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Sensibilization of a motorcycle simulator to the effects of the roll motion: Modelling and experimental validation

Denny Di Miceli, Mirco Bartolozzi ,
Lorenzo Berzi  and Giovanni Savino

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Abstract

When riding a motorcycle, the applied steering torque and the lateral rider body movement influence its trajectory. Reproducing the effect of body and motorcycle roll on a simulator would improve its realism. However, this goal is still challenging, especially on low-complexity simulators such as the MOVING simulator of the University of Florence. In order to achieve this result, this study defined a control logic to introduce steering effects linked with the mockup passive inclination operated by the rider. The logic computed a roll-related steering input consisting of equivalent steering torque. This contribution was added to that the rider exerted on the handlebar. A validation test with participants revealed improvements over the baseline, roll-insensitive approach, especially in stationary and medium-high speed manoeuvres. Interestingly, the riders unconsciously tended to use larger mockup roll angles as the roll sensitivity increased. The logic was optimised for stationary manoeuvres; however, the subjective feedback provided by the participants indicated a good level of riding realism also during transients. This simple and effective logic opens the way for new methodologies to improve the realism of motorcycle simulators, encouraging their development and use.

Keywords

Motorcycle simulator, motorcycle dynamics, subjective validation, roll effects modelling, body leaning, human-machine interaction

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Introduction

Motorcycle riding simulators allow researchers to conduct tests and experiments without putting participants in bodily harm. Sometimes, it is impossible to make tests in the real world because of the substantial risk for the riders. These tools are particularly suitable to test emergencies and develop new safety devices without risk; the effectiveness of some of these technologies depends on the human-machine interaction, which can be investigated through a riding simulator.

In such applications, a critical aspect is the fidelity level in different riding contexts, that is, how the simulator behaves versus how the user expects it to behave. In addition, the user's feedback must be as similar as possible to the one a real motorcycle would provide.¹ Researchers have attempted to increase the physical fidelity to reach good realism, resulting in complex and expensive simulators.

A prerequisite for good realism is to model the main peculiarities of motorcycle riding. Cossalter² showed that, in most cases, riding through a curve in a specific direction requires that the rider applies a steering torque in the opposite direction; this is known as countersteering. For example, if the rider wants to change direction towards the left (counterclockwise yaw rate), they must first apply a clockwise torque to the handlebar. That makes the steering head turn clockwise, creating a centrifugal force that rolls the motorcycle to the left. Then, the rider reduces the steering torque that, in most cases, remains opposed to the turn direction

Università degli Studi di Firenze, Florence, Tuscany, Italy

Corresponding author:

Mirco Bartolozzi, Università degli Studi di Firenze, Via di Santa Marta 3, 50139, Florence, Tuscany 51010, Italy.

Email: mirco.bartolozzi@libero.it

during the stationary phase. A riding simulator must include this effect, to be realistic.

Another critical aspect concerning motorcycle simulators is the reproduction of the roll angle during cornering. In theory, to simulate a curve, it would be necessary to tilt the simulator in the transient phase to make the rider perceive the lateral acceleration present in that phase. In contrast, in the stationary phase, it would be necessary to relocate the mockup in the nominal position (zero roll) because, during real riding, the resultant centrifugal and weight forces tend to crush the torso against the saddle (ideally, during steady cornering this resultant is directed along the line that joins the centre of gravity of the system motorcycle-rider with the point of contact). In practice, this approach is unusual because the rider does not feel in the curve if the motorcycle is not inclined.³ For these reasons, simulators have the roll degree of freedom but are limited to specific values to prevent the rider's lateral fall. Moreover, actuated roll motion is affected by a lag between the rider steering input and the effective roll angle change. This effect reduces the perceived realism and requires advanced techniques to be mitigated.⁴

Shifting the body weight to one side produces a response by the motorcycle; therefore, almost all motorcycle simulators described in the literature provide roll sensitivity.^{5–15} Cossalter¹⁶ developed an advanced motorcycle simulator equipped with sensors that measure several inputs from the rider, including steering torque, lateral body position and throttle and brake controls. The five-degree-of-freedom mockup has a motion system that can produce a lateral shift, roll, yaw, pitch and active steering feedback. Most motorcycle simulators described in the state of the art provide roll sensitivity through analogous active systems. Despite the high degree of physical agreement, the subjective feedback provided by the riders indicated a noticeable difference between the simulated experience and the actual riding experience.

Because of the complexity of this device, the University of Padova also developed a more straightforward motorcycle simulator: it was based on a simplified version of the mathematical model of the previous simulator; however, the mockup had only the rolling degree of freedom (even the steering assembly is fixed, although the steering input is present and measured through a torque sensor), excited through an actuator.¹⁷ That study showed the importance of the roll effects in motorcycle simulators.

The MOVING research group (MObility and Vehicle INnovation Group) from the University of Florence developed a motorcycle simulator based on ABRAM simulator principles¹ that is budget-friendly and easily reproducible. It is a passive (no actuators) simulator that allows the roll degree of freedom which was included to facilitate counter-steering; however, it has no effect on the simulation.

This study aims to develop and validate a control logic modular to the dynamic model of the MOVING simulator, making it sensible to roll motion.

Other constraints about the control logic for roll are:

- It must work with a passive simulator.
- It must not require complex or expensive alteration of the hardware or software system to preserve the simplicity and cost-effectiveness of the simulator.
- It must be optimised for medium-high speeds because the dynamic model of the simulator is conceived to have good behaviour in this speed range.

The article is organised as follows: after a brief review on the effects of lateral body movement on motorcycle riding, the simulator employed is described in more detail. The proposed control logic for roll input is presented along with the hardware required and the software implementation. Next, the functional test is described, and its results discussed. The following section describes the validation test: the objective and subjective results are presented and analysed. Lastly, the conclusions and potential future work are presented.

State of the art on roll effects

Many studies confirm the importance of roll effects^{18–29} and set constraints on the effect produced by the control logic.

In particular, Weir¹⁸ studied the control procedures of a motorcycle, investigating the relationship between several vehicle states and the main control inputs available to the rider. The analyses suggested that control in terms of the roll was the main objective for the rider. According to Weir's results, this goal is most easily achieved through a steering torque input. Upon further analysis, he concluded that the rider employs steering torque to apply a roll to the motorcycle and upper body tilt to control the motorcycle's direction and lateral position.

Katayama²³ used an inverse pendulum rider model consisting of two masses representing the upper and lower parts of the body. The only degree of freedom of the lower body was the rotation around the vehicle's longitudinal axis at ground level; the lower body also acts as a pivot concerning the rotation of the upper body. The rider's inputs were the steering torque at the handlebars and the torques due to the weight force provided by the two masses of the rider, calculated proportionally to the roll angle and an error intended as the difference between the direction of the motorcycle and the desired one. The study examined the model for a lane change manoeuvre using three control methods. It was shown that:

- The steering torque was the control input with the most considerable influence.

- The lower body had an influence that is 1/12 of the steering torque.
- The upper part of the body had an influence of 1/80 compared to the steering torque.

The researchers concluded that the upper body movement is used mainly for comfort reasons, while the lower body movement complements the steering torque input to control the motorcycle. This study suggests that the control logic for roll must ensure a noticeable but moderate effect in the simulation regarding rider perception and must have the right proportion to the rider's other inputs.

Wilson-Jones²⁶ investigated the rider's actions during curve-entry manoeuvres. He discovered that the rider applied a lean torque on the handlebars in the direction of the desired roll when entering a curve and, simultaneously, applied a steering torque opposite to the direction he wanted to steer (i.e. a counter-steering torque). This study and the one by Weir¹⁹ suggest that the control logic for roll could contribute to steering torque since these rider inputs are intrinsically correlated.

Motorcycle simulator and control logic

MOVING's riding simulator is a passive simulator whose riding position is composed of a Cagiva Mito 125, without the engine and the rear swingarm, mounted on a fixed platform^{4,30} (Figures A4 in Appendix 3).

It implements the counter-steering control input via a passive system³¹: a pair of traction springs are mounted between the front fork and the frame (Figure A2b in Appendix 3). The direction of the virtual motorcycle is controlled by the counter-steering torque applied by the rider, which is measured by a load cell suitably connected to the handlebar (Figure A2a in Appendix 3). The simulator is also equipped with a throttle sensor and pressure sensors on the two channels of the braking system for speed control during virtual riding. A microcontroller-based system (Arduino Leonardo) transfers the inputs from the sensors, as in the ABRAM Simulator,¹ to a dynamic car model that, in this case, is developed in MATLAB-Simulink and implemented into Simcenter PreScan.

The calibration of the dynamic car model of the motorcycle simulator was derived from a previous study performed by the MOVING group,⁴ in which a proportionality correspondence between motorcycle steering torque and car steering angle was investigated.

