

# Experimental evaluation of a system for assisting motorcyclists to safely ride road bends

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## Abstract

**Introduction** Road bends of extra-urban and rural roads are known to be particularly relevant for motorcycle riding safety. For this reason a Curve Warning system has been developed for assisting the motorcyclists to safely approach bends and curves.

**System Description** The system is organized in three layers: the first is the scenario detection that uses on-board sensors and digital maps to feed the second layer, which is the risk assessment layer. This second layer combines road geometry, motorcycle dynamics, and rider style in a holistic approach for computing a safe reference maneuver and for detecting potential dangers in the curve negotiation. The safe reference maneuver is continuously recalculated to follow the evolving scenario according to a receding horizon approach. In case of potential danger, the third layer warns the rider by a proper Human Machine Interface, leaving to the rider the vehicle control.

**Paper contents** This paper explains the Curve Warning concept and illustrates its implementation, development, and tuning on a motorcycle prototype. The latter has been used for a pilot campaign of road tests, which demonstrated that

the system is capable of early detection of potential danger situations, and that riders have a positive attitude towards the Curve Warning system itself.

**Keywords** Motorcycle · Curve · Curve warning · Advanced rider assistance systems · Receding horizon control

## 1 Introduction

Motorcycle riding has grown in popularity in the European Union with up to 24 millions circulating vehicles in 2010 [1]. Motivational studies [2, 3] show that motorcyclists are a heterogeneous group of users that use this mode of transport more for the riding experience itself than as a way of satisfying mobility needs. In fact, motorcycles are highly maneuverable vehicles that provide riders with a sense of freedom and intense experience, especially perceived during cornering and accelerations [4, 5]. As motorcyclists get more experienced and improve their riding skills, though, they may become more self-confident and usually tend to push their limits seeking fun and excitement [5, 6]. This self-confidence on their riding technique and ability to control their motorcycle encourage most riders to underrate the risks when riding at very high speeds (e.g. more than double the speed limit) [5]. Being in this state of enthusiastic riding style may cause some riders to become overconfident in their abilities, resulting in a discrepancy between their perceived and actual limits. Therefore, in many cases motorcyclists downplay the potential of injury and death in favor of their own practical experience [7]. Additionally, the proneness to engage in sensation seeking and aggressive riding appears to increase the likelihood of committing awareness and concentration related errors.

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The analysis of accidents statistics give evidence of the correlation between recreational motorcycling outside urban areas and single accident crashes [8]. In fact, it is in non-built-up major roads where 35.9 % of all motorcycle crashes occur [9], the most prominent crash scenario [9–11] being the motorcycle going out of a curve at a relatively high speed, an event that is often associated with limited visibility (in 40 % of relevant accidents according to [12]). The run off the road is primarily caused by rider's errors, such as slide-out and fall due to over-braking, running wide of a curve due to excess or inappropriate speed, or under-cornering [11]. Although inappropriate speed for the bend is the major cause in a large proportion of cases, there is also a significant fraction where the lack of experience is the main cause of accidents on bends. The lack of experience applies to young riders, to older bikers that come back to use a motorcycle after a break period, and to bikers that have to adapt themselves to the performance of new motorcycles with respect to that previously owned.

The above considerations remark the need for improving rider's insight into risk and self-limitations, which can be achieved both with training and thanks to on-board devices [5, 11]. Rider training should focus on improving cornering techniques and on developing raider's ability to plan ahead according to individual capacities [11], but must also be accompanied by personal education to provide self-monitoring attitude [5]. On the other hand, on-board active systems, such as ABS and Traction Control, proved to be effective in reducing accident figures by supporting the rider during braking and deceleration [13]. However, available commercial systems still need to be improved. A relevant role could be potentially played by on-board intelligent warning systems [14], which may act in advance as virtual tutors that know the rider's handling skills and the upcoming road changes, and on this basis they can detect when he/she is pushing to the limits, downplaying hazards, or simply mistaking the curve negotiation.

From this perspective, an intelligent preventive system may help motorcyclists to focus on the road scenario, keep high attention, extend rider's visibility horizon, and in general to better evaluate the risk they are taking, in accordance with their riding skills, vehicle dynamic capabilities, and environmental/traffic conditions. However, design of preventive systems must also take into consideration the emotional aspect, or the (limited) eagerness that motorcycle riders have for adopting such systems, given that motorcyclists ride for reasons other than just mere transportation. In this context, SAFERIDER EU Project [15] has developed and tested—among others—a Curve Warning (CW) function to support motorcycle riders in detection of incorrect, insufficient, or missing actions in extra-urban curve scenarios, and for suggesting them appropriate corrective actions.

The general principles and conceptual architecture of the CW application has been presented in [16] and was first implemented on a motorcycle riding simulator, used for system tuning as well as for selecting Human Machine Interface (HMI) elements and devices according to subjective evaluation from a panel of simulator riders. In particular, two warning concepts were compared from the point-of-view of HMI effectiveness: a force feedback throttle and a haptic glove. The effects of the two driver feedback devices were evaluated both in terms of the simulated riding performance, and the subjective assessment by the riders [17]. Objective results showed that both versions provoke an earlier and stronger adaptation of the motorcycle dynamics to the curve than when the riders were not using the warning system. However, the simulator environment may provide quite different rider's responses contrasted with real life use of the system.

For this reason, the present work describes the CW concept and system implementation on a real motorcycle prototype used for road tests. This paper reports the experimental evaluation of the Curve Warning function performed by naturalistic riding in a predefined track of about 8 km on a public road open to traffic. Moreover, technical limitations of the proposed implementation enforced by the test setup (mainly due to sensors noise), and different grade of riders' satisfaction are discussed in comparison to simulator environment.

To the authors knowledge, the CW function hereafter proposed is the only working example reported in the scientific literature applied to motorcycles. The only exception is represented by the Japan Advanced Safety Vehicle (ASV) initiative, which is developing of a similar application but at the present day no public information is available yet [14].

## 2 The Curve Warning concept

From the literature on motorcycle accidents and riders' motivations above summarized, it emerges that motorcyclists are more prone to commit riding errors on rural and extra-urban roads when driving on bends with curvature radius less than 90 m [12]—especially when they are pushing to their limits for seeking fun.

By definition, an intelligent CW function has to be able to recognize riders' mistakes in advance before negotiating a curve, and then suggest the appropriate countermeasure in a proactive way. However, at the same time it has to know the rider's capability and limitations avoiding unnecessary interferences with his/her enjoyment of riding.

Therefore, CW systems based on the pure calculation of safe speed on curve (as for example [18]) are not adequate: the system also has to know the safe maneuver for negotiating the curve ahead, starting from what the rider is

doing now, which implies to take into account driver's skills and limitations and vehicle dynamics, in addition to road geometry and characteristics.

Therefore, a precondition is the ability to generate (or predict) *reference maneuvers*, which are simulated riding plans satisfying the same rules and limitations that human beings follow when they ride safely. Having such characteristics, a reference maneuver can then be used as a gold standard to be compared with the real rider behavior, thus permitting the identification of a risk condition whenever the real maneuver deviates from the gold standard safe riding.

