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PISa – Powered two-wheeler Integrated Safety.
Development, implementation and testing of PTW integrated safety systems

Authors (name and surname):
Giovanni Savino & Marco Pierini[1]; Rachel Grant, Richard Frampton & Rachel Talbot[2]; Steffen Peldschus & Erich Schuller[3]; Aernout Oudenhuijzen & Jasper Pauwelussen[4]; Bart Scheepers & Arjan Teerhuis[5]; Mangaraju Karanam Venkata & Rengarajan Babu[6]; Bernd Roessler[7]; Matteo Nanetti[8]; Roberto Guggia[9]; Michael G. McCarthy & Wesley Hulshof[10]

Affiliations:
[1] Dipartimento di Meccanica e Tecnologie Industriali, Università degli Studi di Firenze, Italy.
[2] Vehicle Safety Research Centre, Loughborough University, UK.
[3] Institute of Legal Medicine, Ludwig-Maximilians University, Germany.
[4] Human Factors, TNO, The Netherlands.
[5] Automotive, Integrated Safety, TNO, The Netherlands.
[6] TVS Motor Company Limited, India.
[7] Ibeo Automotive Systems GmbH, Germany.
[8] Paioli Meccanica S.p.A., Italy.
[9] Unilab Laboratori Industriali s.r.l., Italy.
[10] Vehicle Safety and Engineering, TRL Limited, UK.

Abstract

The Powered two wheeler Integrated Safety (PISa) project, funded by the European Commission within the 6th Framework, aimed at identifying, developing and testing new technologies to provide integrated safety systems (ISS) for a range of powered two wheelers (PTWs) to improve primary safety and link to secondary safety systems.

From the analysis of representative crashes involving motorcycles and mopeds, a list of safety systems was prioritised in terms of their contribution to crash avoidance or injury severity reduction. These systems were integrated onto two different types of PTW: a large scooter and a light motorcycle.

Experimental tests with the demonstration vehicles showed the potential benefits of the PISa systems compared to unequipped PTWs. Further system development is required before testing the demonstration vehicles with non-professional riders.

Introduction

The large number of road accidents represents one of the concerns of the European Commission (EC). In 2001, there were almost 50.000 road fatalities in Europe; more than 5,000 of these were powered two wheeler (PTW) riders or pillion riders. In the same year, the EC signed the White paper – 'European transport policy for 2010: time to decide', expressing its commitment to sustain the development of new technologies aiming at drastically reducing the number of the road accidents and fatalities. PISa – Powered two wheeler integrated Safety, which started in June 2006 and ended in March 2010, was one of the EC funded projects in the field of road safety and aimed to develop and use new technologies to provide an integrated safety system for a range of PTWs.

The philosophy of the PISa project was to identify the most frequent causes of PTW accidents and select the technologies capable of supporting the riders in critical situations. The review of the previous studies on European PTW accident statistics provided the basis to investigate the most relevant crash types for PTWs in terms of frequency and severity. These were mainly the crashes involving a PTW and a car travelling along the same straight line or approaching a junction from different directions. The systems developed in the PISa project were selected to help riders avoid some of those types of crash and mitigate the consequences of others, thus leading to a reduction in serious injuries.

The integrated approach of PISa consisted in the combination of accident avoidance and injury prevention technologies. Two different integrated systems were implemented, both focused on the identification of hazard and enhanced braking combined with the PTW stability, although with different levels of technical complexity and cost.

Method

Identification of the integrated safety system

The approach taken to identify an effective integrated safety system consisted of analysis of a sample of representative crashes which took place in Europe and involved PTWs. Sixty crashes were selected from British and German in-depth accident databases with the main criterion of matching the most frequent accident scenarios identified by the APROSYS project. Each crash was examined to identify relevant safety functions addressing the pre-crash, crash or post-crash phase, which could have helped to avoid the crash or in mitigating the injury outcome. A list of 43 safety functions was obtained, taking into account both the available automotive technologies and new functions. The safety functions were prioritised by a team of analysts in terms of the contribution to crash avoidance or injury severity reduction for the in-depth crashes. The process was based on the frequency of occurrence and how effective the actions of the system were judged to be in the specific accident circumstances. Among the high priority safety functions, only those which could be installed on a PTW (as opposed to other vehicles or infrastructures) were selected for development. The prioritised safety functions were utilised to define the functional requirements for the development of the integrated safety system. A complimentary survey among motorcyclists in Germany, Italy and the Netherlands was conducted to investigate what the possible rider acceptance of a selection of these safety functions might be.

The safety functions selected for the integrated safety system were:

- Stop PTW - autonomous braking
- PTW to detect other vehicle and warn rider - laser scanner
- Anti-lock braking system (ABS)
- Brake Assist - enhanced braking system (EB)
- Brake Assist - combined braking system/linked brakes (CB)
- Adaptive cruise control (ACC)

Active/anti-dive suspension was also identified, in order to support the operation of the systems identified above.

These safety functions were applied to 2 different PTWs in different combinations as described below.

Figure 1: Malaguti test bike and TVS test bike

Malaguti scooter

A 500 cc Malaguti Spidermax scooter was equipped with a frontal detecting system based on a laser-scanner sensor; a distance support system to help the rider maintain the appropriate distance from a leading vehicle; an intelligent braking system, with active and enhanced braking functionalities, to assist the rider in case of an imminent collision; a vibrating saddle to warn the rider; and active suspension for stability enhancement during emergency braking. A state estimator that estimates the motion of the motorcycle has been developed. The integration of the systems mounted on the scooter was achieved by a decision logic running on a dedicated electronic control unit. All the integrated units communicate with each other via a double channel CAN bus which guarantees the appropriate bus rates and the desired priorities on the messages.

