On Steady-State Cornering Analysis for Motorcycles

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***Abstract*— In this paper, a neutral-path departure algorithm is proposed to define safe handling threshold conditions and dangerous steering situation for powered two-wheeled vehicles. Based on this study, a Self Steering Gradient for motorcycles is proposed as a risk function for neutral-path departure detection. Furthermore, the motorcycle overturning or under-steering are analyzed based on the handling index. This index depends on the intrinsic motorcycle parameters, as well as, the state outputs. The proposed neutral-path departure algorithm aims to assess the risk when the motorcycle begins to drift out of the neutral path. Finally, the effectiveness of the detection scheme is tested using a high-fidelity software BikeSim©.**

***Index Terms*— Steady cornering, Risk function, Motorcycle Safety.**

I. INTRODUCTION

Recently, car manufacturers are constantly seeking to design new intelligent safety systems, in order, to detect malfunctions in riding task and to improve the performance and reliability of active safety systems. Lane departures case account for a significant percentage of roadway fatalities. According to Federal Highway Administration's Roadway (FHWA's), from 2015 to 2017 an average of $19,23$ traffic fatalities resulted from roadway departures crashes [1]. In-Depth Investigations of motorcycle crashes, show that human errors due to tiredness or temporarily distraction are the most important factors. This is why the last few years have seen the emergence of on-board roadway departure assistance systems in cars as a way of improving security and helping to avoid damage or even fatal crashes in dangerous steering situations [2], [3]. In spite of the fact that road-departure system is present in every modern car, it is not yet developed for motorcycle and those implemented for four-wheeled vehicles are not entirely transferable to motorcycles due to the fact that motorcycle dynamics is more complex and unstable. Therefore, departure avoidance systems for motorcycle are the next step, aimed to detect as early as possible, when the motorcycle is involuntary getting out of the lane. Then, the rider corrects his trajectory, maintain stability and keep acceptable performances by means of this early detection systems.

Currently, relevant works are intended to study the design of Lane Departure Warning for Motorcycle (LDWM) from the control point of view. [4]. In [5], author study the motorcycles steering behavior, achieved by the vision-based approach to define the motorcycle dynamic position on the road and to detect the under/oversteer situations. Lane Departure Warning System for a motorcycle is still under development and needs a more thorough investigation to be implemented in new bikes.

A key problem in building up departure warning systems for motorcycle or even vehicles is how to develop a driving risk function, which can be used to warn the rider in the case of passive assistance or engage the control action in the case of active assistance. Car roadway departure system usually defines a lane crossing Time (TLC) and distance to lane crossing (DLC) as a risk index, to assess the time for involuntary trespassing the boundaries, see [2], [3]. Nevertheless, the TLC presents some limitations, it requires accurate road information, moreover, it is approximated geometrically without vehicle dynamics consideration to integrate driver corrections. Also the TLC alone is not adequate for imminent departure situation or not sufficient to characterize road-departure situations. Indeed, even in risk situation of high speed in longitudinal motion and/or overmuch lateral dynamic, in this case, a great value of TLC can be expected with no alarm generation, see [6].

Among other, steady-state analysis and handling capabilities issues are very related to vehicle safe trajectory and roadway departure. Many researches were devoted to study the steady-state handling for cars, see [7], [8], either to define analytical handling criteria or the critical dynamic variables with which the divergent loss of handling occurs. The analysis of the properties of handling highlights certain dynamic aspects that are important to define dangerous/safe stability threshold conditions, as the neutral, overturning or underturning behavior [7], [9]. Unfortunately, this keen interest is not as evident to some other road users. Inspired by steady-state and the handling analysis for cars, our present work tackles the question of the motorcycle's steering behavior based on the stationary cornering condition, followed by the design of a new risk indicator for motorcycle, to describe steering neutral, under or over behavior.

In this paper, a detection approach towards getting circular stationary states and analytical handling conditions is developed for powered two wheeled vehicles (PTWv). Based on the established motorcycle model, a Self Steering Gradient for motorcycles "S_S" is proposed as a risk function. The handling index "S_S" is computed from currently available standard sensors: Inertial Measurement Unit (IMU), steering encoder and Global Navigation Satellite System (GNSS) without the need on state observer. Furthermore, a neutral-path departure (NPD) algorithm based on the "S_S" is proposed to characterize the motorcycle steering behavior: over or under-steering situations. The algorithm monitors signals from sensors and compares intended neutral (theoretical) and actual paths. If the trajectories differ from each other, this

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means that motorcycle is going out neutral path, in this case, the algorithm generates an alarm to warn the rider.