The proposed CW function makes use of a reference maneuver that is calculated at a given time  $t_k$  by solving an optimization problem. Such a problem is formulated for calculating the optimal maneuver that moves from the current estimated state to the target safe state ahead, according to human-like criteria and limitations. In order to comply with road geometry changes and uncertainties, a re-planning strategy is adopted.

The following subsections briefly summarize the mathematical formulation of the optimization problem, how it can be numerically solved, and the strategy to generate the warning by comparing the computed reference maneuver with the current state.

## 2.1 Formulation of the safe optimal maneuver

The optimized planning problem above detailed corresponds to the formulation of a non-linear Receding Horizon Control (RHC) over a planning horizon of length  $L$  as schematized in Fig. 1.

The RHC formulation for calculating the curve reference maneuver is formulated in curvilinear abscissa  $\zeta \in [0, L]$ , measured along the road middle line, and takes the following form:

$$\begin{aligned} \min_{\mathbf{u}_k(\zeta)} \quad & \Phi(\mathbf{x}_k(L)) \\ & + \int_0^L J_1(\mathbf{u}_k(\zeta)) + J_2(\mathbf{x}_k(\zeta)) + J_3(\mathbf{x}_k(\zeta)) d\zeta \end{aligned} \quad (1)$$

subject to:

$$\mathbf{F}(\dot{\mathbf{x}}_k(\zeta), \mathbf{x}_k(\zeta), \mathbf{u}_k(\zeta)) = 0, \quad (2a)$$

$$\mathbf{C}(\mathbf{x}_k(\zeta), \mathbf{u}_k(\zeta)) \leq 0, \quad (2b)$$

$$\mathbf{B}(\mathbf{x}_k(L), \mathbf{u}_k(L)) = 0, \quad (2c)$$

$$\mathbf{x}_k(0) = \hat{\mathbf{x}}_k(t_k), \quad (2d)$$

where  $\mathbf{x}_k(\zeta)$  is the  $k$ -th safe optimal maneuver over the horizon  $L$ ,  $\mathbf{u}_k(\zeta)$  is the associated vector of control inputs that generate the maneuver itself, and the term  $\Phi(\mathbf{x}_k(L))$  is the

*terminal cost function* that will be defined shortly ahead (see Eq. 4).

The target function in Eq. 1 implements the three primary goals defined by the forthcoming Eqs. 3a–3c:

- *smoothness*, which is related to riding comfort (Eq. 3a)
- *limitation of vehicle accelerations*, which is related to both safety and riding styles (Eq. 3b)
- *riding aggressiveness* which is related to the motivation to reduce the travel time or seeking fun (Eq. 3c).

$$J_1(\mathbf{u}_k(\zeta)) = \left( \frac{j_x(\zeta)}{j_{x0}} \right)^2 + \left( \frac{j_y(\zeta)}{j_{y0}} \right)^2, \quad (3a)$$

$$J_2(\mathbf{x}_k(\zeta)) = \max \left( \left| \frac{a_x(\zeta)}{a_{x0}} \right|^n + \left| \frac{a_y(\zeta)}{a_{y0}} \right|^n - 1, 0 \right), \quad (3b)$$

$$J_3(\mathbf{x}_k(\zeta)) = w_T \frac{1}{u(\zeta)} \quad (3c)$$

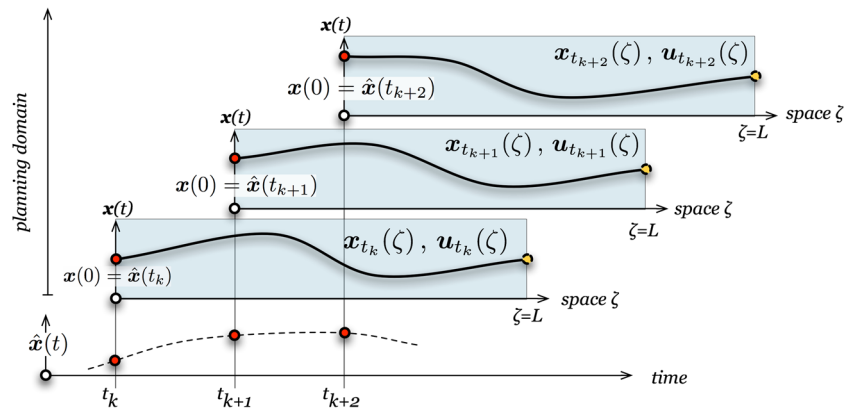
Maneuver smoothness comes from the experimental evidence that human beings operate according to optimized criteria, minimizing jerk [19, 20]. This corresponds to the quadratic term in Eq. 3a, where jerk components are normalized with their longitudinal and lateral limits  $j_{x0}$  and  $j_{y0}$ , respectively.

The limitation on accelerations is also based on the evidence that riders use a limited amount of acceleration, known as *willingness envelope* [21, 22]. The extension of the willingness envelope varies from person to person and also depends on the psychological state (e.g. pushing to the limits relying on ones' riding skills). The term  $J_2$  of Eq. 3b represents a family of willingness envelopes that can be customized by properly changing the exponent  $n$  and the longitudinal and lateral acceleration limits  $a_{x0}$  and  $a_{y0}$ , respectively.

The last term  $J_3$  in Eq. 3c is a minimum time term multiplied by a scaling factor  $w_T$ . By changing the scaling factor  $w_T \in [0, 1]$  it is possible to produce faster maneuvers by relying on larger longitudinal and/or lateral accelerations and jerks. Modification of parameter  $w_T$  lets one model a full set of riding behaviors, ranging from maximum smoothness and comfort ( $w_T = 0$ ) to more aggressive motorcycling ( $w_T = 1$ ) that require more rider's activity on commands. It is worth noting, though, that even with the most aggressive setting  $w_T = 1$ , the basic conditions of safe riding are ensured by acceleration limits (3b) and by the trajectory constraints discussed in the followings.

Regarding to Eqs. 2a–2c, the first equation represents the vehicle dynamics model. Human riders predict the effects of commands they give to the vehicle thanks to a *mental model* of the vehicle itself. This mental model reflects the rider's knowledge about the vehicle dynamic behavior, and its complexity depends on the rider's experience and skills.

**Fig. 1** Receding Horizon Control scheme. Time domain vs. planning domain (defined in space). Sequence of three subsequent optimal plans over horizon  $L$  and starting from estimated state  $\hat{x}$  at time instants  $t_k$ ,  $t_{k+1}$  and  $t_{k+2}$



So Eq. 2a is a formal representation analogous to the human mental model, ensuring that the calculated reference maneuver is realistic and feasible within—or even better than—the rider’s knowledge of vehicle dynamics.

