Bicycle Simulator Improvement and Validation

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ABSTRACT In this paper, we present the new features implemented on the bicycle simulator developed by the Perceptions, Interactions, Behaviors and Simulations Lab for road and street users (PICS-L) at Gustave Eiffel University. The added features were deemed necessary to study road-bicycle interactions. We equipped the simulator platform with: three actuators to render the road profile vibrations, an asphalt specimen attached to the rear tire to render the road adhesion, and a new virtual reality environment to render a part of the city of Vanves in France. Simultaneously, we developed a mathematical model with 6 degrees of freedom including the three rotational angles (Yaw, Pitch and Roll) and their influence on vertical, lateral and longitudinal modeling. In order to validate the simulator and the developed model physically and subjectively, we conducted an experiment involving 36 participants who rode the simulator for around 600 meters with full control on the handlebar, pedals and brakes. The improved simulator/mathematical model will be employed to further study bicycle dynamics, cyclist behavior and the interaction with the infrastructure and other road users.

INDEX TERMS Bicycle modeling, bicycle simulator, experimental validation, road characteristics, simulation.

I. INTRODUCTION

This paper is an extended version of our previous work on modeling and simulation of bicycle dynamics published in [1] and on subjective validity of bicycle simulators published in [2]. Hereinafter, we present more details on the recent developments of the simulator and the underlying mathematical model, as well as its physical and subjective experimental validation.

Experimentation in real environment is not always the appropriate means, due to its costs, bias related to uncontrolled variables and risks facing cyclists [3]–[7]. On the contrary, simulators allow to detect the behavior of cyclists and other road users in various riding situations, while controlling the variables at play and avoiding the risks associated with a real environment [8]. However, simulator studies are valid insofar as: 1) providing results that can be generalized to real-world situations; 2) minimizing the occurrence of unwanted symptoms that may result from motion or exposure to the virtual environment (i.e. simulator sickness).

In order to model a vehicle (including a bicycle), researchers deployed the theoretical physical approach, such as Lagrange, Euler equations or the detailed nonlinear Whipple scientific description [9], [10]; for example, [11] used the Linear–quadratic regulator (LQR algorithm) to analyze the bicycle mathematical model, this method is considered accurate but time-consuming at the same time. For a straightforward and time efficient modeling, the classical single-track model could be an alternative [12].

Overall, bicycle simulators are designed to serve multiple purposes, such as training, sport, immersion in virtual reality, bicycle-dynamical modeling, and evaluation of cyclists’ performance and behavior [13]–[17]. In PICS-L bicycle simulator, the single-track model was used to produce more convenient and accurate results that suit our research goals [18]–[20]. The simulator was developed to study the following environmental determinants of cyclists’ behavior:

1) The environmental elements to which cyclists adapt their behavior (i.e. speed, safety gap, steering, etc.);
2) How cyclists adjust their riding practices as they interact with other road users;
3) How cyclists anticipate risks in hazardous riding situations, and what strategies, equipment or behaviours they employ to cope with those risks;
Any road accident may result from the vehicle-user-infrastructure interaction [21]–[23]. However, few studies have tackled the complex interaction between the three factors. The goal of this study was two-fold: to develop the mathematical model of the bicycle simulator dynamics, and to improve the simulator platform with the addition of vibration actuators to render the haptic feedback of a road profile (which gives more realistic feeling of cycling), and an asphalt specimen attached to the rear wheel to render road adhesion (which plays a key role when accelerating and braking). Furthermore, this will help to study the interaction between bicycles and road surface characteristics and geometries and their effect on cyclists’ behavior. The long-term objective of this research is to improve cycling safety and foster the peaceful coexistence of cyclists and other road users in urban space; by taking into consideration the behavioral aspects in terms of bicycle control and similarity of behavior exhibited in real situations. The paper is structured as follows: the first section gives a brief overview of different bicycle models; the second part is devoted to bicycle modeling; the third part describes the experimentation and discusses the validation results: physically and subjectively; and we finalize with the conclusion and future work in the fourth part.