II. Lateral Motorcycle Dynamics

In this section, the lateral motion of the motorcycle is modeled as a single track vehicle, as shown in Fig. 1 [10], [11]. This model has three degrees of freedom, namely the lateral displacement, roll, and yaw motion, including the tire cornering properties, described by the following differential equations:

$$\left\{\begin{array}{rcl} m(\dot{v}_y+\dot{\psi}v_x) & = & F_{yf}+F_{yr} \\ I_z\ddot{\psi} & = & l_fF_{yf}-l_rF_{yr} \\ I_x\ddot{\phi}+mh(\dot{v}_y+\dot{\psi}v_x) & = & mhg\phi \\ ma_y & = & F_{yf}+F_{yr} \end{array}\right. \tag{1}$$

Where F_{yf} and F_{yr} are the lateral forces on the front and rear wheels, v_x is the forward speed, $\dot{\psi}$ is the yaw rate, a_y is the lateral acceleration, m is the motorcycle mass, l_f and l_r are horizontal distances, h is the height of the gravity center, and I_z and I_x are the moment of inertia with respect to the $z-axis$ and $x-axis$ respectively.

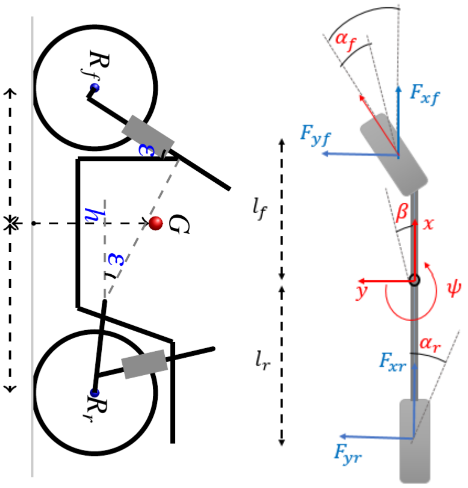


Fig. 1: Motorcycle kinematics.

The lateral cornering forces are given by:

$$\left\{\begin{array}{rcl} F_{yf} & = & -C_{f1}\alpha_f+C_{f2}\gamma_f \\ F_{yr} & = & -C_{r1}\alpha_r+C_{r2}\gamma_r \end{array}\right. \tag{2}$$

where C_{f1}, C_{f2}, C_{r1} and C_{r2} are the cornering stiffness and camber coefficients, α_f and α_r are sideslip angles, γ_f and γ_r are the camber angles of the front and rear tyres, respectively. With :

$$\left\{\begin{array}{rcl} \alpha_f & = & \frac{v_y+l_f\dot{\psi}}{v_x}-\delta\cos(\varepsilon), \quad \gamma_f=\phi+\delta\sin\varepsilon \\ \alpha_r & = & \frac{v_y-l_r\dot{\psi}}{v_x}, \quad \gamma_r=\phi \end{array}\right. \tag{3}$$

After slight calculation, one can obtain:

$$\left\{\begin{array}{l} m(\dot{v}_y+\dot{\psi}v_x)=a_1\frac{v_y}{v_x}+a_2\frac{\dot{\psi}}{v_x}+a_3\delta+a_4\phi \\ I_z\ddot{\psi}=a_5\frac{v_y}{v_x}+a_6\frac{\dot{\psi}}{v_x}+a_7\delta+a_8\phi \\ I_x\ddot{\phi}+mh(\dot{v}_y+\dot{\psi}v_x)=mhg\phi \end{array}\right. \tag{4}$$

whereas, a_i are function of l_f, l_r, ε, C_{fi} and C_{ri} with $i=(1,2)$, given by:

$$\left\{\begin{array}{l} a_1=-(C_{f1}+C_{r1}), \quad a_2=-(l_fC_{f1}-l_rC_{r1}) \\ a_3=(C_{f1}\cos(\varepsilon)+C_{f2}\sin(\varepsilon)), \quad a_4=(C_{f2}+C_{r2}) \\ a_5=a_2, \quad a_6=-(l_f^2C_{f1}+l_r^2C_{r1}) \\ a_7=(l_fC_{f1}\cos(\varepsilon)+l_fC_{f2}\sin(\varepsilon)), \quad a_8=(l_fC_{f2}-l_rC_{r2}) \end{array}\right.$$