Although the riding task is quite complex, in first approximation longitudinal and lateral vehicle dynamics may be considered uncoupled. In other words, the rider controls the longitudinal dynamics using throttle and brakes, whose most relevant output is the vehicle speed. The lateral dynamics is controlled via the handlebar (and secondarily by torso movements): in this case the most relevant output is the vehicle heading. Based on these considerations, the simplest model that captures the essential, first-order motorcycle dynamics is that of a rigid body controlled in terms of speed and yaw rate, and free to roll, as shown in Fig. 2 on the left, and described in detail in [16]. In particular, if one imagines this model as a rolling wheel of proper size and inertia, the proposed basic model includes gyroscopic effects and tire shape features. According to these assumptions, the model is described by 8 state variables:  $\mathbf{x} = \{s_n, \alpha, \phi, u, \omega_\phi, \omega_\psi, a_x, a_\psi\}$  (as defined in Fig. 2),

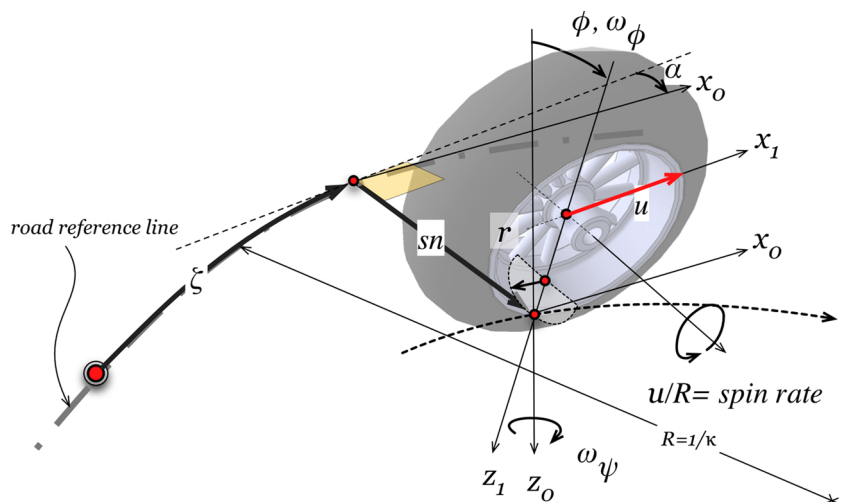
plus the two controls  $\mathbf{u} = \{j_x, j_\psi\}$ , which represent the derivative of longitudinal acceleration and the derivative of yaw acceleration, respectively.

Safety objectives are mainly specified by the constraint inequalities in Eq. 2b, and by the desired final state. The latter is obtained as part of the solution satisfying the terminal constraints in Eq. 2c, which strictly impose the values for a subset of the model states (see Table 1), and by the quadratic term  $\Phi(\mathbf{x}_k(L))$  of the objective function in Eq. 1, which loosely imposes some desired conditions on final state. Equation 1 can be expressed as:

$$\Phi(\mathbf{x}_k(L)) = \left( \frac{a_y(L) - a_{yf}}{\Delta a_y} \right)^2 + \left( \frac{\alpha(L)}{\Delta \alpha} \right)^2 \quad (4)$$

Specifically, Eq. 4 requires the motorcycle to be aligned with the road direction within an angular scaling factor  $\Delta \alpha$ , and the lateral acceleration  $a_y(L)$  to be within target acceleration  $|a_{yf}|$ , assuming  $\Delta a_y$  as a scaling factor. In turn, the target acceleration  $a_{yf}$ , whose modulus must be less than the willingness envelope  $a_{y0}$ , depends on the road curvature at the end of the planning horizon  $L$  and on

**Fig. 2** The rolling wheel model (from [16]). Curvilinear coordinates  $\zeta$ ,  $s_n$ , and  $\alpha$  describe the vehicle position with respect to the road middle line



the lateral position  $s_n(L)$ . Therefore, for circular road segments, the resulting motion is a stationary cornering state within the comfort limits, if possible, and with optimal values for longitudinal velocity, roll angle and yaw rate. It is worth noting that the use of loose final conditions helps in the assessment of uncertainties on parameters and simplifies the model formulation, reducing the computation time.

Finally, equality constraints set in Eq. 2d represent the feedback of the system state  $\hat{\mathbf{x}}_k(t_k)$ . In other words, the estimation of the vehicle state at time  $t_k$  ensures that the safe maneuver is calculated starting from what the rider is actually doing.

## 2.2 Realtime numerical solution

The optimization problem of Eq. 1 is fully non-linear and its real-time solution is a quite challenging task. Hence, a special indirect method for its solution has been adopted and implemented, as detailed in [23]. In short, the costly inequality constraints are replaced by penalty functions, whereas equality constraints are treated by means of Lagrange multipliers. The Pontryagin Principle is used to symbolically derive the equations of optimality, as well as their jacobians. The resulting two-boundary value problem is discretized with a finite difference scheme yielding a large nonlinear system of equations. By means of automatic code generation the nonlinear system is converted into efficient C++ code and solved with a dedicated numerical solution algorithm that exploits the special band structure of the associated matrix. On a 1.4GHz pc104+ with Intel Atom processor—which is the on-board PC used on the demonstrator, as it will be explained in the followings—the time needed to compute the solution is about 5–10 % of the simulated time (1 s), leading to a solution every 50–100 ms in the CW application.

**Table 1** Initial and terminal conditions implemented in the CW application

State variable <sup>a</sup>		Boundary conditions <sup>b</sup>	
Symbol	Description	$\zeta = 0$	$\zeta = L$
$s_n$	Lateral position	$s_n(0) = \hat{s}_n(t_k)$	$s_n(L) = 0$
$\alpha$	Relative yaw angle	$\alpha(0) = \hat{\alpha}(t_k)$	FREE
$\phi$	Roll angle	$\phi(0) = \hat{\phi}(t_k)$	FREE
$u$	Forward speed	$u(0) = \hat{u}(t_k)$	FREE
$\omega_\phi$	Roll rate	$\omega_\phi(0) = \hat{\omega}_\phi(t_k)$	$\omega_\phi(L) = 0$
$\omega_\psi$	Yaw rate	$\omega_\psi(0) = \hat{\omega}_\psi(t_k)$	FREE
$a_x$	Longitudinal acceleration	$a_x(0) = \hat{a}_x(t_k)$	$a_x(L) = 0$
$a_\psi$	Yaw acceleration	$a_\psi(0) = \hat{a}_\psi(t_k)$	$a_\psi(L) = 0$

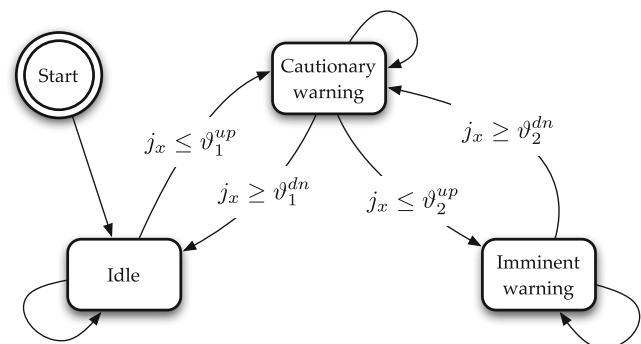
## 2.3 Threat assessment based on Receding Horizon approach

At any given time  $t_k$ , the solution of the optimal control problem of Eq. 1 consists on the predicted optimal trajectory plus the corresponding control history  $\mathbf{u}_k(\zeta)$  that moves the motorcycle from the current estimated state to a safer one. The first part of this maneuver, and in particular the initial optimal input  $\mathbf{u}_k(0)$ , quantifies the action that the rider needs to feed-forward to correct the actual maneuver and to drive the motorcycle towards the reference one.