II. BICYCLE MODELING

The bicycle mathematical model (designed by using Simulink-Matlab from Mathworks) aims to reproduce the dynamics of a bicycle (in simulation or in a real environment). The simulator system allows to log the simulation data and dynamics of a bicycle (in simulation or in a real environment). Simulink-Matlab from Mathworks) aims to reproduce the mathematical model of the bicycle simulator dynamics, and to improve the simulator platform with the addition of vibration actuators to render the haptic feedback of a road profile (which gives more realistic feeling of cycling), and an asphalt specimen attached to the rear wheel to render road adhesion (which plays a key role when accelerating and braking). Furthermore, this will help to study the interaction between bicycles and road surface characteristics and geometries and their effect on cyclists’ behavior. The long-term objective of this research is to improve cycling safety and foster the peaceful coexistence of cyclists and other road users in urban space; by taking into consideration the behavioral aspects in terms of bicycle control and similarity of behavior exhibited in real situations. The paper is structured as follows: the first section gives a brief overview of different bicycle models; the second part is devoted to bicycle modeling; the third part describes the experimentation and discusses the validation results: physically and subjectively; and we finalize with the conclusion and future work in the fourth part.

A. VERTICAL MODELING

The geometrical and mass parameters of the bicycle are divided as follows: the front part includes the steering axis, the front fork, the front wheel and a fraction of the cyclist mass; and the rear part includes the frame, the rear wheel and the other fraction of the cyclist body mass. The reactions of total mass are modelled by springs representing the tires stiffness \((k_F \text{ and } k_R)\) and damping coefficients \((B_F \text{ and } B_R)\). The bicycle has no suspension system. The fractions of the bicycle-rider-bicycle-rider-system mass are \(m_F\) and \(m_R\).

B. LATERAL MODELING

In order to calculate the lateral forces, it is necessary to know the tire slip, the side slip angle and the road adhesion coefficient. The tire side slip angle for both wheels were calculated using (5) and (6) then the lateral forces are calculated in (9) and (10)

\[
\alpha_F = -\dot{\beta} + \delta_v - \frac{l_F \dot{\psi}}{v_{COG}} \tag{5}
\]

\[
\alpha_R = -\dot{\beta} + \frac{l_R \dot{\psi}}{v_{COG}} \tag{6}
\]
where $\alpha_F$ and $\alpha_R$ are the side slip angles for the front and rear tires respectively, $\beta$ is the velocity of the side slip angle at the COG, $\delta_w$ is the steering angle of the handlebar, $l_f$ and $l_r$ are distances from COG to front and rear axles, $v_{COG}$ is the COG velocity, $\dot{\psi}$ is the yaw rate calculated using (7):

$$\dot{\psi} = \frac{V}{R_c}$$

$V$ is the bicycle velocity and $R_c$ is the radius of curvature calculated using (8):

$$R = \frac{l_f + l_r}{\sin \delta_i}$$

where $\delta_i$ is the steering angle. The lateral forces for both front and rear wheel (considering the lateral slope of the road) are obtained using (9) and (10):

$$F_yF = \alpha_F C_y + mF g \sin \phi$$
$$F_yR = \alpha_R C_y + mR g \sin \phi$$

where $F_yF$ and $F_yR$ are the lateral forces of the front and rear wheel respectively, $C_y$ is the lateral stiffness and $\phi$ is the roll angle. The lateral acceleration of the bicycle simulator $(a_y)$ is estimated using (11):

$$a_y = \frac{F_yF + F_yR}{m}$$

where $m$ is the total mass of the bicycle-rider system. The double integration of the acceleration gives the lateral displacement.

**C. LONGITUDINAL MODELING**

The longitudinal frictional forces of front and rear wheels can be calculated from the adhesion coefficient using (12) and (13). This provides the frictional forces in the direction of the wheel ground contact velocity.

$$F_{xF} = \mu F_c \cos \delta + F_f + F_{aero}$$
$$F_{xR} = \mu F_c \cos \delta + F_f + F_{aero}$$

where $F_{xF}$ and $F_{xR}$ are the longitudinal forces for the front and rear wheel respectively, $\mu$ is the adhesion coefficient and $F_c$ and $F_f$ are the vertical forces applied on the front and rear wheels. $F_{xF}$ and $F_{xR}$ are the forces caused by the longitudinal slope of the road calculated using (14) and (15):

$$F_{xF} = m_f g \sin \theta$$
$$F_{xR} = m_r g \sin \theta$$

where $\theta$ is the road longitudinal slope.

The aerodynamic force resistance ($F_{aero}$) is calculated using (16):

$$F_{aero} = 0.5 C_a S \rho v_x^2$$

where $C_a$ is the coefficient of aerodynamic resistance given by the bicycle manufacturer, $\rho$ is the air density in kg/m$^3$, $S$ is the frontal surface area of the bicycle and the rider in m$^2$ and $v_x$ is the longitudinal velocity.