Bikesim© simulation software (Mechanical Simulation Company, Ann Arbor, MI, USA) was used to perform simulations related to motorcycle dynamics. A speed range of 30 km/h–130 km/h (range 8.3–36.1 m/s) and radii of curvature greater than 20 m were considered. The simulations were repeated using different motorcycles and found a similar pattern between the

motorcycle steering torque and the kinematic steering angle of an understeering single-track model in a broad speed-radius region.

The study showed that a car model could be used for a motorcycle simulator, for specific riding conditions and certain approximations. Consequently, MOVING's simulator converts the steering torque signal τ coming from the physical simulator into the kinematic steering angle δ of a car model through a constant gain K_{steer} :

$$\tau = K_{\text{steer}}\delta. \quad (1)$$

The advantage of using a dynamical car model is to reduce the simulator complexity and thus the learning time, which represents one of the main problems of advanced motorcycle simulators. The study by Bartolozzi³¹ provides the car parameters and K_{steer} value that ensure steering response similar to a reference motorcycle.³⁰ K_{steer} is negative, so the applied steering torque and the resulting steering angle have opposite signs (counter-steering torque).

Based on these principles, the MOVING motorcycle simulator has a tilting structure connected to the base platform with two springs and shock absorbers to restore the mockup to the nominal position (Figure A3 in Appendix 3). The roll axis is fixed; the roll is limited to 10° to avoid angles at which the rider must hold onto the handlebar to keep riding, avoiding lateral fall because of the absence of the centrifugal force. Following the study by Savino,⁴ the roll degree of freedom is implemented in the MOVING simulator to improve the perceived realism when riding using counter-steering torques. This fact means that, before the present study, the roll motion of the MOVING simulator did not produce any effect on the virtual vehicle: changing the vehicle's direction in the virtual environment was only possible through applying a steering torque on the handlebar.

Control logic for roll

The work's challenge consisted of correctly employing a car dynamic model to simulate a motorcycle riding experience and using a passive simulator where the rider controls the roll (while, in the real world, they have partial control through their body). This scope is demanding; consequently, the roll control logic described in this paper was developed to behave optimally in stationary conditions; extensions of the method to transient phases may be considered in case of satisfactory results of the validation tests.

The proposed approach is the following: the roll effect is considered equivalent to the effect of the steering torque, as both can produce changes in the radius of curvature. The control logic converts a roll change in a steering torque variation by comparing their effects in terms of radius change.

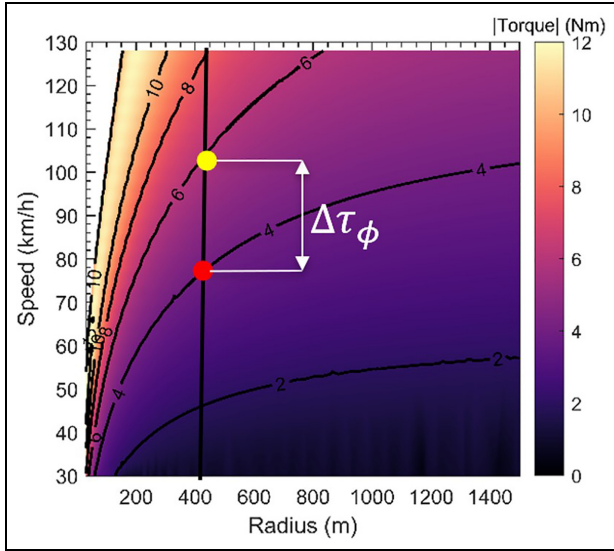


Figure 1. Radius-speed-steering torque 3D map.

The principle of the control logic is that the rider does not lean themselves to emulate the use of the body in the real world but to have the same motorcycle scaled roll angle that it would reach in the real world in the same manoeuvre. The scaled roll is the roll value provided as input to the dynamic model. It is the roll measured by a sensor placed on the mockup ($\varphi_{\text{measured}}$) amplified through a scale factor $K_{\text{roll}} > 1$:

$$\varphi_{\text{scaled}} = K_{\text{roll}} \varphi_{\text{measured}}. \quad (2)$$

The scaled roll is one of the inputs to the roll control logic, which converts this information into an equivalent (in terms of radius variation) steering torque contribution. This contribution is added or subtracted to the steering torque the rider applies on the handlebar to generate the total steering torque, which is then converted into a car steering angle. The roll contribution equals the difference between two steering torques:

- The one required for stationary equilibrium with the radius and speed values relative to the simulation instant with the rider with no lean, called τ_{steady} (red point in the example in Figure 1)
- That required for the stationary equilibrium of a motorcycle cornering with the same curvature radius but having a speed value that would induce a roll value equal to φ_{scaled} . This torque was named τ_{dummy} (yellow point in Figure 1).

Ideally, the control logic would not contribute if the scaled roll of the mockup were equal to the roll angle required in the same manoeuvre in the real world.

The steering angle provided to the car dynamic model by the new logic that adds the roll control logic to the previous one (equation (1)) is:

Table 1. List of notations.

| Symbol | Unit | Description |
|-----------------------------|--------|---|
| V | m/s | Speed |
| K_{roll} | Nm/rad | Measured roll to scaled roll gain |
| K_{steer} | Nm/rad | Steering angle to steering torque gain |
| R | m | Radius of Curvature |
| δ | rad | Steering angle |
| τ | Nm | Steering torque applied by the rider |
| τ_{dummy} | Nm | Leaned steady-state torque |
| τ_{steady} | Nm | No-lean steady-state torque |
| $\varphi_{\text{measured}}$ | rad | Measured roll (the one of the mockup) |
| φ_{scaled} | rad | Scaled roll (the one used in the model) |

$$\begin{aligned} \delta &= \frac{1}{K_{\text{steer}}} [\tau + \Delta\tau_{\phi}(V, R, \varphi)] \\ &= \frac{1}{K_{\text{steer}}} [\tau + (\tau_{\text{dummy}}(R, \varphi) - \tau_{\text{steady}}(V, R))], \end{aligned} \quad (3)$$

where $\Delta\tau_{\phi}$ is the roll-induced steering torque. The roll contribution is proportional to the difference between the two steady-state steering torque values τ_{dummy} and τ_{steady} corresponding to the same corner radius. This contribution is added (with sign) to the steering torque τ applied by the rider. It ensures a good balance between logic simplicity and riding realism.

This approach is correct regarding dynamic and rider expectation: to perform a specific manoeuvre at a certain speed and with a certain radius, if the rider chooses to roll the motorcycle less, they will have to apply more steering torque and vice versa. The roll contribution is not affected by the steering torque the rider applies. This decoupling guarantees the modular characteristic of the logic itself. The quantities considered in this paper are summarised in Table 1.

Implementation on Simulink

Based on the control logic principles described in the previous paragraph, 3D steady-state curve maps, representing the steady-state relationship between speed, roll, curve radius and steering torque, were generated (as described afterwards). Therefore, the logic is optimised for steady-state manoeuvres, as the transient phenomena are not directly modelled. However, when performing a transient manoeuvre, the steady-state terms are still present: therefore, the map-based logic influences the transients too, and this aspect will be analysed.

Since the tilting of the simulator platform is governed by elastic and viscous components (passive motion), the body lean causes the mockup roll. By shifting their body laterally, the rider tilts the mockup: therefore, the body lean influences the simulation directly, as the mockup roll is measured as a proxy for the body displacement. Moreover, measuring the mockup roll is more straightforward than measuring the relative lean of the rider. Measuring the latter

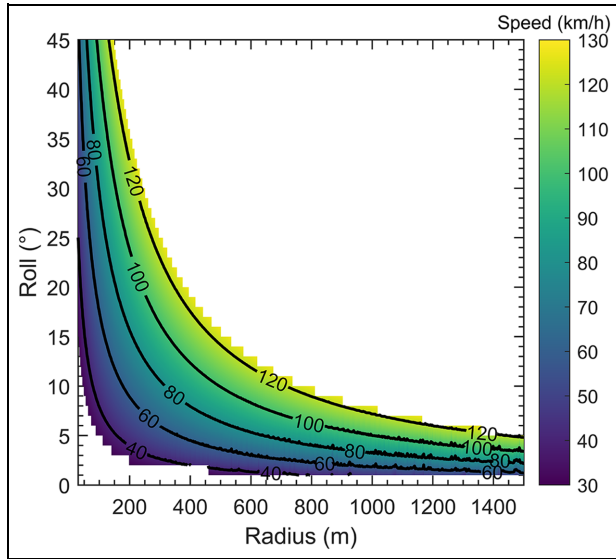


Figure 2. Radius-roll-speed 3D map.

would also make the logic more complex without significant benefits in terms of realism.

These maps were built through an empirical approach that employed dynamics simulations. The *Sport Small BikeSim* motorcycle was chosen for the scope. This motorcycle model was used to reproduce pseudo-stationary riding conditions in the speed range between 30 and 130 km/h and curvature radii between 30 and 1500 m. A slowly increasing speed profile was imposed during a simulation lasting 1000 s. In addition to a speed input, a roll input was applied. A periodic variation of the motorcycle roll between 45° and -45° was set with a 40-second period. During this manoeuvre, a zero relative lean of the virtual rider was imposed. The simulation data were interpolated linearly, obtaining a radius-speed-steering torque map (Figure 1) and a radius-roll-speed map (Figure 2).