III. Steady Steering Behaviour and Handling Analysis

The aim of this section is to extract form the above model (4), the operating steady steering conditions. These characteristics are important and concur to define the sensitivity of the motorcycle's handling [12] whose estimation remains a real problem [13], [14]. Which is commonly judged by how a vehicle reacts to the rider inputs during cornering. Under a steady cornering scenario, the yaw rate $\dot{\psi}$ as well as the steering angle, the lateral velocity and the side slip are constants, it follows:

$$\left\{\begin{array}{l} m\dot{\psi}v_x=a_1\frac{v_y}{v_x}+a_2\frac{\dot{\psi}}{v_x}+a_3\delta+a_4\phi \\ a_5\frac{v_y}{v_x}+a_6\frac{\dot{\psi}}{v_x}+a_7\delta+a_8\phi=0 \\ \dot{\psi}v_x=g\phi \end{array}\right. \tag{5}$$

After quick manipulation, one can write :

$$\left[\underbrace{\left(a_5m-\frac{a_5a_4-a_1a_8}{g}\right)}_{K_1}v_x^2-\underbrace{(a_5a_2-a_1a_6)}_{K_2}\right]\frac{\dot{\psi}}{v_x}=\underbrace{(a_5a_3-a_1a_7)}_{K_3}\delta \tag{6}$$

where

$$\left\{\begin{array}{l} K_1=(-(l_fC_{f1}-l_rC_{r1})m-\frac{(l_f+l_r)(C_{f2}C_{r1}-C_{f1}C_{r2})}{g}) \\ K_2=(l_f-l_r)^2C_{f1}C_{r1} \\ K_3=(l_f+l_r)C_{f1}\left(C_{r1}\cos(\varepsilon)-C_{f2}\sin(\varepsilon)\right) \end{array}\right. \tag{7}$$

The *steering sensitivity* $\frac{\dot{\psi}}{\delta}$ is given by :

$$\frac{\dot{\psi}}{\delta}=\frac{(\frac{K_3}{K_2})v_x}{[Kv_x^2+1]} \tag{8}$$

Where $K=\frac{K_1}{K_3}$ is the handling factor. The aim of this part is to extract from the above model (4), the operating steady steering conditions. The motorcycle steering tendency depends on the yaw rate, the forward velocity v_x and the stability factor K, it follows:

1) $K=0$ for Neutral steering, $\frac{\dot{\psi}}{\delta}=\frac{K_3}{K_2}v_x$ has a linear relation with motorcycle speed with $\frac{K_3}{K_2}$ is the slope.
2) $K>0$ Under-steering, the steering sensitivity is below the neutral steering characteristic. $\frac{d}{dv_x}(\frac{\dot{\psi}}{\delta})=0\rightarrow v_{ch}=\frac{1}{\sqrt{K}}$. It is interpreted as the motorcycle characteristic speed at which the vehicle reacts most sensitively to steering inputs.
3) $K<0$ Over-steering: when $v_{cr}=\frac{1}{\sqrt{-K}}$, the steering sensitivity strives toward infinity, where v_{cr} is the critical speed, for which a motorcycle becomes unstable because its steering is canceled, as even very small steering input would lead to infinite yaw rate.

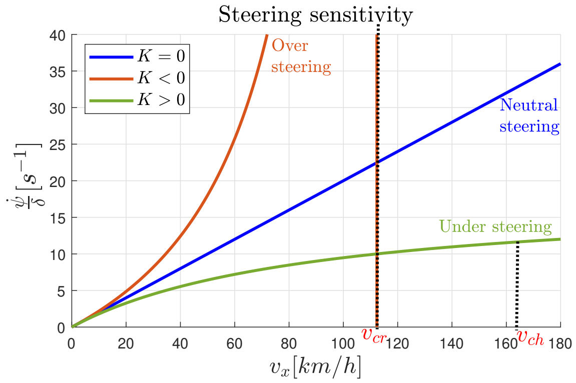


Fig. 2: Motorcycle sensitivity gain.