**D. ROTATIONAL MODELING**

1) **YAW ROTATION**

Yaw rotation modeling can be obtained by using the lateral forces as described in (17):

$$\ddot{\psi} = \frac{F_{xF} l_f - F_{xR} l_r}{I_{zz}}$$

where $\ddot{\psi}$ is the yaw angle acceleration, $F_{xF}$ and $F_{xR}$ are the lateral forces of the front and rear wheel and $I_{zz}$ is the moment of inertia around z-axis. Yaw rate $\dot{\psi}$ was also calculated using (7). The yaw angle value is calculated by integrating the yaw rate.

2) **ROLL ROTATION**

The roll angle about the bicycle’s x-axis ($\phi$) can be calculated using the speed and radius of curvature as in (18):

$$\phi = \arctan\left(\frac{V^2}{g R_c}\right)$$

The roll acceleration ($\ddot{\phi}$) is calculated using the mass and rotation matrices [26] as in (19):

$$\ddot{\phi} = r_{31} \phi + r_{32} \delta + r_{34} v_x \dot{\psi} + r_{36} v_z \dot{\delta} - (m_{13} v_y + m_{23} \dot{\psi} + m_{34} \dot{\delta})/m_3$$

with

$$r_{31} = (m_f j + m_r h) g$$

where $j$ and $h$ are the vertical component of the center of gravity for the front and rear part of the bicycle respectively, and $g$ is the gravitational acceleration.

$$r_{32} = m_f e g - \eta F_{cF}$$

where $e$ is the perpendicular distance between the center of gravity of the front part and the fork and $\eta$ is the bicycle trail.

$$r_{34} = -m_f j - m_r h - \frac{I_{zRF}}{R_f} - \frac{I_{zRR}}{R_r}$$

where $I_{zRF}$ and $I_{zRR}$ are the moments of inertia around the y-axis for the front and rear wheel respectively, $R_f$ and $R_r$ are the radii of front and rear wheel.

$$r_{36} = -\frac{I_{zRF}}{R_f \cos \epsilon}$$

where $\epsilon$ is the bicycle caster angle (i.e. the angular displacement of the steering axis from the vertical axis of a steered wheel).

$$m_{13} = m_f j + m_r h$$
$$m_{23} = m_f j k - C_{cGR} + (I_{zGF} - I_{zGF}) \sin \epsilon \cos \epsilon$$
$$m_{33} = m_f j^2 + m_r h^2 + I_{zGR} + I_{zGF} \cos^2 \epsilon + I_{zGF} \sin^2 \epsilon$$
$$m_{34} = m_f e j + I_{zGF} \sin \epsilon$$

The roll rate is calculated by integrating the roll acceleration.
3) PITCH ROTATION
The pitch angle acceleration of the bicycle body $\ddot{\theta}$ can be calculated depending on the stiffness of the tires as in (28):

$$\ddot{\theta} = -k_R l_r z_R + k_F l_f z_F + (k_R l_r - k_F l_f)\dot{z}$$
$$- (k_R l_r^2 - k_F l_f^2) \sin \theta / I_{yy}$$

(28)

where $I_{yy}$ is the moment of inertia around y-axis. The numerical values of the parameters are given in Appendix A.

III. EXPERIMENTAL VALIDATION

A. EXPERIMENTAL SETUP
The PICS-L bicycle simulator was built by placing a real bicycle on a static platform with one degree of freedom (the steering angle). In order to maximize the immersion in the virtual reality, the simulator consists of several components (Fig. 3) which are:

1) A fan, placed in front of the bicycle, reproduces the airflow felt by cyclists in real situations. The fan speed is proportional to the rear wheel’s speed.

2) Three actuators, installed on the platform, simulate the vibrations caused by the unevenness of the road surface. The acceleration is limited to $+/- 1$ g in order to keep the platform stable, the amplitude is limited to $+/- 2.5$ mm (up to $+/- 5$ mm) when the frequency is 10 Hz (up to 20 Hz).

3) An incremental encoder, attached to the fork, provides haptic force feedback to the handlebars and measures the steering angle and velocity.

4) A passive mechanical lateral suspension system allows participants to slightly tilt the bicycle when turning left or right.

5) A flywheel, attached to the rear wheel, simulates an inertia equal to 60 kg mass in actual cycling.

6) An incremental encoder calculates the speed of the rear wheel and increases the inertia up to 85 kg.

7) A cylindrical asphalt specimen in contact with the rear tire (installed recently to replace a plastic cylinder) simulates road adhesion. The specimen is made of hot mixed asphalt concrete. It is 10 cm in diameter and 12 cm in height, the specimen is penetrated in the center to allow a shaft of 2 cm diameter to pass along its axis for fixation (see Fig. 4).