The automatic transmission was set up on the car model. The transmission was limited to the first three gears. This choice prevented exceeding the maximum speed value included in the mapped domain, and it fit

the 60–100 km/h speed range, for which the simulator is optimised.

Since the simulator's behaviour at low speeds was not of interest, it was sufficient that, below 30 km/h, the simulation did not stop. Therefore, an extrapolation surface was generated between the origin and the steering torque values corresponding to 30 km/h. The *out-of-range* problem for high radii occurs whenever the rider wishes to pass from riding straight ahead (ideally with an infinite radius) to cornering or vice versa: it also affects the transient, which has not been modelled explicitly. The solution adopted was to inhibit the rolling effect above the 1500 m radius threshold while maintaining control with steering according to the previous model. As described later, this solution allowed suitable trajectory corrections during straights with both body lean and steering torque inputs. In fact, due to the coupling between the roll and steering degrees of freedom of the mockup, tilting the motorcycle without applying a steering torque is impossible for the rider when they have their hands on the handlebar.

The logic was activated when the absolute value of the scaled roll was higher than 2° . The scale factor K_{roll} was chosen equal to 7 or 9: with such thresholds, the control logic was activated for a measured roll between 0.2° and 0.3° . This solution made the model insensitive to the roll sensor's slight offset. The value equal to 7 made the maximum roll generally achieved on the mockup (around 6.5°) correspond to 45° scaled roll. During straight-line riding, if the motorcycle did not reach 2° of scaled roll, the movement on the motorcycle did not produce any effects: this allowed both to maintain a straight-line trajectory easily and to obtain an effective turn entrance.

When either threshold is satisfied, the additional roll contribution is set to zero, and the rider's steering torque provided on the handlebar is converted directly into the car steering angle through the conversion coefficient K_{steer} .

If both thresholds are satisfied, the signals enter the block, whose content is shown in Figure 3. The steering

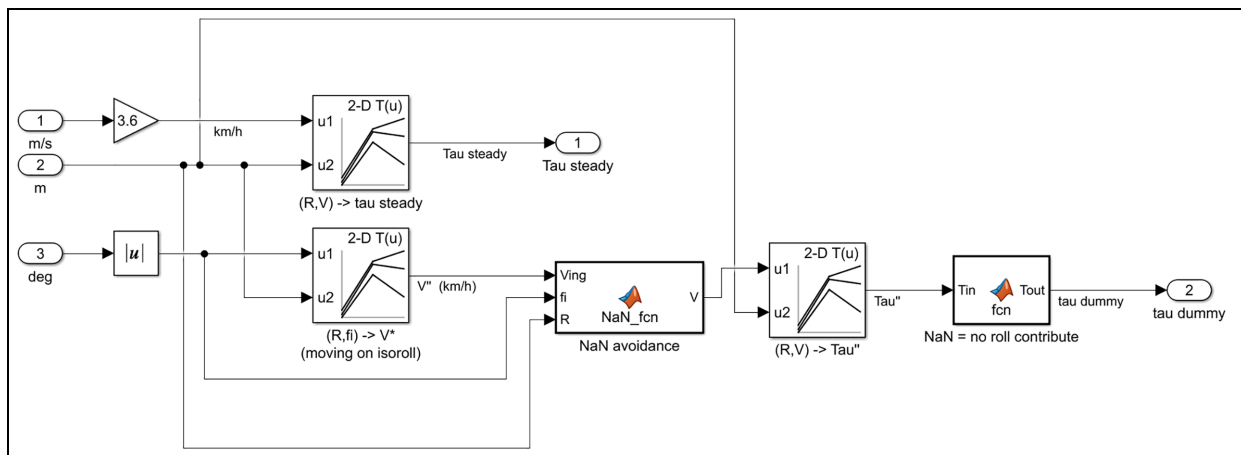


Figure 3. Part of the control logic for the roll in Simulink.

torque value required for stationary equilibrium with zero relative body lean (τ_{steady}) is obtained from the radius-speed-steering torque map. From the radius-roll-velocity map, a speed V^* is calculated. Combined with the instantaneous radius signal, this signal identifies a point in the stationary curve map (radius-speed-steering torque) corresponding to another steering torque value (τ_{dummy}).

If the last map does not output a defined value of τ_{dummy} , the logic sets $\tau_{\text{dummy}} = 0$.

As per equation (3), the τ_{steady} signal is subtracted from the τ_{dummy} signal to obtain the contribution due to mockup roll. This signal is the input of a final Matlab code that:

- Establishes the sign of the roll contribution.
- Sets the roll's contribution equal to zero if $\tau_{\text{dummy}} = 0$.

The roll's contribution is added or subtracted (depending on its sign) to the steering torque applied on the handlebar. Then, the overall steering torque is converted to a car steering angle through the coefficient K_{steer} .

The radius is calculated as the ratio of velocity to yaw rate; these data are taken from the car model.

The 3D maps could receive an infinite radius value as input when the motorcycle is in a straight line. In this case, the logic sets the radius signal of the current time step equal to 2000 m to prevent the simulation from stopping: this way, the control logic is not activated.

The control logic for the roll was introduced in the Simulink car model. The dynamic model is a single-track model consisting of a simplified formulation of the car dynamics.

The maximum achievable roll on the mockup in stationary conditions was around 5° . During transients, because of the inertial effects tied up to the push supplied by the rider, it could reach approximately 7° (subsequently, the roll stabilised to lower values). These evaluations were made for a rider of about 70 kg and average body type. The scale factor K_{roll} was required because the real motorcycle reaches higher roll angles. Since the radius-roll-speed map included the roll angle until 45° and based on some preliminary tests, a default K_{roll} equal to 7 has been chosen.

Inertial platform and its connection to the model

An inertial platform XSENS MTi-670 GNSS/INS was used to measure the roll of the mockup. The sensor can be connected to a special board that allows communication of measured data from the IMU. This board must have two connection cables with pc, allowing:

- The power supply of the module.
- The data communication.

Therefore, communication via CAN-bus was adopted for simplicity and immediacy. A PCAN-USB adapter

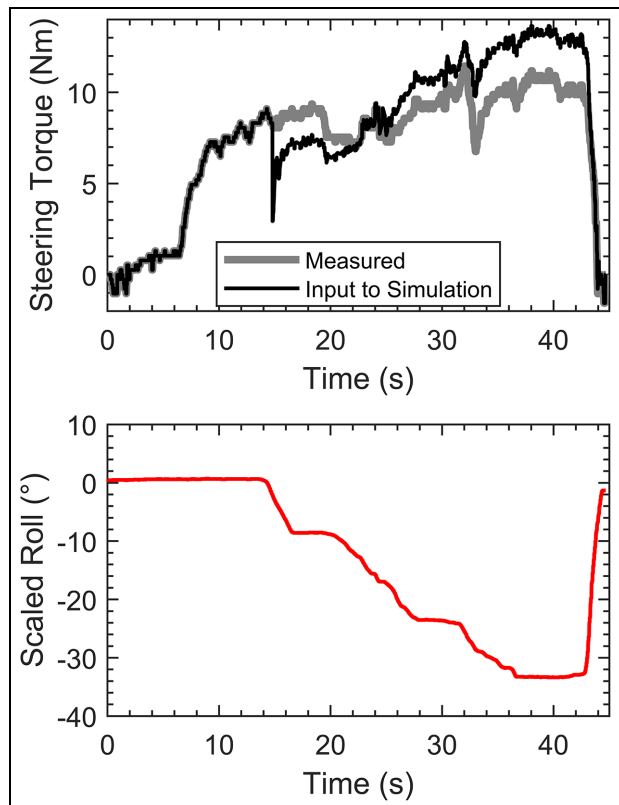


Figure 4. Roll increase test.

from PEAK SYSTEM was used to make that communication possible. A baud rate of 100 kHz and an output frequency of 100 Hz were chosen, corresponding to the step size of the simulation (set constant to 0.01 s). An XSENS CAN database file was used to communicate the data measured by the sensor to the Simulink environment: it contains information used to decode the 'raw' signals coming from the CAN bus. This way, it was possible to receive the value of the roll angle directly in input to the Simulink model. Screws connected the board to a plate fixed to the lower structure of the mockup.

Functional testing

The functional testing aimed to verify if the control logic worked according to the above principles when integrated into the previous car dynamic model. This test, run by participants experienced with the MOVING simulator and its model, was not intended to evaluate the simulator's realism but to study the performance of the new roll-sensitive model and assess its behaviour in a more representative environment.

In the first test (Figure 4), starting from a straight condition, the rider initially increased the steering torque without rolling the mockup. Once he reached a specific steering torque, he kept this constant value while slowly increasing the roll to obtain a quasi-stationary manoeuvre. In the end, he reached a scaled roll of 35° .