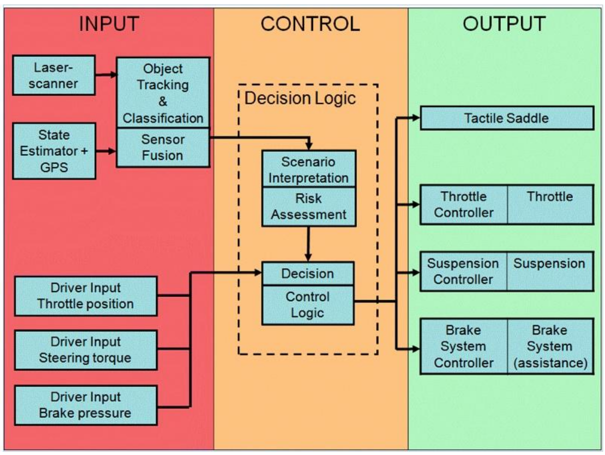

Figure 2: Scheme of the integrated safety system mounted on the Malaguti scooter

Laserscanner

The main task of the object detection sensor system was to detect, classify and track the objects in the PTW's forward field of view. This information is later used in the control level in order to interpret the situation and to issue warnings to the driver, or to activate autonomous actions within the scenarios addressed by the PISa project.

The "heart" of the system was the Ibeo Lux Laser scanner. This device uses a time-of-flight measurement principle at near-infrared wavelength. The measurement range is up to 200 m, however vehicles and other well reflecting objects are typically detected well beyond this distance. The device is eye-safe (class 1) and has the following features:

- Scan frequency: 12.5/25 Hz
- Field of view (horizontal): 100°
- Range: 0.3 m to 200 m
- Resolution angle: 0.1° to 1°
- Laser class 1
- Built-in processing
- 4 parallel and simultaneous scanning layers
- Ethernet- and CAN-interface

Figure 3: Ibeo Lux Laserscanner

The Laserscanner is capable of full automatic pitch compensation, due to four laser beams working in parallel and simultaneously which produce a vertical field of view of 3.2°. The four beams allow the object tracking while the PTW is pitching and make the system robust for rough road surfaces.

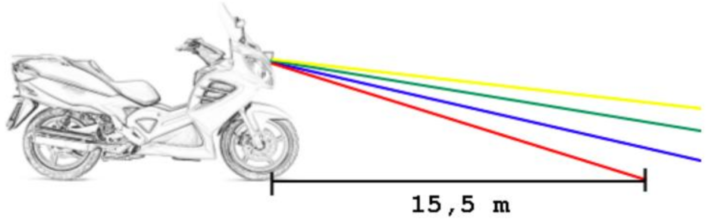

Figure 4: Four layers in parallel produce the automatic pitch compensation

Data processing

The raw data coming from the scanner are internally processed to produce the object tracking. Ibeo customised the Laserscanner for the application on a motorcycle. Compared to the passenger car application, the PTW is more challenging due to the additional degree of freedom represented by the banking angle (roll). Ibeo developed the algorithms for the ground detection, in order that the scan data representing the ground are filtered out before performing the object identification. For the object tracking, the movements of the PTW frame on which the Laserscanner is mounted must be estimated, in order that the scan data movements can be compensated. Therefore a set of vehicle sensors is needed to assess parameters like the yaw rate and the speed of the PTW. Finally, the series of objects identified and tracked by the Laserscanner are sequentially communicated to the integrated safety system via CAN bus.

Integration

For the integration of the sensor into the demonstrator a favourable location had to be identified at the front of the PTW. A special fixture was constructed such that the Laserscanner could be securely connected to the framework of the fairing and thus the chassis of the PTW. As can be seen in Figure 5**Error! Reference source not found.** the sensor fits well into the fairing of the PTW between both headlights. It was not necessary to remove any parts from the PTW in order to integrate the sensor. Installation is an important issue when evaluating the potential future of the system in motorcycles.

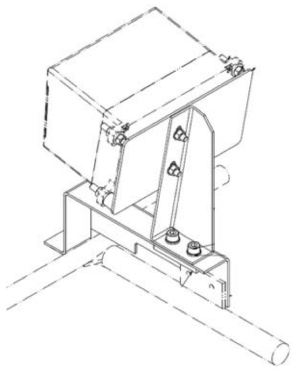

Figure 5: Integration of the Ibeo Lux Laserscanner

State estimator

Another input of the integrated safety system is the state of the host PTW, which is the combination of quantities (e.g. pitch angle, lateral speed, yaw rate etc) that describe the dynamic situation of the motorcycle. This information is necessary to know the path of the PTW and also to give a reference to the object data coming from the Laserscanner. The state of the PTW and the state of the object together give the possibility to identify an imminent threat for collision and eventually choose the intervention strategy.

Sensing the state of the PTW is challenging especially for several variables which cannot be measured directly, e.g. the roll and pitch angle. These quantities can be estimated from other measurements, using a so-called state estimator. TNO investigated the feasibility of a State Estimator for the PISa system having the following benefits:

- the aim to provide reliable and consistent input for vehicle control systems

- estimate signals that are not measured directly
- compensate for sensor inaccuracy and noise
- perform sensor fault detection
- reduce the cost of the measurement system by minimizing the number of required sensors
- enable the use of lower resolution sensors.

The strength of the State Estimator is its model-based design. Inside the State Estimator is a (simplified) model of the system, which consists of only the most important dynamic effects (i.e. degrees of freedom). All these dynamic effects together are called the 'state' of the system. The model is excited using the same inputs (u) as the driver would apply on the PTW (e.g. steering angle, brake/drive moments). All actual sensors on the PTW, such as lateral acceleration, yaw rate, are modelled as well. The estimation algorithm, here the well known Kalman Filter algorithm was used, minimizes the difference between the actual measurements (y) and the modelled measurements ($\hat{y}$) by adjustment of the state vector.

Once an estimate of the state vector is calculated, this new state can be used to also determine any other quantities that can be derived from the state information, such as roll angle, tyre slip angles, tyre forces, etc.

Once the model is tuned, it provides a reliable estimate of the dynamic state of the motorcycle. The crucial aspect is to find a suitable model of the vehicle which correctly interprets the relationship between the state variables.