8) Five visual displays installed in front of the bicycle provide a visual angle of 225 degrees horizontally and 55 degrees vertically. A supplementary display device is placed behind the left shoulder of the cyclist for the rear visualisation of the road.

B. PARTICIPANTS
36 participants (18 male; mean age = 28, SD = 3.76 and 18 females; mean age = 25.25, SD = 2.06) participated in this experiment. All declared normal or corrected-to-normal vision. The mean cycling experience of the participants was 14.5 years. The average number of cycling kilometers per month was 20.6 km. Fig. 5 shows one of the participants during the familiarization phase of the experiment; the bus-bicycle shared lane, and the traffic on both sides.

C. EXPERIMENT SCENARIO
The experiment took place in a simulated urban environment of Vanves (a city situated 7.5 km south-west of Paris). The experiment’s itinerary is shown in Fig. 6. The road consists of an on-street bicycle lane of 1.5 m in width with no separation between the cyclists and the motorized vehicles. Moderate traffic was generated in the same and opposite directions of the cyclist, and buses passed the cyclist from time to time. The participants were asked to ride the simulator for around 5 minutes to familiarize themselves with it (the virtual environment of the familiarization phase was different from the one used for this experiment). After the familiarization
phase, we asked them to perform a simple task consisting of riding the bicycle for a short promenade (650 m) following the directional arrows painted on the bicycle lane until they reached the stop sign. The road geometry included two curves and three intersections. The cyclists were asked to turn right at the third intersection. The participants had full control over the different features of the simulator such as: handlebar, pedals, gears and brakes. The experiment lasted around 10 minutes, a duration which we deemed sufficient to test all the features of the simulator and to collect enough data for the post-analysis without exhausting the participants.

At the end of the experiment, the participants answered three questionnaires: The first one to collect general information about the participants and their cycling experience in real life and using the simulator; the second one was the Simulator Sickness Questionnaire (SSQ) [27]: with 16 questions to evaluate the occurrence of different symptoms during the experiment using a four-level scale (None, Slight, Moderate and Severe); and the third one was the NASA Task Load Index (TLX) [28], to evaluate the overall workload of the cycling task and the importance of each of the 6 work-load-factors under investigation, the participants evaluated each factor on a scale of 10 (1 for low and 10 for high, except for the performance where 1 for good and 10 for poor), then, it was converted to a 100-scale by multiplying by 10. The questionnaires were available both in English and French, as some participants only speak French.

The trajectory and speed profile of one of the participants are shown in Fig. 7 and 8.

D. PHYSICAL VALIDITY

Several tests and scenarios were conducted at various speeds with the bicycle simulator. Sample results of the vertical displacement, side slip angle, lateral and longitudinal forces and rotational angles are presented in this section. The parameters of dynamic model of the bicycle were set to values from the literature [29], [30]. The stiffness and damping coefficients were taken from [31].

1) VERTICAL DISPLACEMENT AND FORCE

The input for the longitudinal road profile was measured along an asphalt driving lane in a previous experiment conducted by IFSTTAR (see Fig. 9). The signal had a frequency of 1 kHz and a maximum amplitude of about ±2.0 cm. A zoom on the time interval [20, 25] s shows the input signal in details. In order to reproduce the unevenness of the road surface we used a sinusoidal signal with random pulses as an input for the vibration actuators shown in Fig. 10.

Fig. 11, 12 and 13 show that the vertical displacement, the vertical acceleration and the vertical force of the front and rear wheels are influenced by the amplitude of the road profile (Fig. 9); this becomes clearer at the peaks and lows caused by the unevenness of the road profile between 22 and 23 s. We also notice that the vertical acceleration of the rear wheel is bigger than the front wheel due to the mass distribution (i.e. the rear wheel carries more weight than the front wheel).
2) SIDE SLIP ANGLE AND LATERAL FORCE

Fig. 14 shows the steering angle and velocity measured and logged during one test using the incremental encoder. Fig. 15 shows the side slip angle of the front and rear wheels calculated using (5) and (6). The simulation results show the direct impact of the steering angle on the calculation of the side slip angle which becomes noticeable at the peak value of 120 s.

Fig. 16 shows the lateral position estimation of the bicycle simulator. The black line results from the former model where the lateral position was estimated depending on the coordinate system of the virtual reality, whereas the red line results from the new model where the lateral position was calculated using (11). The new model shows higher accuracy. This can be observed through the impact of the steering angle and velocity; especially around 70 and 120 s, where high values in steering angle result in substantial changes in the lateral position.