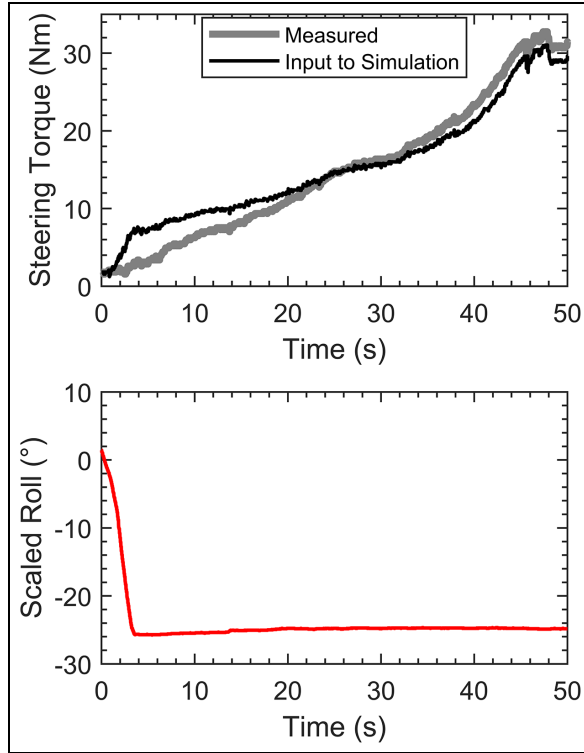


Figure 5. Steering torque increase test.

During the test, the rider maintained a speed of 80 km/h. In the no-roll phase, the steering torque provided as input to the model coincides with that measured: the logic was not activated because the roll threshold was not satisfied (it remained lower than 2°). When the roll threshold was reached, the two curves separated. Since the roll was lower than the one provided by the stationary maps at 80 km/h, the roll contribution to the steering torque was subtractive, and the resulting steering torque was lower than that applied.

Although the rider kept increasing the simulator roll, the turning radius dropped when the roll threshold was satisfied because the overall steering torque decreased. This reduction was about 5 Nm initially; then, the reduction stabilised at about 2 Nm. This sudden drop could potentially be unpleasant for the rider; however, as the Discussion section will show, no participant noticed sudden changes in the steering input. In fact, those presented in this paragraph are peculiar riding conditions that do not usually occur in simulator riding: we, therefore, postpone considerations of this feature to the Discussion paragraph.

During the constant steering torque phase, the overall steering torque increased as the mockup roll grew. This effect makes the rider feel the roll sensitivity of the simulator. The roll contribution had a reduced impact compared to steering torque (up to 30% of overall steering torque), which continued to be, as for real motorcycles, the primary input during corner entry and travel. As hypothesised by Katayama,²³ roll finds its primary use in control tasks and minor trajectory corrections.

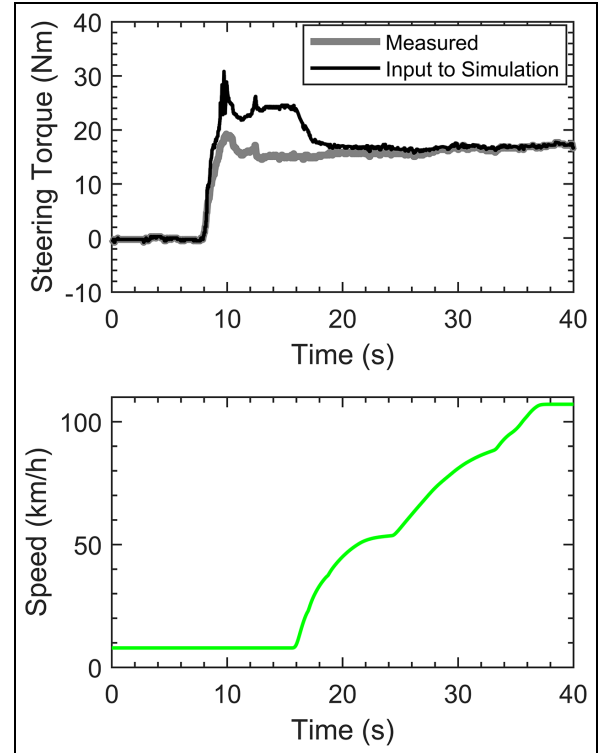


Figure 6. Speed increase test.

In the test shown in Figure 5, the rider kept constant roll and speed while slowly increasing the steering torque. Initially, the roll contribution was additive since the roll would be lower in the corresponding real condition (and in stationary maps). As the steering torque increased, the effect of the roll decreased until it changed sign. Despite this, as the measured steering torque increased, so did the overall steering torque, although at a reduced slope, maintaining good riding realism.

In the test shown in Figure 5, the rider increased the speed while keeping approximately constant roll and steering torque. The roll effect reduced with increasing speed (the two curves got closer). Therefore, changing the speed makes it possible to move the operating point within the roll-speed-torque map (i.e. to modify τ_{steady} , as described in Equation 3). This way, changing trajectory acting only on the throttle is possible, as on a real motorcycle.

In the test shown in Figure 6, the rider started applying a sequence of negative and positive steering torque while keeping the mockup vertical (zero roll). The control logic was not activated because of the roll threshold. Then, at around 18s from the start, the rider inclined the mockup without applying steering torque on the handlebar. This action did not affect the trajectory because the radius threshold was not activated (so the roll contribution was zero), and the steering torque on the handlebar was null.

For the transient phase of a curve entry with high roll acceleration, like the one shown in Figure 7, the lateral springs could generate a steep roll trend consisting of an overshoot in the scaled roll, which is not

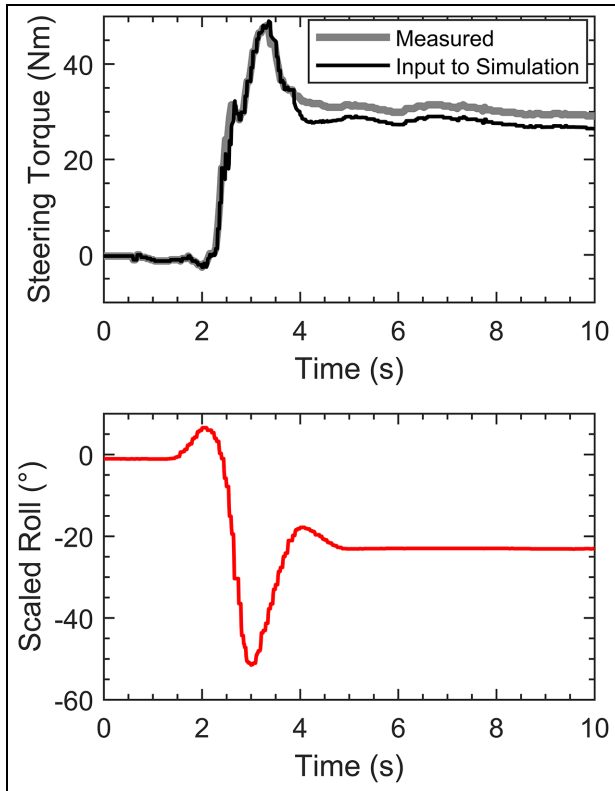


Figure 7. Effect on lateral springs of the simulator in an entry curve manoeuvre.

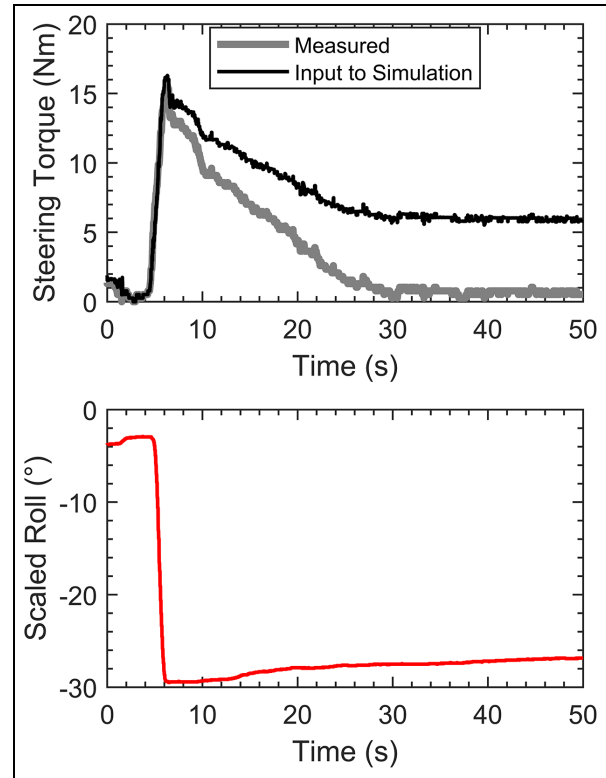


Figure 8. Effect of steering torque reduction with a constant roll.

present during real riding where the stationary roll is gradually reached. Nevertheless, the spring effect was not evident in the steering torque trend. The steering torque plot also shows that, during the transient, the stationary roll contribution was tiny, as in a real motorcycle. Although the logic is optimised only for stationary manoeuvring phases, it behaves well even during transient manoeuvres.