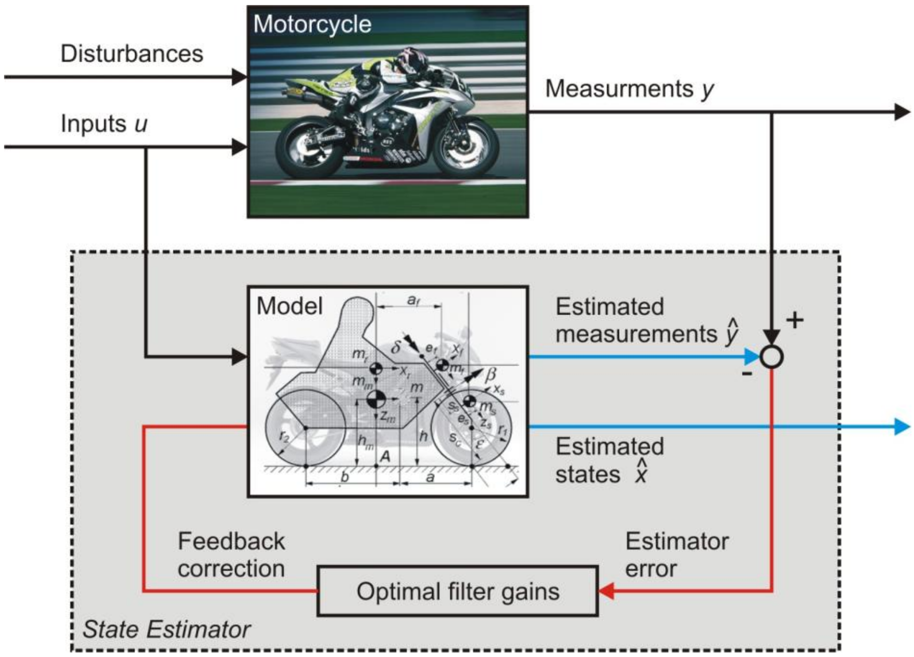

Figure 6: Functional scheme of the state estimator

A four-degree-of-freedom analytic model was selected to reproduce the behaviour of the motorcycle. The state estimator was evaluated in a slalom and in a roundabout manoeuvre. As can be seen in Figures Figure 7 and Figure 8, the estimator is able to estimate the lateral velocity and roll angle in an accurate way. It can be concluded that state estimation based on Kalman filtering is a feasible method for estimating the states of a motorcycle.

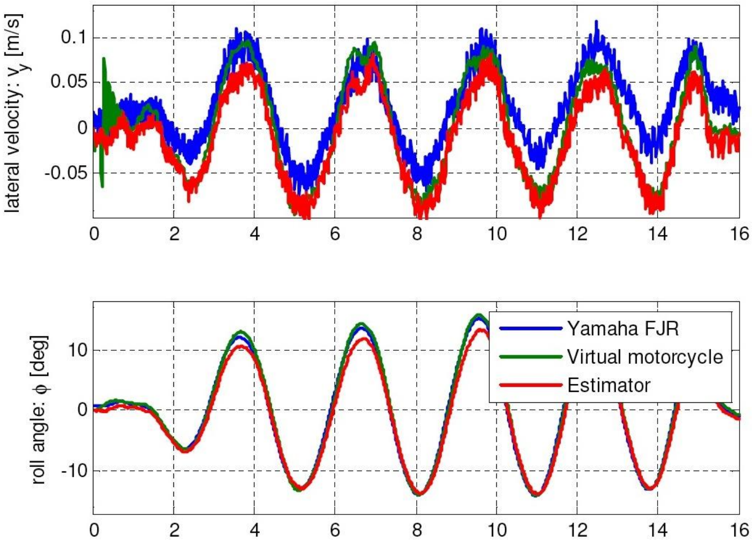

Figure 7: Results of the state estimator in a slalom

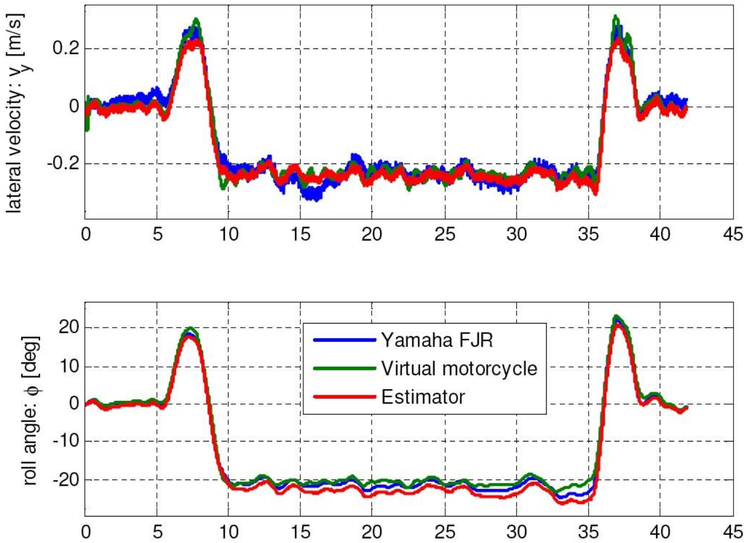

Figure 8: Results of the state estimator in a roundabout

Because the outcome of the feasibility study was not known beforehand, it was unknown whether the state estimator output would satisfy the requirements. Therefore, to guarantee the availability of motion signals with desired quality, the state estimator functionality on the PISa PTW was provided by an off-the-shelf Inertial Measurement Unit (IMU) which delivered the necessary data for the PISa applications. However, its high price would make it unsuitable for production motorcycles; further development of the lower cost state estimator might provide a way to implement this in a more cost effective manner.

Figure 9: Off-the-shelf inertial measurement unit 'Xsens'

DS system

The Distance Support (DS) system assists the rider to maintain a safe distance during the car-following task by providing an appropriate force feedback on the throttle twist grip. The basic concept of the DS is that when the rider maintains the appropriate values of speed and distance from the lead vehicle, the torque on the throttle is constant. If the lead vehicle slows down, the distance starts to reduce. The attentive rider would react reducing the torque on the twist grip throttle, while the inattentive rider does not react and keeps a constant torque, and the gap consequently reduces. The DS system uses the information coming from the IMU and the Laserscanner to detect the need for slowing down and consequently increases the resistant torque on the handle-grip, thus reducing the throttle and slowing down the PTW unless the rider reacts.