In other words,  $\mathbf{u}_k(0)$  is a measure of the rider's error in terms of the correction required to adapt the longitudinal acceleration. When the corrective action is close to zero (or even positive) the rider is controlling the motorcycle in a way close to the ideal maneuver (or even more conservatively), and the motorcycle future evolution will surely meet the specified safety criterion.

On the contrary, whenever one of the components of the control input  $\mathbf{u}_k(0)$  is negative, it means that the actual vehicle state is not compatible with the road geometry ahead and with rider's limitations, hence the driver shall correct the maneuver. The larger the mismatch, the greater is the urgency for a correction. In particular, the initial value of longitudinal jerk  $j_x(0)$  (which is negative when in risk) is used as a criterion to suggest a deceleration in case of potential danger, whereas the steer control is left to the rider's responsibility only, being more critical for motorcycle stability [24, 25].

The logic to generate the warning was implemented as a simple Finite State Machine (FSM) with three states as shown in Fig. 3. The *idle* state corresponds to the safe riding condition. The *cautionary warning* state engages when the motorcyclist is riding close to his/her limits. The *imminent warning* state evidences a riding conditions overcoming personal limits and thus potentially close to tyre adherence limits or other physical limits.



**Fig. 3** Finite State Machine that generates the warning level based on the longitudinal jerk  $j_x$ . Note that thresholds are negative values



The transitions between each couple of states is governed by two different thresholds:  $\vartheta_i^{up}$  to switch up to the upper  $i$ -th state, and  $\vartheta_i^{dn}$  to switch back to the lower state. According to the above considerations, these thresholds are negative values, and threshold  $\vartheta_i^{up}$  must be obviously less than  $\vartheta_i^{dn}$  to avoid the warning jumping back and forth between two states. The four thresholds have been tuned according to the subjective risk evaluation of expert riders in dedicated tests sessions held before the pilot tests. Further developments of the system could consider customizable jerk thresholds according to different rider skills.

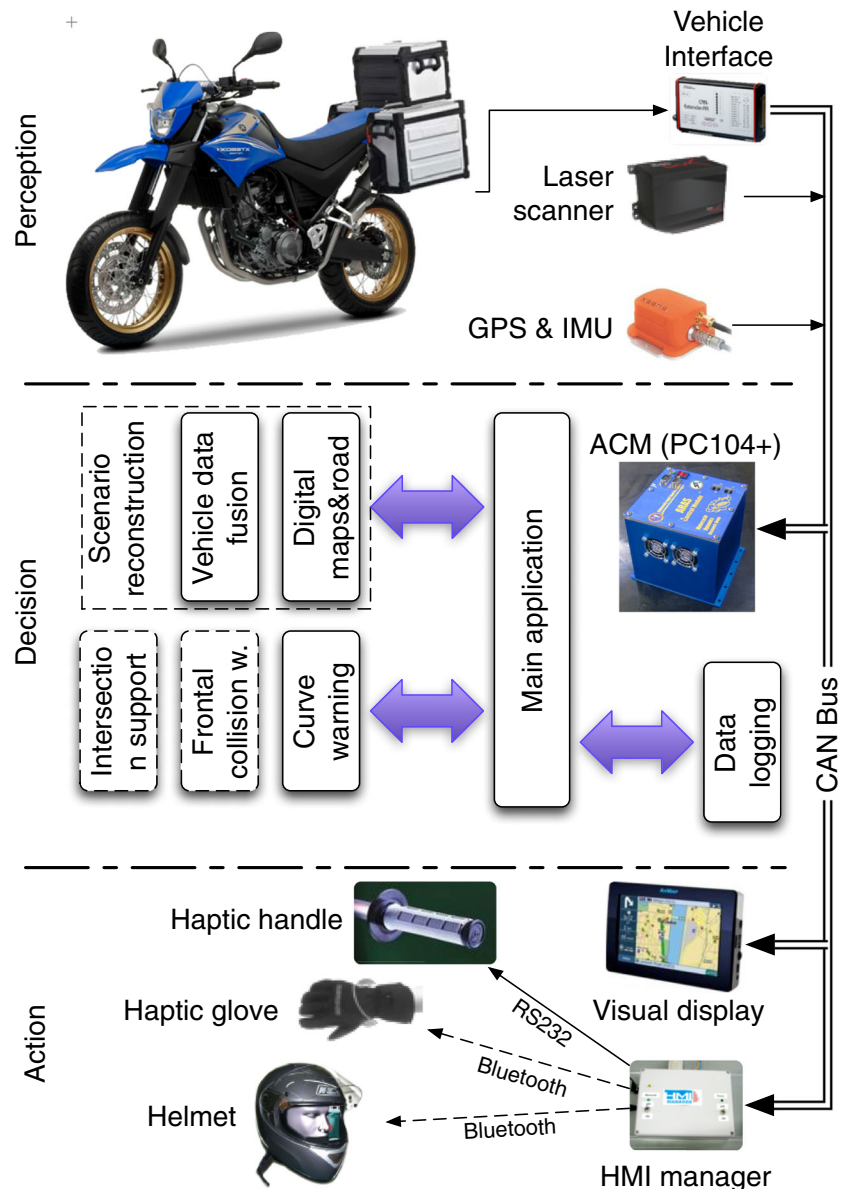
Finally, it is important to remark that, being a preemptive warning method, the suggested correction of the longitudinal acceleration is asked *before* the curve entrance. Therefore, the rider has sufficient time to decelerate *before* the

motorcycle is engaged with (possibly high) roll angles, with positive effects on vehicle stability and maneuver safety.

### 3 Implementation

The CW is based on the ARAS (Advanced Rider Assistance Systems) architecture developed within the SAFERIDER Project, which implements the *perception-decision-action* paradigm on a dedicated CAN network, as shown in Fig. 4. The *perception* layer encompasses the sensors that are used to measure the vehicle state, such as the GPS device, the Inertial Measurement Unit (IMU), plus some vehicle-embedded sensors like the speedometer and the brake pressure transducer. All sensors are connected to the

**Fig. 4** Curve Warning system architecture and its implementation on the riding simulator



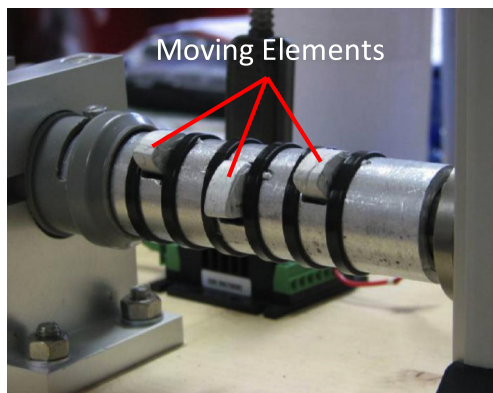
SAFERIDER CAN network by means of a dedicated interface, which does not interfere with the internal vehicle architecture.