During the manoeuvre shown in Figure 8, the rider, starting from a stationary turn condition, slowly reduced the steering torque while keeping the roll and the speed constant until the value was set to zero. The roll contribution grew as the steering torque decreased because the cornering radius increased: the real motion condition (steady condition) moves along an iso-speed line on the stationary map (Figure 1). In contrast, the dummy motion condition moves along an iso-roll curve. These two conditions moved apart during the manoeuvre, causing an increase of the roll contribution. Concurrently, the overall steering torque decreased because of the reduced steering torque applied to the handlebar. The cornering radius was still finite when the steering torque went to zero because of the roll effect.

The final condition was the same as in the second phase of the test shown in Figure 9 (no steering torque and non-zero roll). Unlike in that case, the logic

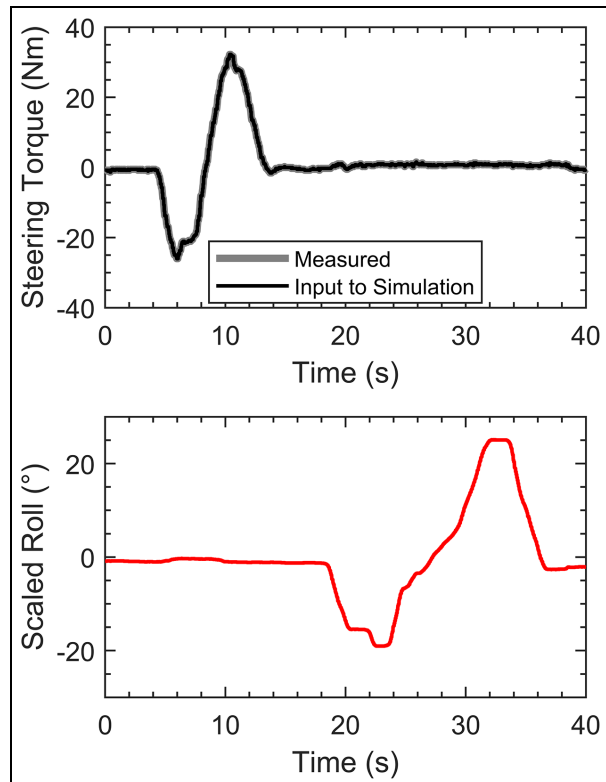


Figure 9. Extreme cases test.

remained active for all the manoeuvres because all thresholds were initially satisfied.

Validation test

The validation test aimed to validate the new model analysed during functional tests. The test involved four external male participants, aged between 22 and 25 years and weighing between 60 and 80 kg. They were asked to wear helmets and gloves for motorcycle use while riding to increase the experiment's immersiveness and safety level.

The participants were initially invited to perform a 15-min familiarisation ride to obtain the necessary confidence with the simulator in a circuit different from the test track, but with similar manoeuvres. During this phase, the rider was free to ride as they wished, to experiment with the operation of the simulator controls.

The test circuit included common manoeuvres, such as:

- two medium-speed constant radius cornering (200 m radius);
- two high-speed constant radius cornering (600 m radius);
- spiral curve with low visibility;
- straight (500 m length);
- lane change (4 m offset, 20 m transition distance); and
- 'U' turn (100 m radius, constant).

The test consisted of three sessions of two laps each for each participant. Each session differed in the model used; riders were unaware of either the dynamic model used in each session or that the simulator model was automotive.

The models tested by the riders are:

- roll-insensitive car model (i.e. the one previous to this study): $K_{roll} = 0$ (KR0 model);
- roll-sensitive car model with $K_{roll} = 7$ (KR7 model);
- roll-sensitive car model with $K_{roll} = 9$ (KR9 model).

The participants tried the models in different orders. The two circuits used for the test were built with *Simcenter Prescan*. All sessions were video recorded by two cameras. Each participant was given two questionnaires, the first after the session with a scale factor equal to 7 to compare the riding simulator experience with a real motorcycle, and the second after each session to compare the different models. The first questionnaire used the Cooper-Harper scale³² (Figure A1 in Appendix 2), an aviation-derived scale developed to assess the controllability of a system by a trained pilot. It is often used comparatively to evaluate the controllability of a prototype system against a reference configuration. It is based on a decision tree that assesses controllability, performance, and user satisfaction. A rating of one indicates 'excellent behaviour' while a

rating of 10 indicates 'major deficiencies'. A score of 4 indicates 'Minor but annoying deficiencies' and 'Desired performance requires moderate pilot compensation'.

The test ended with a final interview to discuss the overall experience.

Results

Subjective results

The first questionnaire used the Cooper-Harper scale to assess the handling. In straights, steering torque control was considered good by most participants (mean value of 3.25). In contrast, roll control received discordant results across participants (standard deviation of 2.16), although the rating was slightly unpleasant concerning body control (mean value of 5.25). The roll control during straights appeared poorly reactive compared to what happens in the real world. Riders expected a roll that was at least as responsive as the steering input and with more influence on the trajectory.

Regarding realism in the different manoeuvres of the test circuit, in stationary cornering, both body control and steering control were evaluated positively (mean value of 3).

The lane change showed contrasting results (mean value of 4.50, standard deviation of 2.06), indicating that the feeling reached during the familiarisation phase and the confidence with this type of motorcycle make the difference. The 'U' turn presented a mean value of 4.00: the participants indicated a good level of realism for the transient manoeuvres, considering that the control logic is optimised only for stationary manoeuvres.

Three out of four participants considered the spiral curve the most complex manoeuvre. The spiral curve had to be performed at low speed, and the simulator was not optimised for speeds below 50 km/h. Considering these aspects, the subjective evaluation results (mean value of 4.50) were positive, as three out of four riders showed good control during this manoeuvre.

When comparing these data to previous tests, no increase in the required familiarisation time was detected, even though the new model is more complex than the control strategy without roll-related steering input.

According to the questionnaire results in Appendix 1, the participants rated the KR9 model the most realistic overall. Additionally, both roll-sensitive models were considered more realistic than the roll-insensitive one (both the overall opinion and the specific item related to the perception of the roll).

In the final interview, three participants expressed a desire for a more significant roll effect. All participants reported that they would have preferred a more compliant roll motion, allowing them to reach higher roll angles closer to those achievable on a real motorcycle. Moreover, they explained that they exhibited small lean

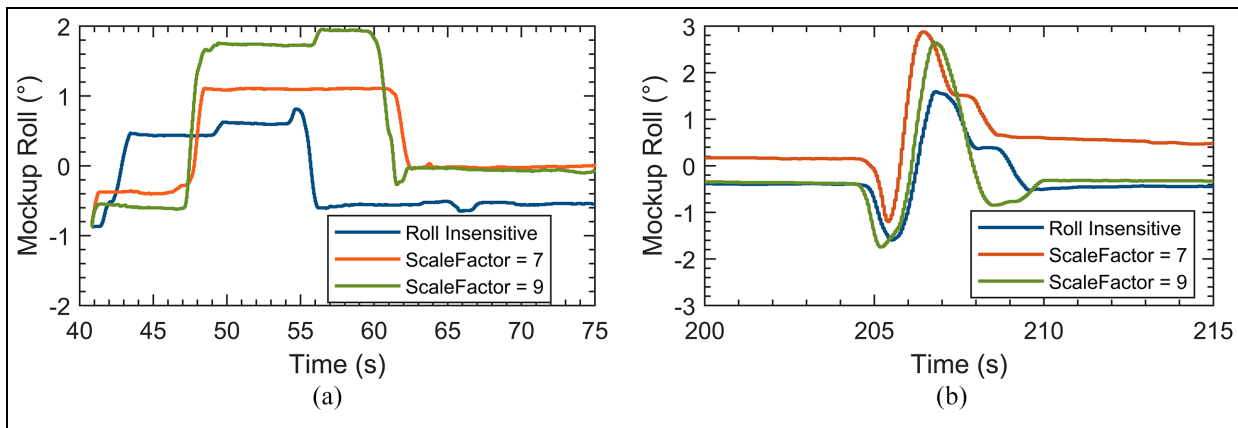


Figure 10. Measured roll of a participant in different manoeuvres: (a) stationary curve and (b) lane change.

angles because of the high effort needed to roll and because the lean produced a smaller effect in control and trajectory change compared to real riding. Two participants stated that how the roll motion behaved partially disincentivised the use of the roll effect.

All participants highlighted their discomfort concerning the effect of the springs during transients (there is no similar action in real motorcycle riding). One participant suggested that the springs produced less leg use in riding than in the real world, resulting in reduced use of the roll-related steering torque.