Fig. 17 shows the lateral force of the front and rear wheels calculated using (9) and (10). The graph shows that the increase of the side slip angle causes an increase in the lateral force, this is particularly noticeable around 70, 100 and 120 s.

3) LONGITUDINAL FORCE

During the simulation we used three different values of road adhesion coefficient to represent different surfaces and...
weather conditions. The longitudinal force shown in Fig. 19, which was calculated based on the adhesion coefficient in Fig. 18, shows the influence of different adhesion coefficients. For example, when the road surface is dry ($\mu = 0.8$) the longitudinal friction force peaks, whereas a wet surface ($\mu = 0.2$) results in a low longitudinal friction force.
4) ROLL ANGLE
Fig. 20 shows the simulation output for the roll angle. As noticed, the roll angle runs similarly to the steering angle as the increase of the steering angle implies a decrease of the radius of curvature. This effect of steering angle and radius of curvature is also noticed in roll speed and acceleration shown in Fig. 21 and 22. In the former model, the roll angle acceleration was calculated using the second derivative of the roll angle, whereas the new model calculates the roll angle acceleration using (19). Fig. 22 compare the outputs of the former and new models, it shows the improvement brought by the new model regarding accuracy and noise removal.

5) YAW ANGLE
Fig. 23 shows the simulation output of the yaw angle, we notice the direct effect of the lateral position (Fig. 11) on yaw angle calculation. Yaw rate and acceleration are shown in Fig. 24 and 25. In the former model, yaw angle acceleration was calculated using the second derivative of the yaw angle, whereas the new model calculates the Yaw acceleration using (17). By comparing the results of the old and the new model (Fig. 25) we notice the improvement brought by the new model regarding accuracy and noise removal.

6) PITCH ANGLE
The simulation output of the pitch rotation angle, rate and acceleration are shown in Fig. 26, 27 and 28. The small values could be explained by cycling on a flat surface which has minor impact on the pitch angle. An increase of the pitch angle could be noticed in acceleration and breaking phases. By comparing results between the previous and the new model (Fig. 28) we see the advantages of the new model regarding accuracy and noise removal.

E. SUBJECTIVE VALIDITY
The analysis of the first questionnaire shows that 7 of the participants had participated in a previous experiment using the same bicycle simulator before the recent improvement [1]. 8 of them declared sensitivity to motion sickness; 5 of them when reading during travelling. On evaluating the realism of the simulator (compared to riding a real bicycle) the
participants rating ranges between 3 and 9 on scale of 10 (mean = 6.74, SD = 1.57). This shows an improvement of the simulator compared to a previous experiment, where the participants evaluated the simulator with 6.1/10 [2]. The physical feeling of cycling, the design of the virtual road, traffic generation and other sensory cues, such as wind and the sound of the passing traffic were mentioned as the most realistic aspects of the simulator. However, some of the participants mentioned lacking the effect of the body posture when turning. This is because turning in the virtual reality is only affected by the steering angle and the body posture has no effect. The complete answers to the first questionnaire are shown in Appendix B.

Table 1 summarizes the results of NASA TLX questionnaire for the 36 participants. The first column shows the scales under assessment, the second column represents the average weight of each scale according to the personal opinion of each participant. This was calculated by answering 15 questions in which the scorer chose between two scales according to their importance. The weight of each scale is the number of times it was chosen. The third column is the average raw rating taken from the TLX questionnaire; and the last column represents the adjusted weighting, which is the multiplication of the weight and raw rating of each factor. The raw rating results show that the simulator requires intermediate mental/physical/temporal demand and effort.
TABLE 1. Weighted rating of TLX questionnaire. The overall workload (OW) = mean of weighted ratings.

| Scale title       | Weight | Raw Rating | Adjusted rating |
|-------------------|--------|------------|-----------------|
| Mental Demand     | 3.13   | 45.56      | 142.61          |
| Physical Demand   | 2.35   | 45.28      | 106.30          |
| Temporal Demand   | 2.26   | 40.83      | 92.32           |
| Performance       | 3.35   | 22.50      | 75.33           |
| Effort            | 2.17   | 44.44      | 96.62           |
| Frustration       | 1.74   | 24.17      | 42.03           |
| Overall workload  | 37.13  | 92.53      |                 |

FIGURE 29. Nasa Task Load Index analysis results: Weighted work load score. The width of each column represents the importance weight of each factor.