The *perception layer* feeds the ARAS Control Module (ACM), which represents the *decision layer* and is hosted on a PC/104+ with a 1.4 GHz CPU running realtime Linux OS.

Finally, the *action layer* includes the HMI manager and the HMI elements: the navigator display for visual cues, the smart helmet for acoustic cues, the haptic throttle and handle, and the vibrating glove [26] for haptic cues. In particular, the haptic handle, which actually resembles a normal left handle, is a mechanical device which provide a tactile feedback to the rider's hand by changing the handle shape with moving inner parts (see Fig. 5). The effect felt by the rider is a pulsating pressure on the palm of his/her hand. The haptic throttle is a force-feedback system that may artificially increase the reaction torque (i.e. the stiffness) of the throttle handle that forces the rider to increase its torque on the handle to keep the same position. The resulting effect is a “strongly suggested” deceleration.

The haptic glove is a special motorcycle glove equipped with motorized eccentric rotors that produces vibrations, a Bluetooth module to communicate, and a lithium battery. The glove can provide feedback by pulsed vibrations on four different points of user's wrist, possibly tuned in terms of frequency and magnitude. The smart helmet has a Bluetooth audio system for acoustic warning and two motorized eccentric rotors, inside both cheek pads, which may produce vibrations as well. The visual display consists of a  $180 \times 120$  mm touch-screen that is integrated into the motorcycle dashboard, used for conveying visual cues in form of blinking icons. The touch-screen visual interface was designed according to the guidelines described in the public technical report [27].

Depending on the risk assessment provided by the ACM, the HMI manager activates the relevant HMI elements,



**Fig. 5** Haptic handle mechanisms, after removing the outer rubber shell (after [26])

which are connected either through a RS-232 interface or via Bluetooth wireless connection.

The intelligent CW function is implemented within the ARAS Control Module (ACM), which in turn encompasses several sub-modules implementing more specific tasks. In particular, the module called Main Application (MA) is the program in charge of the higher level operations that coordinates and synchronizes the communication between lower-level submodules. In short, the main loop starts with a message published by the Navigation System (NS), which informs the ARAS module about the selected route the rider will ride on, and triggers the system forthcoming actions. The CAN-bus line is populated with data messages published by the perception layer sensors, which are received and stored by the CAN Manager module and passed to the Scenario Reconstruction module, which is responsible for the data fusion, i.e. the computation of data coming from heterogeneous sensors to produce a consistent estimation of the vehicle state of motion and of its position with respect to the road (also exploiting a digital road model provided by the Digital Road database). The reconstructed scenario is passed by the MA to the CW module. According to the CW output, the MA sends the possible warning message through the CAN bus. Finally, the data logging module allows the MA to keep trace of the data exchanged between modules and the state of execution of the whole program, allowing post-process analysis of the entire system behavior. All the modules run asynchronously and all data are time-stamped.

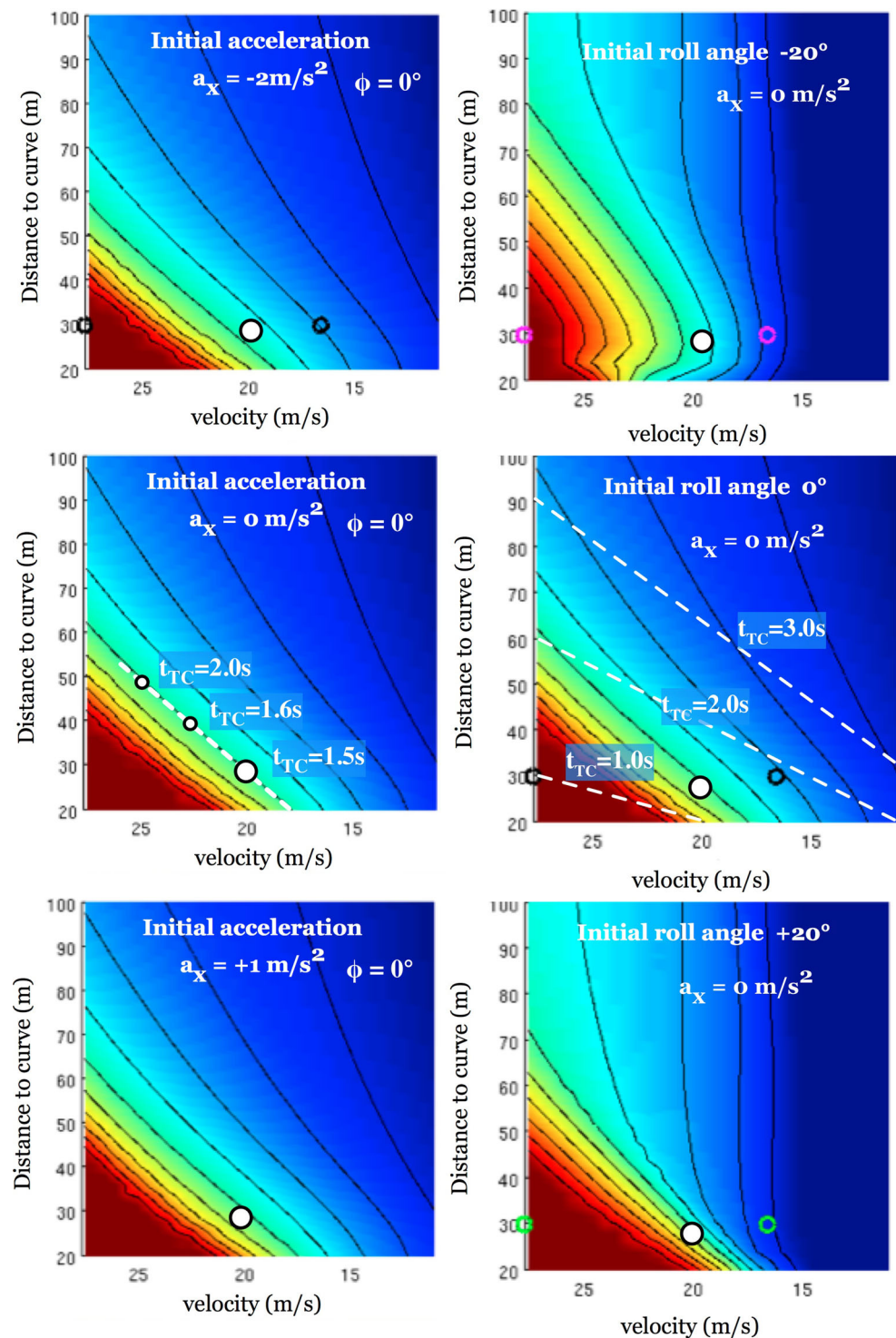
The HMI elements are particularly relevant since they are the only part of the system that interact with the rider. As above mentioned, within the SAFERIDER Project several HMI concepts have been previously tested on a motorcycle simulator [26, 28, 29]. An experimental campaign with experienced riders [17] allowed to tune FSM thresholds as well as to setup the HMI interfaces. In particular, the haptic throttle has not been added to the real demonstrator, since it was perceived as less effective by simulator test riders, which judged the haptic glove as more effective in conveying warnings.