The human-machine interface based on the force feedback was chosen to fulfil the most important requirements for a safety application: the rider can react intuitively in a proper way; the rider can keep his/her eyes on the road without being distracted; the control effort required for the rider should not increase.

The development process consisted of three activities: the definition of the algorithms for controlling the amount of feedback; the selection of the functional parameters, which are the value of the maximum feedback torque and the shape followed by the torque to build up; and the development of the hardware to implement the DS on the test motorcycle.

The intervention algorithm is based on two kinematic algorithms: the time headway (THW) and the time to collision (TTC). The THW guarantees that the distance between host PTW and lead vehicle is adequate also when the difference in speed Δv is zero. The TTC allows identifying the torque feedback when Δv is different from zero.

The intervention parameters and the force build-up were selected through an experimental campaign conducted with a static riding simulator (Figure 10). The volunteers were asked to keep a constant THW during the car following task simulated by the computer while the throttle twist grip was actuated by an electric motor to simulate the force feedback produced by the DS system. The volunteers repeated the task while the max torque and the build-up curve varied; at the end they filled in a questionnaire. The best value for the max torque and the torque build-up were selected based on the results of the questionnaires.

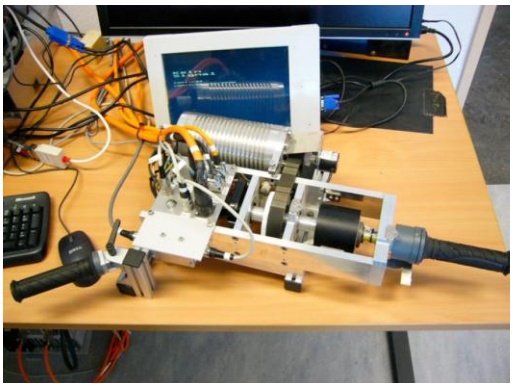

Figure 10: Riding simulator used during the preliminary tests

The hardware of the DS was developed and tuned to reproduce the prescribed values of torque and the correct shape to build up the torque. The DS is obtained through a device which exploits the vacuum created by the engine in the inlet pipe and produces the desired force feedback using intermitting valves. The force feedback is converted into a torque feedback at the throttle twist grip of the test bike via wire.

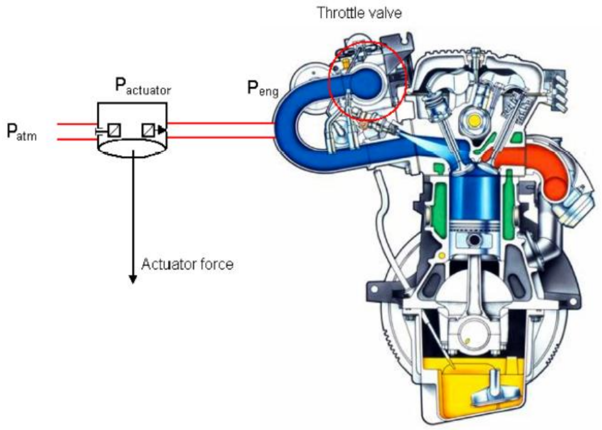

Figure 11: Operating principle of the DS system

Active Braking

The term active braking (AB), in the context of this project, refers to slowing down the vehicle without any braking input from the rider i.e. autonomous braking. This system is necessarily linked with the design of the decision logic.

Laboratory tests were performed by LMU in order to find a feasible level of deceleration for the active braking. Those sled tests had an idealised set-up mimicking the deceleration process of a PTW in a very basic way. Based on this experimental activity, a deceleration of 2.5 m/s^2 was shown to be adequate in the sense of not producing excessive motion, or possible instability, of the volunteer riders. This level was then selected as a target deceleration for the active braking. For the enhanced braking (EB), the target deceleration was 6 m/s^2, which is the maximum value before experiencing cases of front wheel lock with the Malaguti scooter.

The active braking device was designed and realised by Carver Engineering. It utilises an independent hydraulic system acting on the right hand disk mounted on the front wheel. The front brake is also under control of the rider through the left braking disk.

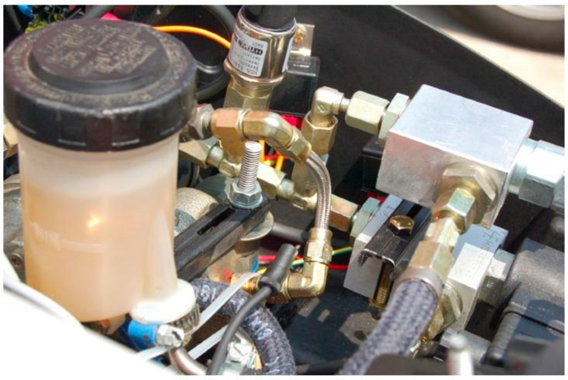

Figure 12: Active braking device

The active braking device consists of a dedicated braking disk, the hydraulic circuit and calliper, an electric motor and pump to build up the pressure, a pressure sensor, the electronic control unit, and the power supply. When the active braking is idle, the pump is off and the pressure inside the circuit is close to the atmospheric value, therefore no braking torque is applied on the right braking disk and the rider has full control of the braking action on the front wheel. When the electronic control unit receives the input to start the active braking function, the electric motor connected with the pump is activated, the pump starts building up the pressure in the braking circuit and the calliper produces a braking torque on the right disk on the front wheel.

The predetermined deceleration d_{ref} is obtained controlling the pump in closed loop with the pressure sensor, so that a target pressure can be achieved. Tests with the prototype were performed to identify the target pressure needed for obtaining the target deceleration d_{ref}.

Semi-active front fork

Within the PISa project Paioli developed a different front fork suspension for each prototype vehicle aiming to improve the stability before and during emergency braking events.