On the other hand, the application of steering torque ensured a more favourable relationship between the effort required and the visible consequences in the simulation, so much so that this was the dominant riding strategy.

One participant perceived the lack of gyroscopic moment, which causes poor steering feedback.

All participants indicated a good realism of the roll effect at medium-high speed, while it got worse at low speed, where they preferred the steering torque control.

The roll-insensitive model had more run-offs in the session than the others. All participants expressed that virtual riding required low physical and modest psychological effort, like an authentic riding experience.

Objective results

Participants reported riding approximately the same way in all sessions. However, the data revealed that the participants increased the amount of leaning used as the model's roll sensitivity increased. For example, the first participant recorded a mean of the roll absolute value (during each session's entire test) of 2.2°, 3.2° and 4.0° with the KR0, KR7 and KR9 models.

Figure 10 shows the measured roll plots for two different test circuit manoeuvres where this trend of the roll angle is evident: the roll peak of the most roll-sensitive model was tripled in the stationary curve compared to the insensitive model. This trend was observed in both stationary and transient manoeuvres.

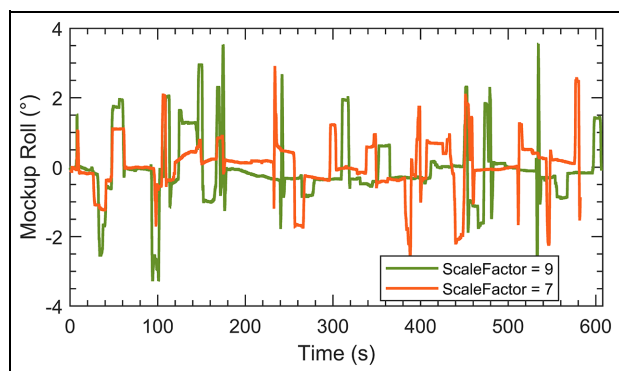


Figure 11. Roll measured in sessions with the roll-sensitive model with a scale factor of 7 and 9.

Figure 10(a) shows that during the session with the roll-insensitive model, the rider performed the straight following the curve with a non-zero roll. This effect manifested for all participants and did not occur during sessions with the other models.

Figure 11 shows an example of the measured roll for an entire riding session: in general, all participants only occasionally exceeded 3° of roll.

During a session with the KR9 model, one participant went off exiting the spiral curve in the second lap: the variables of this manoeuvre are circled with a red, solid line in Figure 12, around 400 s. In the Discussion paragraph, this manoeuvre will be compared with the one performed in the first lap (circled with a blue dashed line, around 100 s).

In Figure 13 the rider made a few trajectory corrections using his body (and the roll effect) during a straight. This action would not have produced any effect had he used only the simulator roll, as shown in Figure 9. Despite this he confirmed that he could feel the roll effect.

A part of the circuit consisted of an abrupt and unexpected narrowing of the carriageway; the participants reacted by using the roll effect extensively. This scenario surprised participants and induced them to take an emergency evasive manoeuvre. The result of

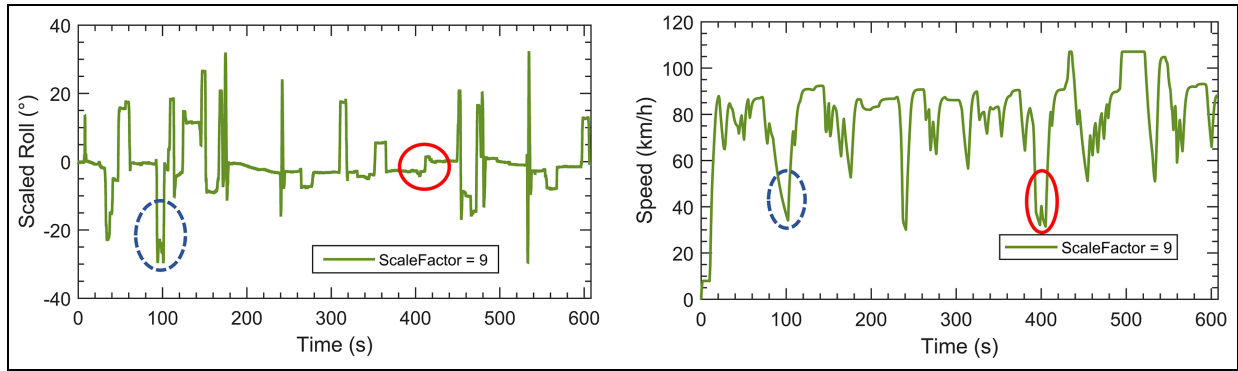


Figure 12. Steering torque and speed in one participant's session with the KR9 model.

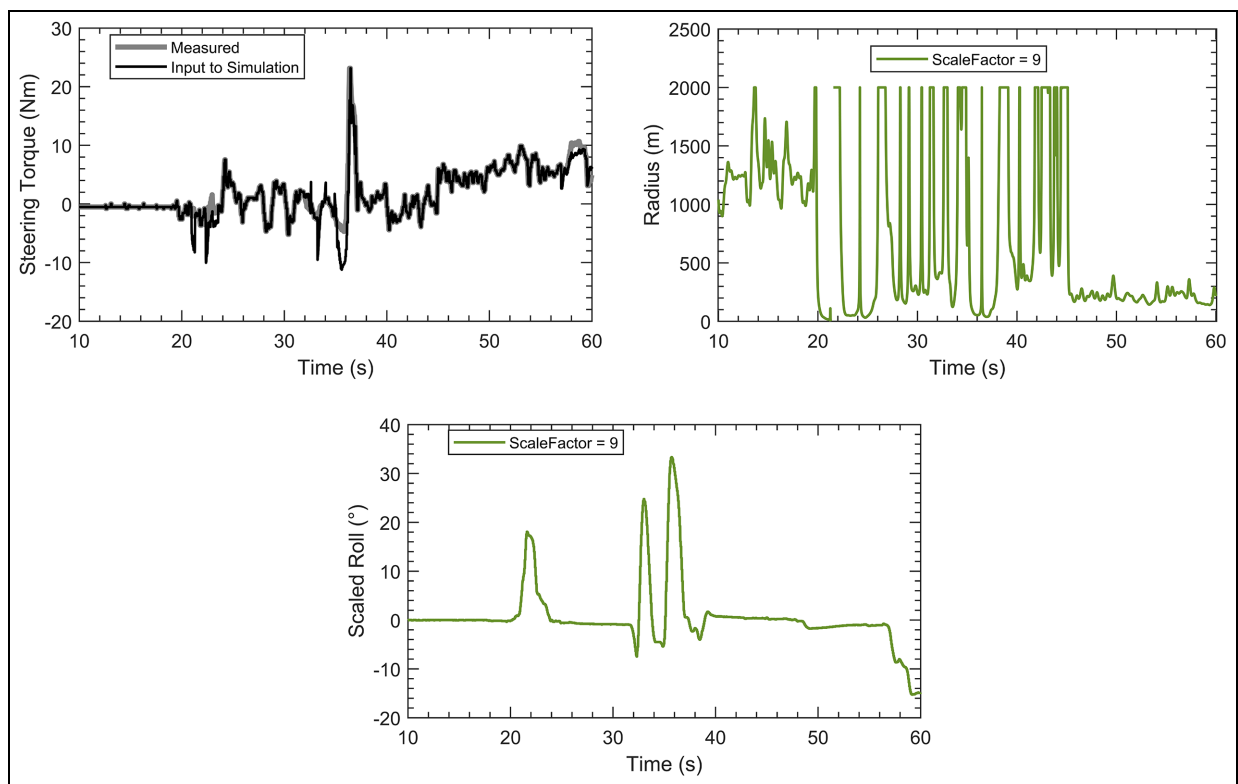


Figure 13. Trajectory corrections with the body in a roll-sensitive model session.

one participant is shown in Figure 14. They also used the steering torque significantly.

Discussion

This study aimed to validate an improved model for a motorcycle simulator that allows the virtual vehicle to be sensitive to the mockup roll.

During straights, the riders expected roll motion responsiveness comparable to the steering torque; however, roll contribution was adequately lower than the steering torque during functional tests. This feeling was because the logic did not activate for low rolls or high

radii: one solution could be extending the domain of the stationary maps.