It is worth pointing out that such architecture and HMI elements are shared with additional ARAS functions such as the Frontal Collision Warning [30] and the Intersection Support [31], whose description is out of the scope of this paper.

#### 4 System tuning

The riding simulator tests were first used to define the thresholds of the Finite State Machine. A parametric analysis of the main system parameters (mainly initial states and road curvature) was carried out to understand how those parameters influence the warning generation. Figure 6

**Fig. 6** Longitudinal jerk as function of forward speed and distance to a 90° curve with curvature radius  $R = 50\text{ m}$ . Red color is associated to negative jerks  $j_x$  and blue color zero or positive jerk values. White dash lines on central plot on left column corresponds to constant  $t_{TC}$  lines



shows an example of the CW function response (i.e. initial jerk value  $j_x$ ) for different values of forward speed and distance when approaching to a 90° right curve with curvature radius  $R = 50\text{ m}$ . Each contour plot shows the isolines of  $j_x$  with different initial longitudinal accelerations (three plots on top row, nominal case in the centre) and initial roll angles (three plots on first column). From the point of view

of the warning generation, the selection of the first threshold  $\vartheta_1^{up}$  would mean to select a specific isoline (for example the dashed white line in Fig. 6), which separates the set of states (i.e. distance to curve and speed) that do not generate warning from the set of states that do generate the warning.

The contour line can also be expressed as warning time to curve ( $t_{TC}$ ), which is the time that the motorcycle needs



**Table 2** HMI setups for CW function tested on demonstrator

Type	Type of warning	
of feedback	Cautionary	Imminent
Tactile 1	Vibrating glove low intensity	Vibrating glove high intensity
Tactile 2	Vibrating helmet low intensity	Vibrating helmet high intensity
Visual	Constant orange icon	Blinking red icon

for covering the distance to the curve start from the position when the warning is first raised. As one may see, for the selected contour line of Fig. 6 the parameter  $t_{TC}$  goes from 1.5 s for low velocities and short distances, and increases up to 2 s for larger velocities and distances. This means that, for a given threshold, the faster is the motorcycle the earlier the warning is generated, allowing more time for the rider to react.

Finally, the charts also show that the initial longitudinal acceleration and roll angle change the shape of the contour lines, and therefore the time  $t_{TC}$ . For example, positive longitudinal accelerations shift the isolines to the right, which

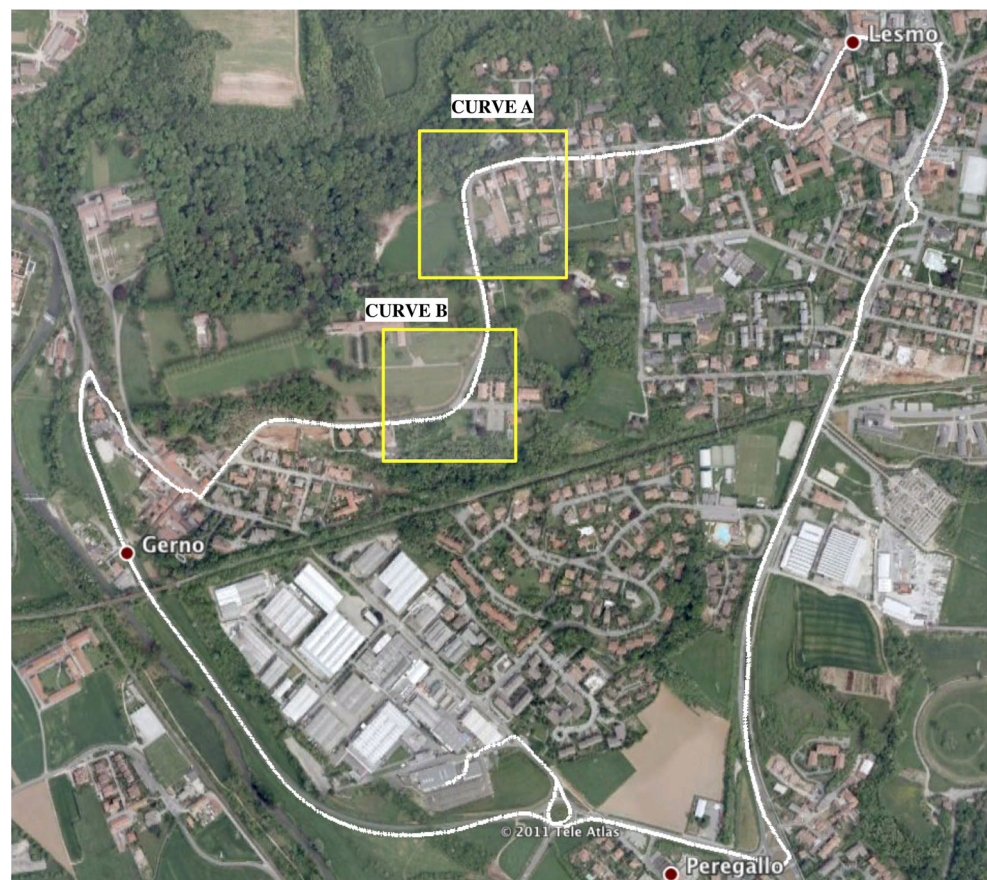
means that for the same threshold  $\vartheta_1^{up}$  the warning is generated for lower speed and larger distance to the curve start. Therefore, the effect of initial states on the warning generation has to be considered when, for technical reasons, some state of the motorcycle (e.g. lateral position) cannot be estimated.

Based on the above considerations and accordingly to the expert riders' opinion, a threshold of  $\vartheta_1^{up} = -0.1 \text{ m/s}^3$  has been chosen for the cautionary warning, and a threshold of  $\vartheta_2^{up} = -0.5 \text{ m/s}^3$  for imminent warning.

## 5 Road tests: results and discussion

The demonstrator motorcycle described in the previous sections was tested on road with HMI functions set up according to Table 2 by ten different riders, the same that were previously employed for testing the simulator. Each component of the test team had a long riding experience and an average of 10,000 km riding per year. There were two experimental conditions: one ride without ARAS (Baseline), one ride with the CW active (Setup 1). At the end of each ride the riders' were asked to fill a questionnaires for the subjective assessment and the evaluation of the experienced system and to go through an interview.