The behaviour of the suspension system was fully reversible although the activation time should be quick enough to be beneficial since the first phase of the braking manoeuvre.

For the Malaguti bike the requirement for the fork was to be capable of continuous adjustment of the damping coefficient on a wide range, although the reaction time for a full adjustment is around 0.2 and 0.3 s.

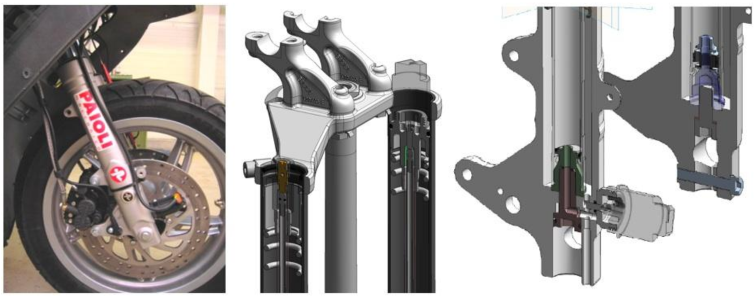

Figure 13: Semi-active front fork installed on the Malaguti

Decision logic

The elaboration of the input signals coming from the sensors and the control of the actuators mounted on the Malaguti are performed by the decision logic running on a prototyping electronic control unit.

The inputs to the decision logic are summarised as follows:

- the state of all the objects detected and tracked by the Laserscanner;
- the state of the host PTW provided by the inertial measurement unit;
- the rider inputs which are the brake pressures, the throttle position and the steering position.

The decision logic has control over the following devices:

- the throttle actuator of the DS system;
- the active braking device that implements the active and enhanced braking functionalities;
- the semi-active front suspension;
- the tactile saddle that generates warning signals to the rider.

The development of the decision logic was under the responsibility of UNIFI and focused on two accident configurations. The first one is the car following and consists in the PTW going straight on when the leading vehicle slows down or stops. The second accident configuration is the intersection scenario and consists of the PTW and another vehicle both crossing an X-junction while they are travelling straight on.

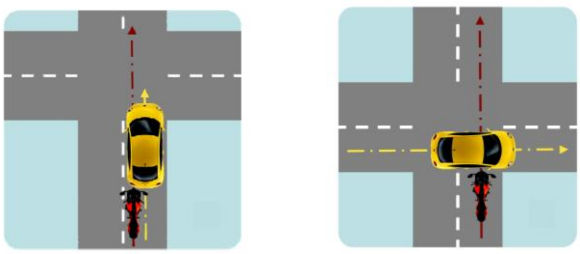

Figure 14: ‘Car following’ and ‘intersection’ accident scenarios

In the car following scenario the haptic throttle supports the rider in keeping the appropriate time headway (THW). In case of imminent collision, e.g. when the leading vehicle suddenly slows down or stops in front of the PTW, the haptic throttle will provide the maximum torque to induce the rider to decelerate, while the decision logic will decide whether to activate the active braking device for the AB or the EB.

The autonomous deceleration on a PTW is potentially dangerous due to the intrinsic instability of the vehicle. For this reason both the AB and EB are inhibited when the PTW is travelling along a curve. However, in the case of a straight path the main criterion utilised to trigger the AB or the EB is to assess that the collision against the leading vehicle has become unavoidable by braking and swerving as well.

The possibility to avoid the collision by braking is evaluated by computing the required deceleration parameter d_{req} as follows:

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

where v_{PTW} is the PTW speed, v_L is the lead vehicle speed, a_L is the lead vehicle acceleration, and L is the relative distance between PTW and leading vehicle. At every instant, d_{req} represents the constant value of deceleration the rider should apply to avoid the collision with the leading vehicle assuming that the leading vehicle is proceeding along a straight line with constant deceleration. The decision logic constantly computes the value of the required deceleration and compares it with a threshold value representing the maximum feasible deceleration. When d_{req} is greater than the threshold the braking avoidance manoeuvre is considered not possible anymore. The threshold value was initially set to 10 m/s^2 which corresponds to the theoretical limit on dry road conditions with common tyres. During the tests the threshold was adjusted to different values between 3 to 10 m/s^2 to investigate the system reliability and the level of acceptance from the test riders.

The possibility to avoid the collision by swerving is assessed comparing the distance L between the PTW and the leading vehicle with the minimum swerving distance L_{sw}:

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

where $k = \frac{1}{\tan\varphi_{\max} \cdot g}$, s is the tolerated distance between the centres of gravity of the PTW and the object, φ_{max} is the maximum feasible roll angle for the PTW during emergency curving and g is the gravitational acceleration.

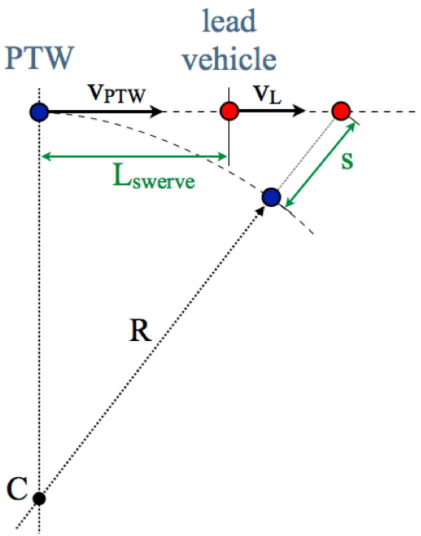

Figure 15: Kinematic scheme of the minimum swerving distance

As show in Figure 15, the minimum swerving distance L_{sw} is computed assuming that the radius of the path R suddenly changes from infinite (straight path) to a constant value R_{min}:

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

When L is smaller than L_{sw}, the collision is considered unavoidable with a swerving manoeuvre.

The decision logic triggers the active braking device when the distance between the PTW and the object is lower than both the minimum braking distance and the minimum swerving distance. When considering the possible collision against a fixed object, the minimum braking distance and the minimum swerving distance are functions of the initial speed of the PTW, as shown in Figure 16. The decision logic will trigger the active braking when the distance L is below the two curves. At low speed the collision can be avoided at a lower distance by braking, while at high speed by swerving.