FIGURE 30. Frequency distribution of total sickness scores (N = 36).

FIGURE 31. Mean scores observed in each item of the simulator sickness questionnaire. The O, D and N letters following the name of each item indicate in which class(es) of symptoms the corresponding item was involved: O corresponds to Oculomotor discomfort, D to Disorientation and N to Nausea.

FIGURE 32. Mean scores observed in each item of the simulator sickness questionnaire during the experiment. (a) Men (blue area) and women (red area). The O, D and N letters following the name of each item indicate in which class(es) of symptoms the corresponding item was involved: O corresponds to Oculomotor discomfort, D to Disorientation and N to Nausea.

This is explained by the effort and concentration required when riding any bicycle and interacting with traffic since it is an active transport mode.

Fig. 29 compares the weighted average of each workload scale. It can be seen that the performance factor received a relatively low rating but a high importance, whereas the frustration factor received an intermediate rating but a low importance (meaning that the task was simple and easy to accomplish), so that both factors contribute in the similar amounts to the overall workload.

The analysis of the simulator sickness questionnaire listed in Table 2 shows that the average total severity for all
TABLE 4. The dynamical and mechanical parameters of the Bicycle simulator used during the simulation.

| Parameter                              | Symbol | Unit | Value |
|----------------------------------------|--------|------|-------|
| Wheelbase                              | w      | m    | 1.101 |
| Mass of bicycle + rider                | m      | kg   | 85    |
| Center of gravity (bicycle+ rider)     | COG    | m    | x = 0.291, y = -1.09 |
| Distance from COG to the center of rear wheel | l_r    | m    | 0.293 |
| Distance from COG to the center of front wheel | l_f    | m    | 0.808 |
| the horizontal distance between G_f and G_r | K      | m    | 0.614 |
| the frontal surface for the bike and the cyclist body | S      | m²  | 0.4   |
| coefficient of aerodynamic resistance  | C_a   | %    | 0.824 |
| Steer Axis tilt (caster angle)         | e      | rad  | 0.367 |
| trail                                  | c      | m    | 0.083 |
| mass of the front part of the bike/rider | m_f  | kg   | 23    |
| Vertical stiffness                     | k      | N/m  | 108000 |
| Damping ratio                          | B      | N.s/m| 5448  |
| Moment of inertia around x             | I_x, f | kg.m² | 0.387 |
| Moment of inertia around z             | I_z, f | kg.m³ | 0.167 |
| Mass of the rear part of the bike/rider | m_R  | kg   | 62    |
| Moment of inertia around x             | I_x, R | kg.m² | 11.96 |
| Moment of inertia around z             | I_z, R | kg.m³ | 3.105 |
| Wheel radii                            | r      | m    | 0.35  |
| Front tire lateral stiffness           | C_y   | N/m  | 490   |
| front wheel moment of inertia around y axis | I_P_y | kg.m³ | 0.144 |

Fig. 33 shows that participants with corrected vision experienced higher symptoms in general discomfort and fatigue, whereas normal vision participants experienced more eye strain and difficulty focusing.

IV. CONCLUSION AND FUTURE WORK

In this paper, we proposed an original mathematical model of bicycle dynamics which was experimentally validated on an immersive bicycle simulator at various speeds and different cycling maneuvers. The developed model deals with 6 degrees of freedom (longitudinal, lateral, vertical, Yaw, Pitch and Roll). The main advantages of the model are its simplicity, compatibility with the bicycle simulator, and its ability to be applied to a real bicycle.

The inputs of the model, such as steering angle, pedaling and braking were measured and logged in real time. Their influence on vertical, lateral and longitudinal forces, velocities and displacements were observed. The comparison between the previous mathematical model and the model discussed in this paper shows that the proposed model produces more accurate estimations. Improvements were noticed in the following areas: the compatibility of the lateral position with the trajectory and yaw angle, the noise removal when calculating yaw, pitch and roll accelerations, the impact of the unevenness of the road profile on the vertical displacement and force, the steering angle effect on the side slip angle, lateral displacement and yaw, and the effect of road adhesion on the longitudinal force.