IV. The side slip dynamics

The following study defines a new handling factors proper to motorcycle. In steady cornering, the state variables are given by:

$$\phi = \frac{\dot\psi v_x}{g}, \quad \rho = \frac{\dot\psi}{v_x} = \frac{1}{R}, \quad a_y = \dot\psi v_x \tag{9}$$

The side slip relation can be expressed as a function of motorcycle intrinsic and dynamic variables from equations (1 and 2): $\alpha_f - \alpha_r = f_1(\phi, \delta, a_y, \varepsilon, m, l_f, l_r, C_{fi}, C_{ri})$, as well as from the kinematics equation (3): $\alpha_f - \alpha_r = f_2(\delta, R, \varepsilon, l_f, l_r)$. Now, replacing cornering forces (2) into (1), it follows:

$$\begin{bmatrix} \alpha_f \\ \alpha_r \end{bmatrix} = \begin{bmatrix} C_{f1} & C_{r1} \\ l_f C_{f1} & -l_r C_{r1} \end{bmatrix}^{-1} \left(\begin{bmatrix} m a_y \\ 0 \end{bmatrix} - \begin{bmatrix} C_{f2} & C_{r2} \\ l_f C_{f2} & -l_r C_{r2} \end{bmatrix} \begin{bmatrix} \gamma_f \\ \gamma_r \end{bmatrix} \right) \tag{10}$$

From the above equation:

$$\begin{cases} \alpha_f = \frac{(l_r m)}{(C_{f1} l_f + C_{f1} l_r)} a_y - \frac{C_{f2} l_r + C_{f2} l_f}{(C_{f1} l_f + C_{f1} l_r)} \gamma_f \\ \alpha_r = \frac{(l_f m)}{(C_{r1} l_f + C_{r1} l_r)} a_y - \frac{C_{r2} l_r + C_{r2} l_f}{(C_{r1} l_f + C_{r1} l_r)} \gamma_r \end{cases} \tag{11}$$

Replacing the camber angles ($\gamma_f = \phi + \delta \sin(\varepsilon)$, $\quad \gamma_r = \phi$) in equation (11), one gets side slip relation:

$$\begin{aligned} \alpha_f - \alpha_r &= \underbrace{\left(\frac{C_{r2} C_{f1} - C_{f2} C_{r1}}{C_{r1} C_{f1}}\right)}_{EG_2} \phi - \underbrace{\frac{C_{f2}}{C_{f1}} \sin(\varepsilon)}_{EG_3} \delta + \\ & \underbrace{\frac{(C_{r1} l_r - C_{f1} l_f)}{C_{f1} C_{r1}} \frac{m}{(l_f + l_r)}}_{EG_1} a_y \\ &= EG_1 a_y + EG_2 \phi - EG_3 \delta \end{aligned} \tag{12}$$

From the following kinematics equations:

$$\alpha_f = -\frac{v_y + l_f \dot\psi}{v_x} + \delta \cos(\varepsilon), \quad \alpha_r = -\frac{v_y - l_r \dot\psi}{v_x} \tag{13}$$

The side slip relation is also described as:

$$\begin{aligned} \alpha_f - \alpha_r &= -\frac{v_y + l_f \dot\psi}{v_x} + \cos(\varepsilon)\delta + \frac{v_y - l_r \dot\psi}{v_x} \\ &= -(l_f + l_r)\frac{\dot\psi}{v_x} + \cos(\varepsilon)\delta \\ &= -\frac{(l_f + l_r)}{R} + \cos(\varepsilon)\delta \end{aligned} \tag{14}$$

The self-steering behavior depends on the sideslip difference:

$$\begin{cases} \alpha_f - \alpha_r = EG_1 a_y + EG_2 \phi - EG_3 \delta \\ \alpha_f - \alpha_r = -\frac{(l_f + l_r)}{R} + \cos(\varepsilon)\delta \end{cases} \tag{15}$$

by identifying the above equations, one gets:

$$\begin{aligned} \delta &= \frac{(l_f + l_r)}{R(\cos(\varepsilon) + EG_3)} + a_y \frac{EG_1}{(\cos(\varepsilon) + EG_3)} + \phi \frac{EG_2}{(\cos(\varepsilon) + EG_3)} \\ &= \delta_A + \Delta\delta \end{aligned} \tag{16}$$

With

$$\delta_A = \frac{(l_f + l_r)}{R(\cos(\varepsilon) + EG_3)} \tag{17}$$

The steering angle δ_A resulting from equation (16), is called the neutral steering angle. The additional $\Delta\delta$ angle is caused by the motorcycle's dynamics.