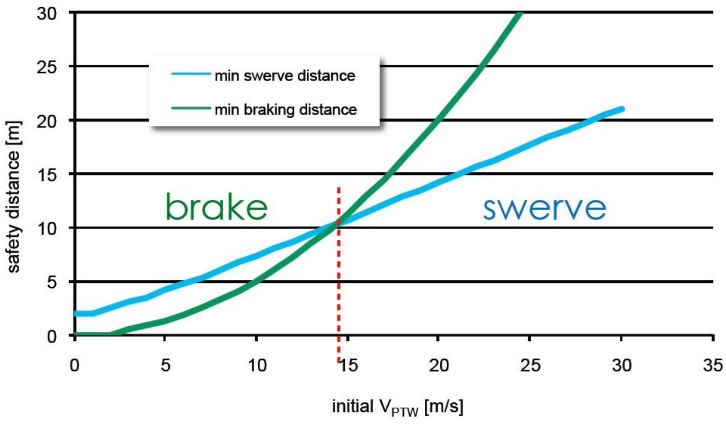

Figure 16: Minimum braking and swerving distances

A plot of the data acquired during a test run is shown in Figure 17 to illustrate the activation sequence of the active braking. The PTW is approaching a fixed obstacle at constant speed. The required deceleration d_{req} increases, due to the reduction of the distance of the object. When d_{req} overcomes the threshold value of 6 m/s^2 selected for the test run, a warning is given to the rider through the vibration of the haptic saddle. At the same time the semi-active suspension is controlled to switch to the maximum damping coefficient. After a delay time of 0.3 s the AB is triggered: the active braking device is activated and the PTW starts decelerating without any input from the rider with a target deceleration of 2.5 m/s^2. If the rider starts braking the decision logic switches from AB to EB and the active braking device increases the braking pressure to obtain an extra deceleration of 3.5 m/s^2.

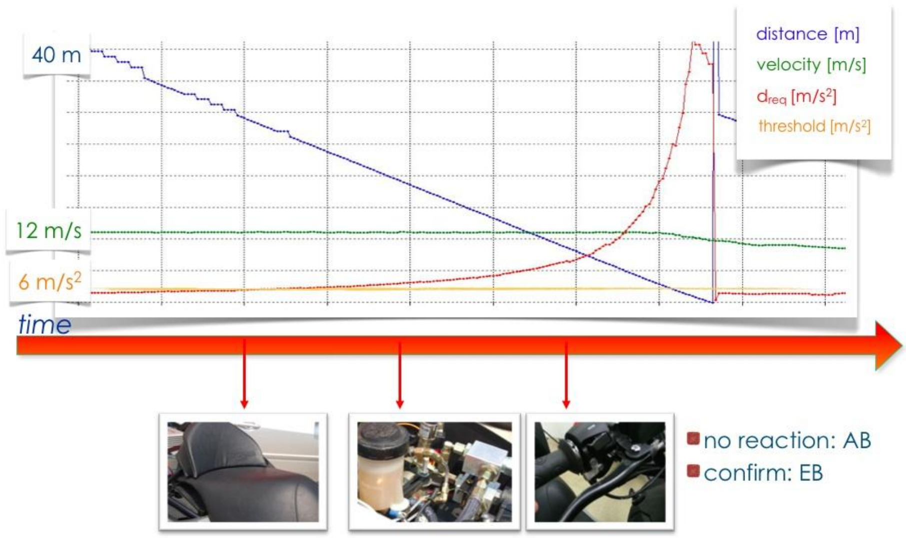

Figure 17: Activation sequence of the active braking

TVS motorcycle

A TVS Apache 160 cc motorcycle was equipped with the combined braking (CB) system to improve the emergency braking performances of non-skilled riders and the anti-dive suspension for stability enhancement during the emergency braking. The development of these two devices complied with the criterion of containing the costs of a product appropriate for the Indian motorcycle market.

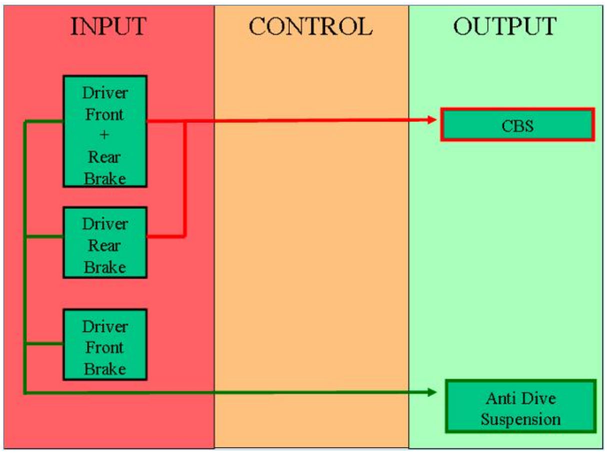

Figure 18: Scheme of the integrated system mounted on the TVS motorcycle

The physics of the braking manoeuvre for two wheeled vehicles demonstrates that the maximum deceleration can be obtained with an appropriate distribution of braking force on the two wheels, where the distribution is a function of the deceleration and the geometry of vehicle including the passengers. In the case of emergency braking, when the rider performs an erroneous distribution of the braking force the consequences are a lower deceleration of the vehicle and the possible wheel locking. A survey of riders conducted by TVS in India showed that in emergency conditions rider brake too hard on the rear brake while not fully exploiting the front brake. Accordingly, the CB system implemented by TVS for the PISa project aimed at transferring part of the braking force from the rear to the front brake. The CB device utilised a pressure distributor which redirected part of the braking pressure of one of the hydraulic circuits to the other, with constant distribution ratio. The TVS Apache used in the PISa project was set up such that the front disc was operated by the front brake lever and the rear brake force (applied by the brake pedal) was distributed between the front and rear wheels. The expected results are the higher deceleration during emergency braking and a reduction of the risk of the rear wheel skidding.