The analysis of the simulator sickness questionnaire shows a drop in the severity of the simulator (TS = 14.65) compared to the old experiment (TS = 32.54). This could be explained by using more realistic virtual reality which affected (alongside the installment of the actuators and the asphalt specimen)
TABLE 5. Participants’ responses to the general questionnaire about their cycling experience.

| Participant Number | Age | Gender | Do you wear glasses? | Do you wear lenses? | Cycling per month (km) | Cycling experience (years) | Previous experiment on a bicycle simulator | motion sickness symptoms |
|--------------------|-----|--------|----------------------|---------------------|------------------------|----------------------------|------------------------------------------|-------------------------|
| 1                  | 25  | Female | No                   | No                  | 20                     | 20                        | No                        | No                      | -                      |
| 2                  | 26  | Female | No                   | No                  | 0                      | 18                        | Yes                       | No                      | -                      |
| 3                  | 28  | Female | No                   | No                  | 0                      | 23                        | Yes                       | No                      | -                      |
| 4                  | 26  | Male   | No                   | No                  | 5                      | 20                        | Yes                       | No                      | -                      |
| 5                  | 22  | Male   | No                   | No                  | 0                      | 10                        | No                        | No                      | -                      |
| 6                  | 40  | Male   | No                   | No                  | 40                     | 20                        | No                        | No                      | -                      |
| 7                  | 22  | Male   | No                   | No                  | 40                     | 15                        | No                        | Yes (nausea, in bus)     | -                      |
| 8                  | 25  | Female | Yes                  | No                  | 0                      | 2                         | Yes                       | Yes (car motion sickness)| -                      |
| 9                  | 21  | Male   | No                   | No                  | 0                      | 2                         | No                        | Yes (Stomach sickness)   | -                      |
| 10                 | 23  | Male   | No                   | No                  | 400                    | 16                        | No                        | No                      | -                      |
| 11                 | 23  | Male   | Yes                  | No                  | 0                      | 15                        | No                        | No                      | -                      |
| 12                 | 22  | Male   | Yes                  | No                  | 40                     | 15                        | No                        | No                      | -                      |
| 13                 | 21  | Male   | Yes                  | No                  | 40                     | 15                        | No                        | No                      | -                      |
| 14                 | 22  | Male   | Yes                  | No                  | 20                     | 18                        | No                        | No                      | -                      |
| 15                 | 25  | Male   | No                   | No                  | 15                     | 15                        | Yes (while reading in a vehicle)| -                      |
| 16                 | 22  | Female | No                   | No                  | 20                     | 14                        | No                        | No                      | -                      |
| 17                 | 50  | Female | Yes                  | No                  | 0                      | 45                        | No                        | No                      | -                      |
| 18                 | 23  | Female | No                   | No                  | 0                      | 0                         | No                        | No                      | -                      |
| 19                 | 29  | Male   | No                   | No                  | 0                      | 15                        | No                        | No                      | -                      |
| 20                 | 29  | Female | Yes                  | No                  | 0                      | 18                        | No                        | No                      | -                      |
| 21                 | 30  | Male   | No                   | No                  | 2.5                    | 20                        | Yes                       | Yes (while reading in a vehicle)| -                      |
| 22                 | 27  | Male   | No                   | No                  | 8                      | 21                        | Yes                       | No                      | -                      |
| 23                 | 26  | Male   | No                   | No                  | 7                      | 18                        | Yes                       | No                      | -                      |
| 24                 | 28  | Male   | No                   | No                  | 40                     | 20                        | No                        | No                      | -                      |
| 25                 | 26  | Female | No                   | No                  | 0                      | 0                         | No                        | No                      | -                      |
| 26                 | 24  | Female | Yes                  | No                  | 0                      | 0                         | No                        | No                      | -                      |
| 27                 | 69  | Female | Yes                  | No                  | 0                      | 20                        | No                        | Yes (while reading in a vehicle)| -                      |
| 28                 | 29  | Female | Yes                  | No                  | 5                      | 23                        | No                        | No                      | -                      |
| 29                 | 26  | Female | Yes                  | No                  | 0                      | 5                         | Yes                       | Yes (while reading in a vehicle)| -                      |
| 30                 | 25  | Female | Yes                  | No                  | 8                      | 17                        | Yes                       | No                      | -                      |
| 31                 | 27  | Female | Yes                  | No                  | 30                     | 4                         | Yes                       | No                      | -                      |
| 32                 | 28  | Male   | No                   | No                  | 0                      | 3                         | No                        | No                      | -                      |
| 33                 | 23  | Male   | No                   | No                  | 0                      | 0                         | No                        | No                      | -                      |
| 34                 | 32  | Female | No                   | No                  | 0                      | 22                        | No                        | No                      | -                      |
| 35                 | 25  | Male   | No                   | No                  | 0                      | 7                         | No                        | No                      | -                      |
| 36                 | 35  | Female | No                   | No                  | 0                      | 29                        | No                        | No                      | -                      |

mean 27.81    168K/18F  11 yes  2 yes  20.57  14.53  7 yes  7 yes  -
SD  9.01      -      -      -      66.62  9.62   -     -     -
min  21       -      -      -      0      0      -     -     -
max  69       -      -      -      400    45     -     -     -

the subjective evaluation of the realism of the simulator increased from 6.1 to 6.74/10.