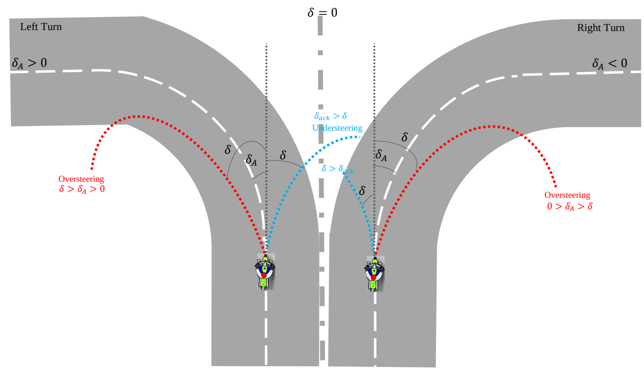


Fig. 3: Over and Under steering situation.

Now, in order to propose a detection algorithm for the over and under steer situations, we propose a risk function defined from the self steer behavior in equation (16). Therefore, the steering behavior can also be described as follows:

$$S_S = \frac{\delta - \delta_A}{a_y(1 + \frac{EG_2 \phi}{EG_1 a_y})} \frac{(\cos(\varepsilon) + EG_3)}{EG_1} \tag{18}$$

where S_S represents the Self-Steer Motorcycle Gradient. In the straight-line road, the lateral acceleration is small, and S_S values become very large. Thus we use the algebraic function sign(a_y) instead of a_y to avoid the detection of false alarms due to $S_S \to \infty$. Now, the expression of the steering behavior (18) is completely defined, a simple analysis of S_S makes it possible to characterize the steering behavior of the PTWv.

V. Neutral Path Detection Algorithm

Neutral Path Departure algorithm aims to help a rider in maintaining safe travel, where the goal is to detect an over or an understeer behavior compared with the neutral dynamics and to warn the rider of a lose of friction between the front and rear wheels. The NPD algorithm depends on a risk function S_S proper for a motorcycle, this index is required to detect the drift out from the neutral steady dynamics, the sign of the S_S signifies the understeer and oversteer behavior of the motorcycle in left and right turn. Then, the rider adjusts the steering angle, rider's posture and/or forward speed to recover the neutral trajectory without a controller. Moreover

Algorithm 1: `Neutral Path Departure (NPD)`

Input

$$Recovered \begin{cases} \delta_A,\ \delta,\ \phi,\ a_y \Rightarrow S_S,\ \overbrace{S_S}^{\cdot} \\ \zeta_1, \zeta_2 (\text{decision variable}) \\ \zeta_1 = \begin{cases} 1 & \text{Over steer alarm} \\ 0 & \text{Neutral steer} \\ -1 & \text{Under steer alarm} \end{cases} \\ \zeta_2 = \begin{cases} 1 & \text{Counter steering} \\ 0 & \text{No correction} \\ -1 & \text{Under steer correction} \end{cases} \end{cases} \quad (19)$$

if $(S_S = 0\ \&\ \overbrace{S_S}^{\cdot} = 0)$ **then**
  Neutral steer: $\zeta_1 = 0,\ \zeta_2 = 0$
if $(\delta_A > 0 \rightarrow$ *Left turn*$)$ **then**
  if $(S_S > 0)$ **then**
    if $(\overbrace{S_S}^{\cdot} \geq 0)$ **then**
      Over steer: $\zeta_1 = 1,\ \zeta_2 = 0$
    else
      Counter steer: $\zeta_1 = 1,\ \zeta_2 = 1$
  if $(S_S < 0)$ **then**
    if $(\overbrace{S_S}^{\cdot} \leq 0)$ **then**
      Under steer: $\zeta_1 = -1,\ \zeta_2 = 0$
    else
      Under steer correction: $\zeta_1 = -1,\ \zeta_2 = -1$
else
  $(\delta_A < 0 \rightarrow$ Right turn $)$
  if $(S_S > 0)$ **then**
    if $(\overbrace{S_S}^{\cdot} \geq 0)$ **then**
      Under steer: $\zeta_1 = -1,\ \zeta_2 = 0$
    else
      Under steer steer: $\zeta_1 = -1,\ \zeta_2 = 1$
  if $(S_S < 0)$ **then**
    if $(\overbrace{S_S}^{\cdot} \leq 0)$ **then**
      Over steer: $\zeta_1 = 1,\ \zeta_2 = 0$
    else
      Counter steering: $\zeta_1 = 1,\ \zeta_2 = 1$

to improve the confidence of the results, the analysis of the derivative $\overbrace{S_S}^{\cdot}$ is very interesting to detect the changing in the steering action if any correction is taken by the rider. This consideration is made to avoid false alarms when the driver is already correcting his maneuver. Therefore, the sign of S_S and derivative $\overbrace{S_S}^{\cdot}$ is used to define two decision variables (ζ_1, ζ_2). The process of providing a neutral departure warning is summarized in the following algorithm (1).