**Fig. 7** Road test track and GPS data (white line). Curve A and B are marked with boxes



The riders drove on the same test track: a urban and rural road including curves and bends chosen to be relevant for the testing of CW function. Figure 7 reports a map of the test track, which is about 8 km long, with a sample of GPS track data for rider #2. The same Figure also highlights the curves A and B, which will be referenced in the following being the ones with the higher number of CW function interventions.

By closely looking at the GPS track (see for example the forthcoming Figs. 9 and 10), it can be easily observed that the raw GPS data provide a scattered path, which sometimes appears to lay out of the road lane as reported on the map. Therefore an extended Kalman filter was developed to localize the motorcycle on the road lane at least in the longitudinal position (i.e. curvilinear abscissa). The filter fuses the information of several sensors such as a GPS, an Inertial Measurement Unit, an odometer and an high precision road map database. A detailed description of the filter is out of the scope of this work, but a possible implementation is described in [32].

The lateral position and orientation of the motorcycle with respect to the road middle line could not be estimated with sufficient accuracy with the available sensors. Therefore, for the sake of solving the optimal maneuver computation, the motorcycle was assumed to be located on the middle of the lane and parallel to the lane direction. This choice obviously affected the warning generation and, in particular, the time-to-curve from warning onset, as predicted by the parametric analysis described in Section 4.

The comfort lateral acceleration value  $a_{y0}$  used in Eq. 3b for the road test was set to  $3.5 \text{ m/s}^2$ , which corresponds approximately to a stationary roll angle of  $20^\circ$ . This choice is related to liability considerations, being the test performed on a road opened to public traffic.

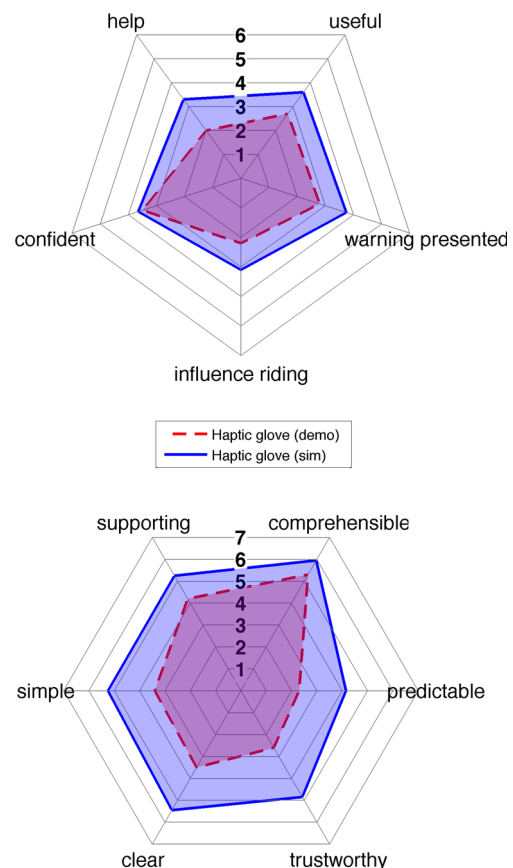
A general observation concerning ergonomic attributes is related to the vibration level of the haptic glove and of the helmet, which should be decreased because it was perceived as too invasive. Nevertheless the vibration modality through the haptic glove and helmet was one of the most appreciated features of the system since it is perceivable also with high noise level of the motorcycle. On the contrary, the acoustic warning was generally judged distracting if not annoying. Concerning the visual display a specific evaluation is reported in [33]. Anyway, in the few comments that appear in the interviews, the warning icons were judged as difficult to see or useless.

When compared to the results obtained from the same set of test drivers on the simulator, the subjective evaluation of the CW function revealed that the system appreciation—both in terms of overall and ergonomic assessment—was statistically lower for the demonstrator motorcycle than for the simulator. Such a comparison is summarized in

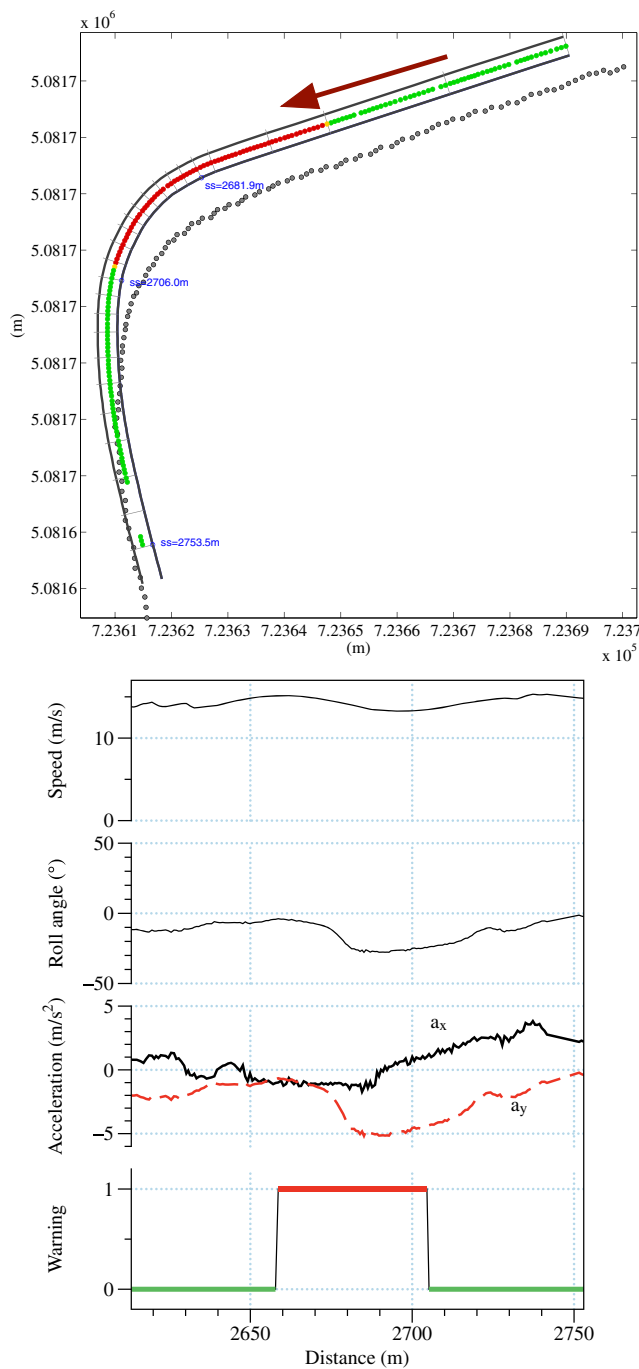
Fig. 8, and suggests that the selection and tuning of HMI feedback to the rider is more challenging when performed for real road conditions than for the motorcycle simulator.