An input like that shown in Figure 12 should not cause any effect because of the presence of the thresholds. The participant declared that he felt the roll effect: the MOVING simulator was built to make it challenging to lean the upper body without steering or vice versa. The rider is forced to push his torso, applying a force to the handlebars to increase the mockup roll by inclining their body, which is converted into a steering torque. Riders are often unaware of this mechanism, which triggers the radius threshold, providing the roll effect. This fact would not be possible without the

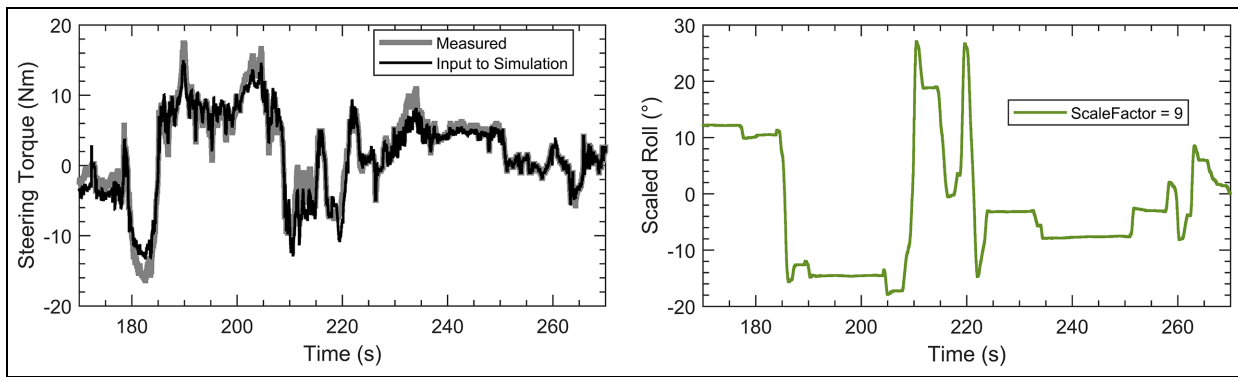


Figure 14. Emergency manoeuvre in the test circuit.

intrinsic connection on the mockup between steering torque and roll (also present in real motorcycles, as the study of Weir¹⁹ hypothesised).

Although the model provided the best performance during stationary manoeuvres, the realism of transient manoeuvres received a mean rating above 'sufficient' (Appendix 1). Moreover, stationary curve and line change received the same mean rating for the most realistic model (KR9 model): this confirms (after the results of the functional tests) that the logic, although optimised for stationary manoeuvres, has good behaviour even during transients.

The perceived realism worsens during low-speed curves because the previous model was optimised for medium-high speed, so this behaviour is outside the domain of interest.

The roll effect was designed to be optimal with scale factor 7 (considered the best after functionality tests), assuming that riders achieved 5° of measured roll. The reason the KR9 model was considered the most realistic could be that, as visible in Figure 11, the roll values reached during sessions were lower than expected because of the limited experience of the participants with the MOVING simulator. With that model, for the same measured roll, the effect was more significant and similar to that obtained during functional tests with the KR7 model.

Another reason for this rider behaviour was the excessive effort required to roll the simulator, compared to that needed in real motorcycles, concerning the benefits of control. When starting from a non-zero roll condition, the rider must make an effort to roll the vehicle further. There is no opposition force similar to springs in a real motorcycle, so it is easier to increase the roll in reality. The stiffness of the lateral springs was chosen to facilitate the counter-steer action and the return to the nominal position starting from the tilted simulator condition.

Some participants stated that they would have preferred a higher permitted roll and a more significant roll effect. Being ordinary riders, the participants thought that the roll was the primary riding input. The 10° roll

limit was chosen to avoid both the fall and an unrealistic action of the forces on the rider's body while riding.

Moreover, although the participants did not know what model they used during each session, roll-sensitive models received a higher average rating of realism, confirming that this new model constitutes an improvement over the previous without increasing familiarisation time.

The riders have, on average, rolled the mockup more in the sessions in which the model was more sensitive to the roll. Riders perceived a more significant roll effect on the trajectory in these sessions and exploited it but surprisingly were convinced that they rode the same way during all sessions in terms of the roll. It can be deduced that it is easy for riders to adapt to the new logic and that, when using it, they are inclined to use their bodies more (also in transient manoeuvres). These data confirm that participants felt a need to introduce roll sensitivity.

In Figure 10(a), it is shown that during the session with the roll-insensitive model, riders often performed the straights with the mockup inclined by a non-zero value and higher than the roll threshold of the models sensitive to this degree of freedom. The roll-sensitive model makes riders more focused on this aspect, improving riding realism.

The data and the participants agree that the steering torque was the primary riding strategy, while the roll was used to control the motorcycle more precisely. The same happens in a real motorcycle, as hypothesised by Katayama.²³ This behaviour was also influenced by the fact that the mockup was the same used with the previous simulator version, in which the roll was present only to facilitate counter-steer riding.

In Figure 12, the rider went off the track exiting a corner on the second lap (circled in red) because this manoeuvre was performed with an insufficient roll for such low corner radii; in the first lap, the same curve (circled in blue), correctly executed, required a much higher scaled roll. Therefore, the simulator also responds realistically to incorrect inputs from the riders, especially regarding the roll.

In emergencies, like the one shown in Figure 14, the rider used the simulator's roll a lot, meaning that this input allows him to increase control over the vehicle, avoiding obstacles.

None of the participants complained about the effect of the instantaneous steering torque variation verified in the functional test (Figure 4). This effect does not occur in normal riding conditions because it is shorter and less evident. Moreover, it happens during the transient phase, while this work was focused on the stationary phase.

Conclusion

This paper presented the model and the validation test of the proposed control logic for the roll input, developed for a passive motorcycle simulator based on a car dynamic model.

The model produces a roll contribution consisting of a steering torque added to that applied on the handlebar. This approach gives riders more control and sensibility over the virtual vehicle compared to simulators with an active roll system. The novelty of this work is that, while in the active simulators the roll is a consequence of the reprocessing of the rider inputs by the dynamic model, in the MOVING simulator, the roll is intentionally considered as an additional input controlled directly by the rider and only later provided to the model.

The experiment resulted in higher satisfaction with the roll-sensitive model than the previous one. The roll effect was mainly used to control the motorcycle in emergencies and for minor trajectory corrections that are effective in a straight and when cornering. As in real motorcycles, the steering torque remained the primary vehicle control input.

The natural continuation of this work is to extend the operation of the roll logic to all riding situations, including transient manoeuvres, where the control logic already provides satisfactory performance.


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ORCID iDs

Mirco Bartolozzi  <https://orcid.org/0000-0003-4094-9205>

Lorenzo Berzi  <https://orcid.org/0000-0002-9897-1387>

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Appendix I

Table A1. Questions from the questionnaire on individual manoeuvres.

| Manoeuvres | Question | Question code |
|-----------------|--|---------------|
| Stationary turn | Perceived roll effect in the overall experience | A |
| | Realism of the steering control | B |
| | Was the motorcycle response adequate for the effort on the handlebars? | C |
| | Was the motorcycle response adequate for the effort required to roll the motorcycle? | D |
| | Overall satisfaction | E |
| Lane change | Realism of the steering control | F |
| | Perceived difficulty level of the manoeuvre (considering the familiarisation acquired) | G |
| | Was the motorcycle response adequate for the effort required to roll the motorcycle? | H |
| | Overall satisfaction | I |
| Spiral curve | Roll's effect perceived in the overall experience | L |
| | Realism of the steering control | M |
| | Realism of the body control in terms of the effect on the virtual environment | N |
| | Was the motorcycle response adequate for the effort required to roll the motorcycle? | O |
| 'U' curve | Overall control of the virtual motorcycle | P |
| | Realism of the steering control | Q |
| | Was the motorcycle response to the effort required to roll the motorcycle? | R |
| | Realism of the body control in terms of the effect on the virtual environment | S |

Table A2. Grades of the questionnaire on individual manoeuvres.

| Grades | Meaning |
|--------|-----------------------|
| 1 | Really bad |
| 2 | Bad but improvable |
| 3 | Acceptable/sufficient |
| 4 | Good |
| 5 | Excellent |

Table A3. Results of questionnaires provided to participants after each session of the validation test.