The validity of the bicycle simulator allows us to safely study cyclists’ behavior in risky situations and analyze their reactions and interactions with different features of the infrastructure such as, radius of curvature, intersections and lateral and longitudinal slopes. In future work, we will conduct real life experiments using an instrumented bicycle in different locations and countries, particularly Sweden and Spain, in order to compare the output from the developed algorithms on the simulator with the road and to test the robustness of the proposed approach.

APPENDIX A
DYNAMICAL AND MECHANICAL PARAMETERS OF THE BICYCLE SIMULATOR USED DURING THE SIMULATION
See Table 4.

APPENDIX B
PARTICIPANT RESPONSES TO THE GENERAL QUESTIONNAIRE ABOUT THEIR CYCLING EXPERIENCE
See Table 5.

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**TABLE 5. (Continued.)**

| Participant Number | Realism of the simulator | the most realistic aspects | features to be improved |
|--------------------|--------------------------|---------------------------|-------------------------|
| 1                  | 9                        | buildings and cars        | the streets              |
| 2                  | 8                        | Sounds, physical effects, virtual environment | Virtual picture when turning the bicycle |
| 3                  | 5                        | the setting on the screen | the bicycle should be more constrained to the soil |
| 4                  | 7                        | The driving of the bicycle itself, like the physical implication and muscle memory you put in the driving. | The realism of the environment - The fact that you when you turn, you should lean on the side you’re turning - a lot or a bit, depending on your speed and the angle of the turn. |
| 5                  | 6                        |                           | An ability for the bike to lean in turns |
| 6                  | 7                        |                           | Processing speed. There was a delay in seeing ones action getting translated onto the screen. |
| 7                  | 8                        | Cars coming into the bike lane | The sense of speed |
| 10                 | 8                        | The pedaling and wind action | May be having some kind of a virtual environment which can give a actual feel of cycling on a road. |
| 12                 | 6                        | The apparatus (the bike and the components) | Feeling of turning |
| 13                 | 7                        | The bicycle itself including turning maneuvers | Reaction of bus behind the cyclist to avoid flattening him/her. |
| 15                 | 7                        | The true feel that you get while cycling at a real road. The bicycle simulator did a great job, but somehow I felt that I didn't have a feeling of anxiousness that you get while cycling at an actual road with real traffic. | The air dynamics as while we are riding in real the air motion surrounding us is different. |
| 16                 | 7                        | Airflow from fans, road resistance | The connection between the bike and the road. I don’t feel like I can control the path of my bike very well. |
| 17                 | 9                        | Movement of scenery around me | j’ai eu l’impression d’être lent à l’écran alors que je pédalaïs vite breaking, scenarios and perceived speed |
| 18                 | 7                        | For sure the feeling of riding the bike as it was real and also the road in front of you. | The behavior of the buses/cars as they disregard cyclists and can drive-by too close to the cyclist. |
| 19                 | 5                        | The bike was real. | There should be more pedestrians walking along the streets, perhaps other cyclists on the lane. |
| 21                 | 5                        | le fait de pouvoir voir à gauche, droite et derrière, le vélo, la ventilation (bien qu’un peu forte) | The part I was most uncomfortable with was because it was fixed in a way I could not feel the gravity acting when I stop or the natural inclination the bicycle does when I turn right or left, for example. |
| 22                 | 8                        | pedaling | Perhaps, the part with the bycycle |
| 24                 | 7                        | The roads with the ground lines, traffic lights/signs and so on. | More cars, people crossing the street or traffic light. |
| 25                 | 3                        | the road evolution | More sound |
| 26                 | 7                        | Cycling on a real bicycle, feeling of the "wind" blowing, the danger of cycling along a busy street, seeing the shops go by | |
| 27                 | 7                        | The acceleration and break systems | |
| 28                 | 8                        | the road evolution | |
| 29                 | 4                        | Cars | |
| 30                 | 5                        | | |
| 31                 | 8                        | | |
| 32                 | 3                        | | |
| 33                 | 8                        | | |
| 34                 | 3                        | | |
| 35                 | 8                        | | |
| 36                 | 8                        | | |

| mean 6.74 | SD 1.57  | min 3 | max 9 |

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