In terms of warning effectiveness, despite the fact that from the interviews it emerged that the system is potentially useful and comprehensible (as shown in Fig. 8), the majority of riders complained for the warning being raised too late. Figure 9 shows an example of the CW function response when the rider #10 negotiated the curve A (similar results are available for other testers). The rider entered in the curve with a relatively low constant speed, which was enough to perform the curve with a lateral acceleration over the  $3 \text{ m/s}^2$  due to the small curvature radius (50 m). The warning was set on about 30 m before the curve, which is 2 s before the curve start when riding at a speed of 15 m/s.

However, in some cases the warning was raised by the CW function too late. For example, the analysis of the following curve B for the same rider #10 shows that the warning is actually issued less than 1 s before the curve, as illustrated in Fig. 10.

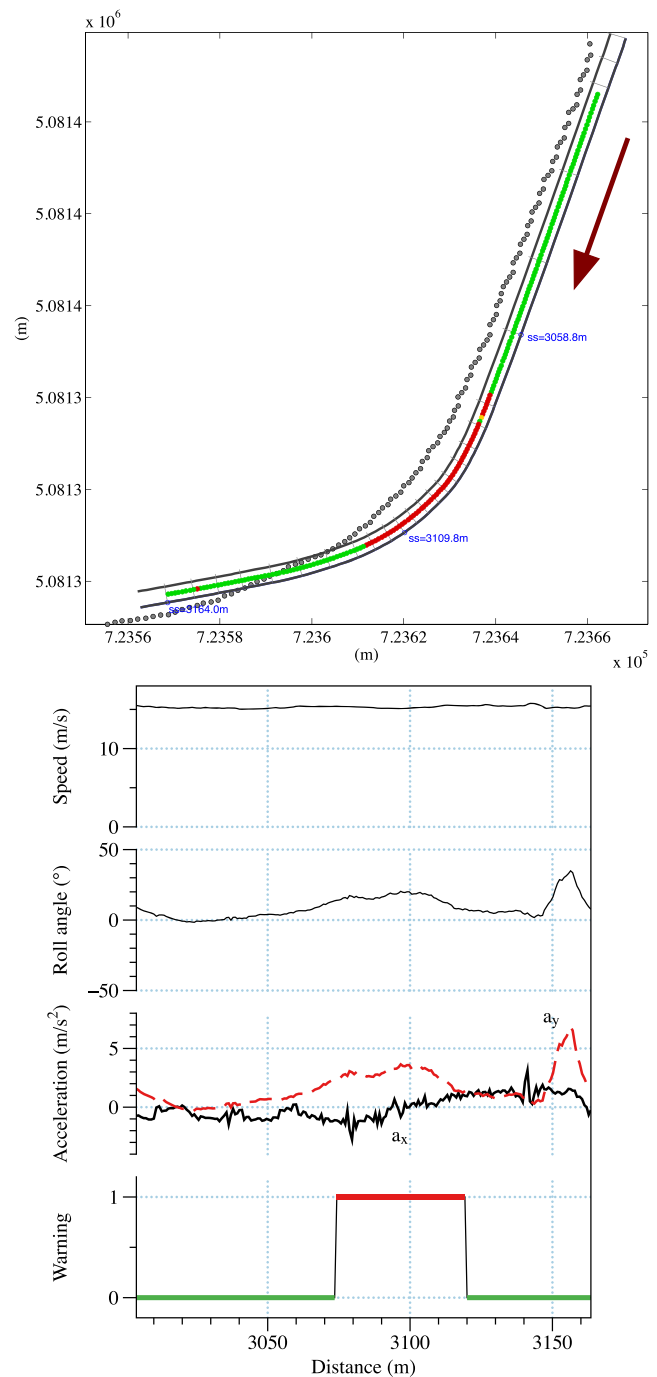


**Fig. 8** Comparison of haptic glove HMI between simulator and demonstrator: subjective evaluation. Overall effectiveness evaluation of CW function (*top*). Ergonomic evaluation of CW function (*bottom*)



**Fig. 9** Experimental data for rider #10 in curve A. *On the top chart:* reconstructed trajectory colored with warning activation (red = warning set on) and raw GPS data. *On the bottom chart:* estimated vehicle states variables as a function of curvilinear abscissa: forward speed, roll angle, accelerations, and warning activation

By investigating the data logs related to the road segments with delayed warnings, it can be observed that these events usually happen due to excess noise affecting the raw measurements within the perception layer. In fact, the level of vibrations on the demonstrator motorcycle was relatively



**Fig. 10** Experimental data for rider #10 in curve B. *On the top chart:* reconstructed trajectory colored with warning activation (red = warning set on) and raw GPS data. *On the bottom chart:* estimated vehicle states variables as a function of curvilinear abscissa: forward speed, roll angle, accelerations, and warning activation

high and a strong filtering was thus necessarily applied on signals. Moreover, as above observed, due to lack of sufficient accuracy when estimating the motorcycle position with respect to the lane center, the optimal maneuver problem was always solved assuming a mid lane position.



This has a direct effect on the estimation of longitudinal and lateral accelerations, which in turn affects the system performance.

Further investigations are thus necessary to make the system more robust and to study the possibility of using enhanced data fusion algorithms in combination with more suitable sensors. Accelerometers and sensors mounted on the demonstrator, in fact, were devices designed and typically used in automotive applications, where the typical noise level is significantly reduced. In this regards, it is also worth noting that data fusion algorithms have been widely studied for cars but less is known for motorcycles since state-of-the-art applications in this field are limited to motorcycle racing and therefore not publicly disclosed. Nevertheless, the fact that the system can provide reliable and timely warnings when the scenario reconstruction layer is able to provide good quality information is a proof of the high potential of the proposed solution for the development of an intelligent curve-assistance system for real usage on motorcycles.

## 6 Conclusions

This work described the SAFERIDER Curve Warning function, which was designed to assist motorcycle riders when they negotiate curves of extra-urban and rural roads. The CW function uses a reference maneuver as a gold standard to assess the rider's behavior. The system was largely appreciated by test riders in term of ergonomics and effectiveness on riding behavior in simulator tests. In the road tests, the appreciation was less pronounced and testers asked for a better function tuning. Objective analysis of experimental data showed that the CW function can provide the rider with correct and effective warnings, although in some cases it tends to raise the warning too late. By investigating these missed warnings, it has been observed that, since the CW function is sensitive to motorcycle estimated state in relation to motorcycle distance to the curve start, an accurate motorcycle state estimation is a key element. Given that the sensors used in the demonstrator vehicle are automotive-class sensors, and the noise level typical of motorcycles is noticeably higher than that for car applications, it has been concluded that more strict technical specifications on the sensors and on the level of accuracy of the scenario reconstruction module are necessary to ensure better system effectiveness and robustness. A second conclusion is that the HMI selection is better evaluated with road tests since the real riding conditions occur in a noisy and less standard environment that cannot be accurately replicated on a motorcycle simulator. As a final remark, the glove and helmet vibration were the most appreciated haptic channels to effectively deliver the warning to the rider.

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