An anti-dive front fork was designed by Paioli for the TVS Apache with the aim to reduce the diving movement during an emergency braking event. The system utilised economical components, to achieve the specifications related to a possible applicability to the Indian market. For this reason, no electronic control unit was adopted and the activation of the fork was obtained from the front or rear braking signals. The fork is similar to the standard production but a solenoid valve is added to open or close the duct of the oil, thus drastically modify the damping coefficient. The valve has a short reaction time (less than 0.03 s), although no fine adjustment is possible.

Figure 19: Anti-dive suspension on the TVS motorcycle

Results

Professional riders tested the prototype vehicles. The aims of the tests were the validation of the integrated safety systems, an objective and subjective evaluation of the system performances and the identification of the recommendations for further development and testing of the proposed systems.

Results from the Malaguti test programme

For the Malaguti, the tests focussed on the DS, the AB and the EB systems. The final tests of the Malaguti vehicle were conducted on the TRL research track.

The validation of the DS system consisted of an experiment with the rider simulator and a pilot test on the track. In both the experiments the subject was asked to perform a car following task with and without the DS system. The experiments with the rider simulator showed that the DS could significantly improve the ability of the rider to maintain the target THW from the lead vehicle. In addition, when the DS system was on the throttle position was more stable, thus showing that the DS is capable of reducing the control effort of the rider during the car following task.

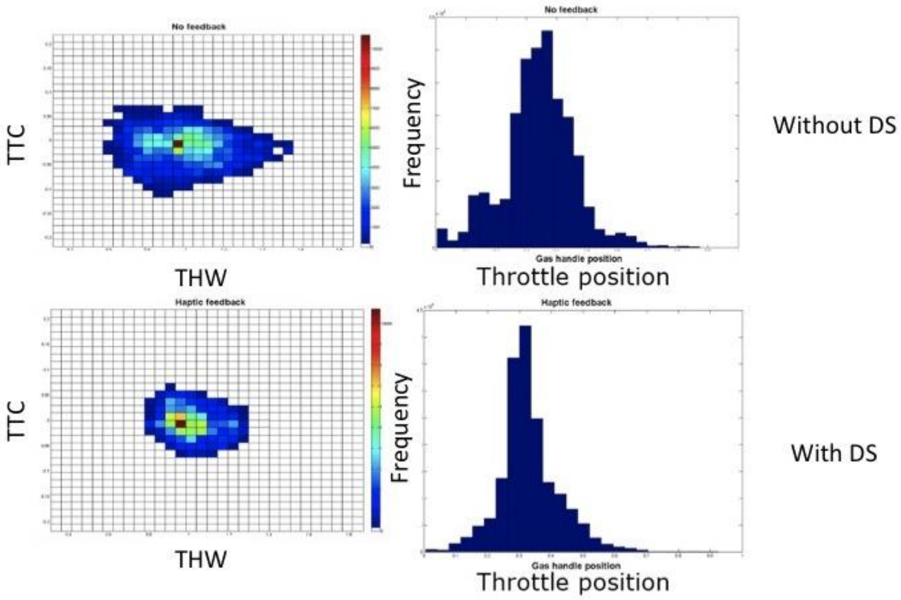

Figure 20: Simulation tests with and without DS: TTC vs. THW and frequencies of the throttle position

In contrast, the track tests conducted with 5 subjects were not able to highlight analogous differences with and without the use of the DS system. In particular, the standard deviation of the THW during the car following tests with the DS system on was not significantly lower compared to the tests without the DS. It was noted that during the track tests the Laserscanner detected other objects apart from the lead vehicle and this problem could negatively affect the quality of the feedback given to the riders. However, the subjective evaluation of the DS system made by the riders reported a positive opinion about the usefulness of the system. The final recommendation was to repeat the track tests with a wider set of test riders and improve the object detection in order to obtain results which could be better compared with those achieved in the simulation tests.

The AB tests were performed riding the Malaguti at a target speed of 12.5 m/s (45 km/h) towards a static obstacle. For safety reasons, the activation of the AB was allowed by the decision logic even if the obstacle was situated within a lateral distance of 3 m from the host vehicle. The threshold for the activation of the AB was set at the required deceleration of 3, 5, 7 and 9 m/s^2, which means that the active braking aimed to deploy when the collision could be avoided with a constant deceleration of 3, 5, 7 or 9 m/s^2. During the tests, the dSPACE device recorded 34 parameters at a frequency of 50Hz. The recorded data included the state of the host PTW, the objects detected from the Laserscanner, the inputs from the rider and other computed variables utilised by the decision logic.

Each test run was analysed to assess the correct identification of the obstacle and the correct deployment of the AB (successful test). The test runs in which the static obstacle was not identified, the AB failed to trigger or the AB had a false triggering were considered unsuccessful. The result was that the successful cases varied between 83% and 100% with thresholds of 3, 5 and 9 m/s^2, while they were the 56% for the threshold of 7 m/s^2. The system did not function correctly mainly because of crashes of the post-processing software of the Laserscanner or because the Laserscanner picked up incorrect objects.

Considering the successful runs, the AB was able to produce the active deceleration with a mean value of 2.8 m/s^2 (sd = 0.7 m/s^2) without any loss of control of the rider. The speed reduction and the kinetic energy reduction are dependent on the initial speed and their mean values are reported in Table 1.

AB trigger setting	Mean speed (km/h)	Mean trigger dist (m)	Mean speed after AB (km/h)	Mean speed reduction (%)	Mean kinetic energy reduction (%)
3	46.7	23.3	24.1	48.5	73.0
5	46.6	14.8	29.9	35.9	56.2
7	47.0	7.8	34.7	26.2	44.9
9	46.3	6.2	37.0	20.2	36.0

Table 1: Test results of the AB

The EB was tested at the speed of 25, 30, 35, 40, 45 and 55 km/h. The test riders were asked to apply a mild force on the rear brake lever just after the AB triggered. The decelerations obtained by the EB system were compared with the best performances in terms of deceleration obtained by the same test riders when they were asked to perform an emergency braking by applying both the rear and the front brake. The results synthesised in Figure 21 show that the difference between the stopping distances obtained by the professional riders applying full braking and those obtained with the EB on and the riders applying a partial force on the rear brake are small.