The following cases are considered:

1) $S_S \approx \mathbf{0}$ ($\overbrace{S_S}^{\cdot} = 0$): The motorcycle is neutral-steering ($\alpha_f = \alpha_r$). In this case, the steering powers are equal in the front and rear wheels. When cornering, no change in steer angle is required to maintain the correct radius when the speed varies.

2) **Right turn,** $\delta_A < 0$ (clockwise):

   -$S_S < 0$ ($\overbrace{S_S}^{\cdot} < 0$), when motorcycle steers towards the right: this reflects over-steering behavior. The actual cornering radius is smaller than the neutral one.

   -$S_S < 0$ ($\overbrace{S_S}^{\cdot} > 0$) reflects counter-steering behavior (correction of the over steer)

   -$S_S > 0$ ($\overbrace{S_S}^{\cdot} > 0$) reflects under-steering behavior. It is necessary to steer the steering angle in the clockwise sense to stay on the right radius.

   -$S_S > 0$ ($\overbrace{S_S}^{\cdot} < 0$) correction of the under-steer.

3) **Left turn,** $\delta_A > 0$ (anticlockwise):

   -$S_S > 0$ ($\overbrace{S_S}^{\cdot} > 0$) reflects over-steering behavior, the actual cornering radius is smaller than the neutral one.

   -$S_S > 0$ ($\overbrace{S_S}^{\cdot} < 0$) counter-steering behaviour.

   -$S_S < 0$ ($\overbrace{S_S}^{\cdot} < 0$) reflects under-steering behavior, the rider has to steer towards the left side or tilt to increase roll angle to reach the correct radius.

   -$S_S < 0$ ($\overbrace{S_S}^{\cdot} > 0$) under-steer correction.

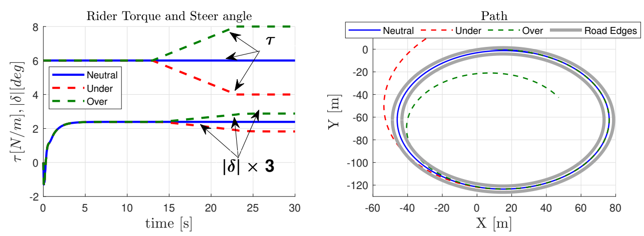
Remark 1: Moreover, a hysteresis function $Hys(S_S)$ or a memory block can be used to avoid multiple switching. This block holds the value of (S_S) when the algorithm switches to test the rider correction by $\overbrace{S_S}^{\cdot}$. The use of this block can minimize unwanted behavior when switching between the algorithm loops.

VI. Simulation

The proposed approach is evaluated by co-simulation with Bikesim© software under different riding maneuver . A PTWv model is chosen from the dataset *Big Sport Baseline* 8 bodies and default parameters. Note that BikeSim offers several driver models with different control strategies. In our case, it is an open-loop control on the steering torque, more suitable to simulate steering behavior.

A. Scenario 1

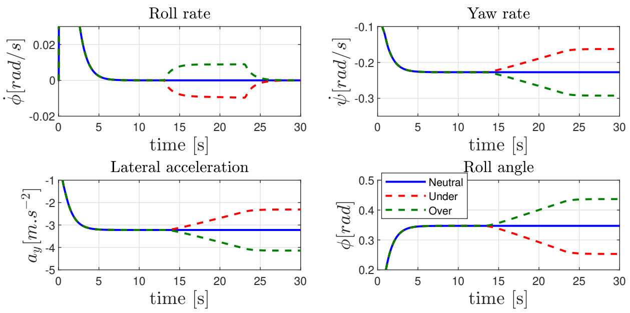
In this subsection, it is proposed to validate the risk function selected for the detection of under and oversteer on the handlebar of a PTWv.



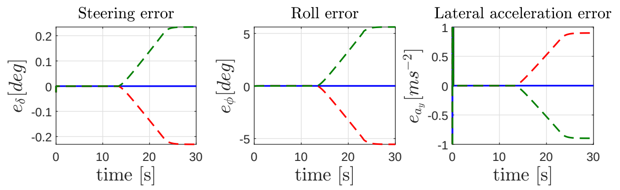
(a) Rider torque and steering angle. (b) Neutral Path Departure.

