}($10 m/s^2$), the collision is unavoidable by braking. When the distance of the leading vehicle is lower than L_{swerve} the collision is unavoidable by swerving. The triggering is deployed when both the conditions are satisfied, hence avoiding the possibility of false triggering.

The computed theoretical benefits for the AB and EB reveal significant reduction in the impact speeds and energies. Further studies are required to identify the appropriate values for intervention parameters.

The PTW, integrated with the Laserscanner and the IMU, was used to perform preliminary tests for the car following configuration. The tests were conducted with PTW following a moving car and PTW travelling towards a fixed obstacle with simulated different rider behaviours. The datasets acquired are utilised for performing the off-line evaluation of the decision logic deployment strategy. The results show that in none of the cases false triggering is generated.

Further investigation is still necessary to validate the deployment strategy in real traffic conditions.

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