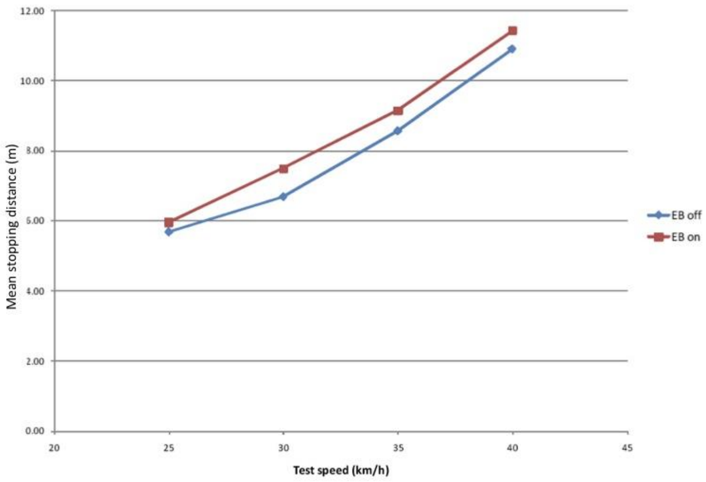

Figure 21: Mean stopping distance with and without EB

All the EB tests were repeated after enabling the semi-active front fork, with two different settings for the damping coefficient (medium and maximum). The mean stopping distances obtained with normal front fork and with semi-active front fork were compared, showing a significant reduction when the semi-active fork is on. Nevertheless no relevant difference was highlighted between the two settings for the damping coefficient.

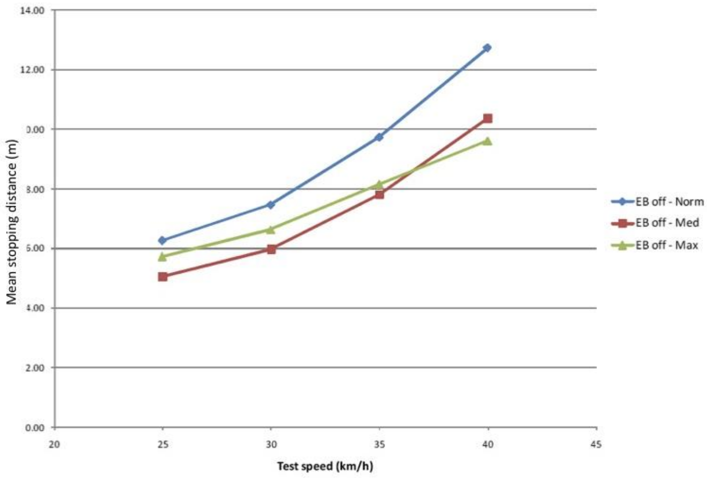

Figure 22: Mean stopping distance with different settings for the semi-active suspension

Results from the TVS test programme

The tests on the TVS motorcycle were straight line braking tests conducted with the CB system on and off and with the anti-dive suspension on and off. The tests were performed by two test riders and ten tests were done per each single condition; a total of 160 runs. The performances were evaluated on the stopping distance.

The comparison of the mean stopping distances with and without the CB depicted in Figure 23 shows that the stopping distances obtained when the CB is on are shorter and the benefit tends to increase at higher speeds. The anti-dive suspension had a negligible influence on the stopping distance for both the test riders.

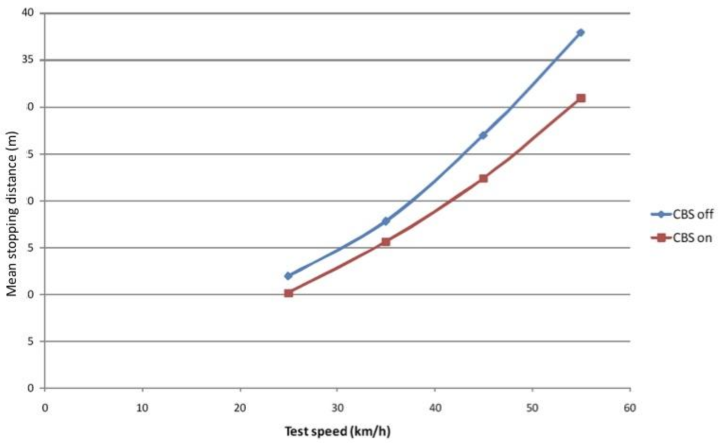

Figure 23: Mean stopping distance with and without CB

Conclusions

The PISa project aimed to develop an integrated safety system for PTWs which would contribute to the avoidance of a crash and the reduction of injuries resulting from a crash, by supporting the rider in safety critical situations. Two integrated safety systems were defined based on the functional requirements identified from the accident analysis and the technical solutions available within the Consortium. The integrated safety systems were implemented on a large scooter and a light motorcycle. The development of the systems tried to take account of a first set of problems related to a future application on production PTWs. In particular, a state estimator was developed demonstrating the feasibility of an economical alternative for the inertial measurement unit; a Laserscanner was customised for the PTW application; economical solutions were investigated, especially for the Indian market.

The prototype vehicles were tested to validate the system functions and to evaluate the overall performance. The active braking tests showed the feasibility of an active braking system on a PTW; the recommended autonomous deceleration was appropriate for the test conditions and the AB triggering was successful in most of the test runs conducted against a fixed obstacle. The enhanced braking system was efficacious in improving the braking deceleration in case of imminent collision against a fixed obstacle, reaching decelerations comparable with the performances of the test riders when they applied full braking with both the front and the rear brake. The combined braking system associated with the two-stage anti-dive suspension developed for the light Indian motorcycle obtained an improvement in the mean stopping distance over the tested speed range.

Although the results of the first tests were encouraging, further development and evaluation of the system is necessary in a wider range of test conditions and with a more representative population of riders.

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