Fig. 4: Steering behavior.

To do this, we have simulated a circular trajectory with a constant radius of 61.4 meters for three different riding scenarios, conducted for different steering torques. Figure 4a shows the steering torques applied to the PTWv. On the same figure, we can also see the steering angle corresponding to a scale factor of 3.



(a) Steady Outputs.



(b) State errors.

Fig. 5: Steady Steering behavior.

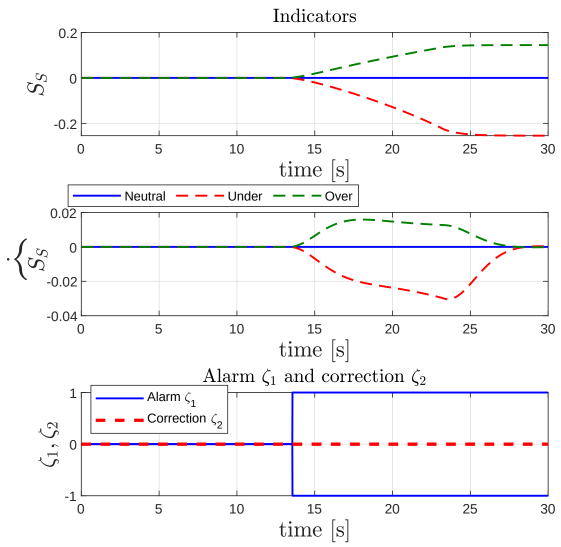


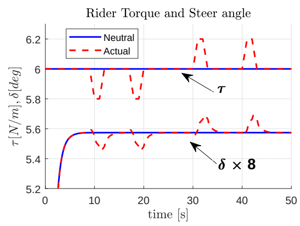
Fig. 6: Alarm and corrections.

The input steering angle used in this tests is defined such that the wheel lift-off occurs at 13 *sec*, whereas in neutral test no wheel lift-off occurs. For the neutral scenario, the torque applied to the handlebar is $\tau = 6$ N/m. When a PTWv is oversteers, the torque applied by the rider on the handlebars is too large compared to the geometry of the turn. PTWv tends to turn inward of the curve. Conversely, when understeers the applied torque is lower than the neutral one, the PTWv tends to increase the trajectory to the road exit. The vertical dashed line refers to the time from which the steering behavior is significantly affected by the over or understeer phenomenon. Figure 4b shows the different trajectories of the PTWv during the constant turn. In blue, the motorcycle trajectory for a neutral turning. In which the motorcycle path is parallel to that of the road edges. While in red, we show the trajectories of over turning, respectively in black under turning. Figures 5a and 5b show the consequences of the over and under-steering phenomena on the steady state variables for the three cases. It can be seen that the slightest action on the handlebars when cornering has significant consequences on the complete dynamics of the PTWv ($\dot{\psi}$, a_y, ϕ, etc).

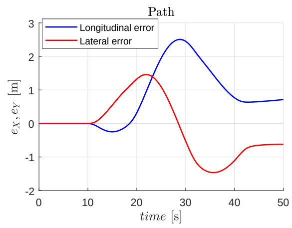
Figure 6 shows the steering index calculated from equation (18) for the three scenarios. It can be noted that the alarm and correction signals remain at zero when no wheel lift-off occurs. Then, these signals detect the motorcycle is drifting out: $\zeta_1 = -1$ understeer or $\zeta_1 = 1$ oversteer. In these scenarios, no correction is taken by the ride $\zeta_2 = 0$. The S_S shows good efficiency to early detect the steering errors from the neutral path. This advantage is very interesting since the neutral path departure has to be quickly avoided.

B. Scenario 2

This part is devoted to evaluating the neutral path departure warning algorithm in noisy case.



(a) Rider torque and steering angle.



(b) Trajectory errors Departure.

Fig. 7: Steering behavior.

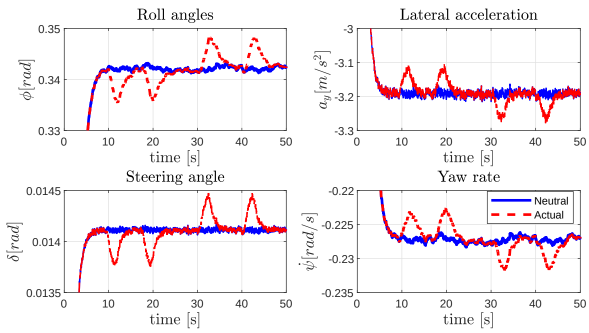


Fig. 8: Noisy outputs.