| ID Participant | Model | A | B | C | D | E | F | G | H | I | L | M | N | O | P | Q | R | S | Overall Grade |
|----------------|-------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|---------------|
| ID1 | KR0 | 4 | 3 | 3 | 2 | 3 | 2 | 4 | 2 | 2 | 2 | 3 | 3 | 2 | 4 | 4 | 4 | 3 | |
| ID1 | KR9 | 4 | 3 | 3 | 2 | 3 | 2 | 4 | 2 | 2 | 2 | 3 | 3 | 2 | 3 | 3 | 2 | 3 | |
| ID1 | KR7 | 4 | 4 | 4 | 2 | 4 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 3 | 3 | |
| ID2 | KR9 | 2 | 2 | 3 | 2 | 2 | 3 | 3 | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | |
| ID2 | KR7 | 3 | 3 | 3 | 2 | 2 | 3 | 3 | 2 | 2 | 2 | 3 | 2 | 2 | 3 | 3 | 3 | 3 | |
| ID2 | KR0 | 3 | 3 | 3 | 2 | 2 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 3 | 3 | 2 | 2 | |
| ID3 | KR7 | 4 | 3 | 4 | 2 | 3 | 2 | 3 | 3 | 3 | 4 | 3 | 3 | 4 | 3 | 3 | 2 | 3 | |
| ID3 | KR0 | 4 | 3 | 2 | 4 | 4 | 3 | 4 | 4 | 4 | 4 | 3 | 2 | 3 | 1 | 2 | 3 | 2 | |
| ID3 | KR9 | 5 | 3 | 4 | 4 | 4 | 4 | 3 | 3 | 4 | 2 | 3 | 2 | 3 | 2 | 2 | 3 | 4 | |
| ID4 | KR0 | 2 | 4 | 4 | 1 | 3 | 4 | 1 | 4 | 4 | 3 | 4 | 2 | 1 | 3 | 4 | 2 | 2 | |
| ID4 | KR7 | 3 | 4 | 5 | 1 | 3 | 4 | 2 | 4 | 4 | 2 | 3 | 2 | 2 | 3 | 4 | 2 | 2 | |
| ID4 | KR9 | 3 | 3 | 4 | 3 | 4 | 4 | 1 | 4 | 4 | 3 | 4 | 3 | 4 | 4 | 3 | 4 | 3 | |
| Mean | KR0 | 3.25 | 3.25 | 3.00 | 2.25 | 3.00 | 3.00 | 3.00 | 3.25 | 3.25 | 2.75 | 3.00 | 2.25 | 2.00 | 2.75 | 3.25 | 2.75 | 2.25 | 2.84 |
| | KR7 | 3.50 | 3.50 | 4.00 | 1.75 | 3.00 | 2.75 | 2.50 | 2.75 | 3.00 | 2.75 | 3.00 | 2.50 | 2.75 | 3.25 | 3.50 | 2.50 | 2.75 | 2.93 |
| | KR9 | 3.50 | 2.75 | 3.50 | 2.75 | 3.25 | 2.75 | 2.75 | 3.00 | 3.25 | 2.25 | 3.25 | 2.75 | 3.00 | 3.00 | 2.75 | 3.00 | 3.25 | 3.01 |

Model KR0 = Roll-insensitive car model ($K_{roll} = 0$).Model KR7 = Roll-sensitive car model with $K_{roll} = 7$.Model KR9 = Roll-sensitive car model with $K_{roll} = 9$.

Appendix 2

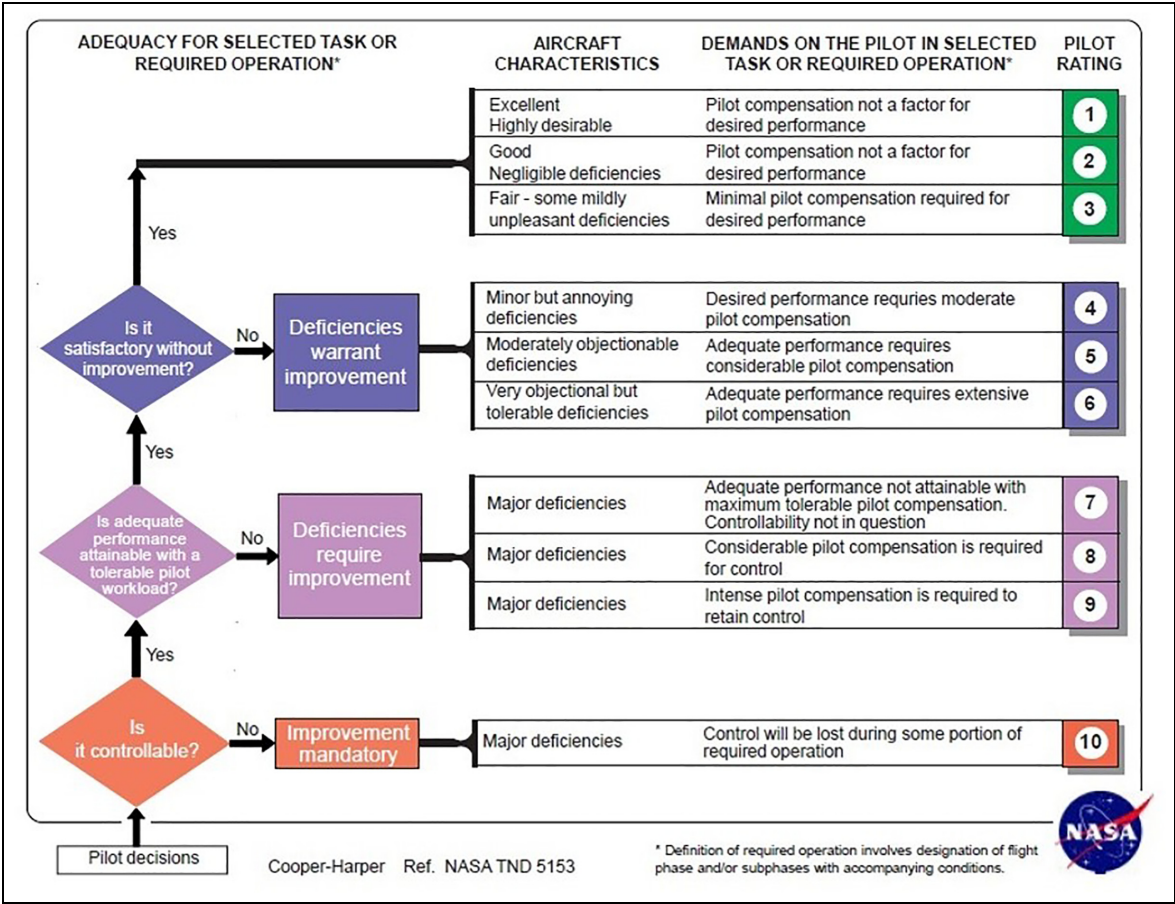


Figure A1. Cooper-Harper handling qualities rating scale.³²

Appendix 3

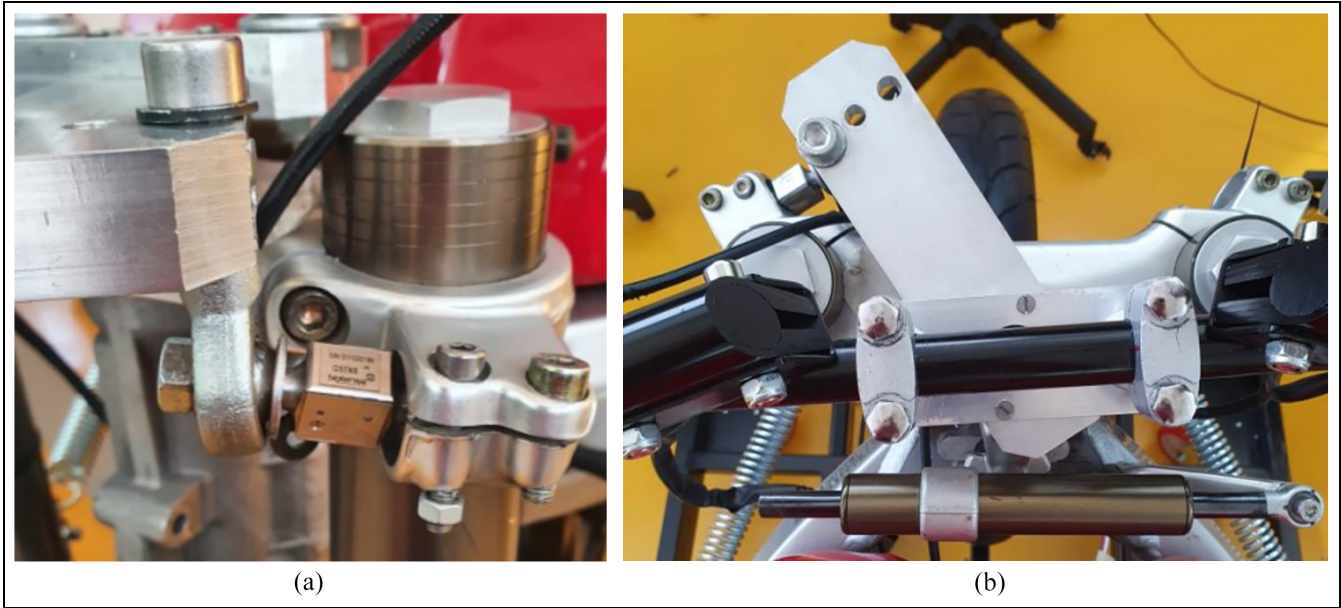


Figure A2. Same details about the MOVING motorcycle simulator: (a) load cell to measure steering torque and (b) steering damper.

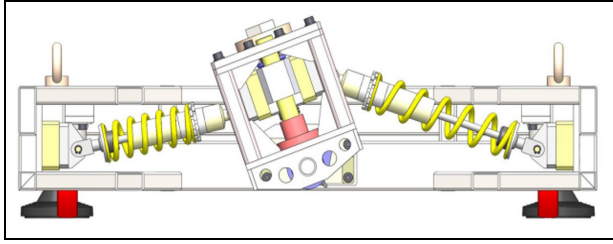


Figure A3. Cross-sectional view of the complete inclined roll mechanism.



Figure A4. MOVING motorcycle simulator.