During this scenario, the motorcycle is driven to perfectly follow the neutral path road until 9 *sec*. Then, the wheel drifts out will occurs first as understeer until 30 *sec* including a rider correction, then as oversteer until 50 *s* with some adjustment from the rider, seeking to catch the neutral line. Figure 7a shows the steering torques applied by the rider and the corresponding steering angle.

Figure 7b shows the lateral and longitudinal errors. While, figures 8 shows the consequences of the neutral path departure on the motorcycle states.

Figure 9 illustrates the relevant indicators proposed for the characterization of steering behavior. The risk indicator S_S is computed here from the noisy measurement of the actual steering, lateral acceleration, and roll angle of the PTWv. Moreover, the analysis of $\dot{S_S}$ is very interesting to characterize the changing in the rider steering action. Note that the raw data (unfiltered) is difficult to exploit because of the noise amplified by the derivation. This is why the S_S have been filtered with a simple first-order Butterworth filter. Therefore, we prefer to use the S_S and derivative $\dot{S_S}$ to define two levels of risk: the first level detects the over/understeering and the second level detects if any correction is taking by rider.

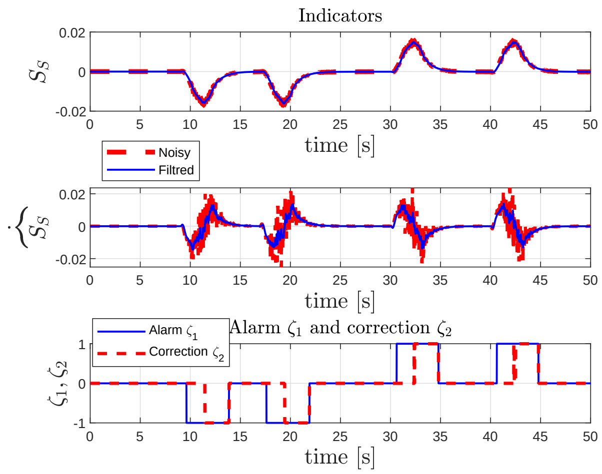


Fig. 9: Risk functions, alarm and corrections.

One can see in figures (9) that the used steering risk indicators and the alarm signal given by the detection algorithm are very interesting to detect the rider errors and the neutral path drift out even with noisy outputs. It can be noted that the alarm signal remains at zero when no neutral path departure is detected $S_S = 0$. Then the alarm signals take the correct values depending on which direction the motorcycle is drifting out $\zeta_1 = -1$ understeer or $\zeta_1 = 1$ oversteer. Also, one can see the alarm corresponding to rider correction ζ_2 which means that the rider is trying to bring back the PTWv to the neutral path.

C. Result discussion

Finally, simulation results from the BikeSim software have shown that the synthesis of the detection algorithm-based risk function has undeniable potential to characterize the steering behavior. Indeed, it is much informative since it is based on the analysis of two parameters S_S and $\dot{S_S}$. These results highlight the effectiveness of the detection algorithm to detect in an early stage the steering deviation. This advantage is very interesting since the road departure has to be earlier avoided. Although the results are really encouraging, the idea presented in this paper deserves to be deepened. Indeed, for the validation of the approach, we are limited to the co-simulation case and improvements should be made to avoid bad detection in case of using estimated data instead of measurement outputs in some situations.

VII. Conclusion

In this paper, we proposed a synthesis of a new risk function for the characterization of rider steering behavior. While conventional approaches use kinematics or geometric functions, to detect the intersection point on the road edges. We propose here a new neutral-path departure algorithm to overcome rider steering errors when the drifts out of the neutral lane. The motorcycle tendency to under or oversteer in steady turning is also analyzed, based on handling conditions. Besides, the NPD algorithm is designed based on the S_S and $\dot{S_S}$. Then, the detection method was tested in co-simulation using BikeSim© under different steering maneuvers to highlight the effectiveness of the proposed algorithm to detect in an early stage the over/under steering deviation from the neutral path, to improve motorcycle handling and correct the unsafe maneuver. Indeed, the proposed solution is very economical, limiting the amount of energy needed since it only requires a conventional IMU and a steering encoder without the need on the state observer.

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