Technische Universität Braunschweig

INSTITUT FÜR FAHRZEUGTECHNIK
PROF. DR.-ING. FERIT KÜÇÜKAY

DLR

Construction, parameterization and evaluation of a bicycle simulator for a realistic and interactive simulation environment

Masterarbeit

von

Donaji Martinez Garcia

4903990

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Task definition

MASTER THESIS

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Area of expertise:	Mechatronics, Simulation

Topic: Construction, parameterization and evaluation of a bicycle simulator for a realistic and interactive simulation environment

Studies carried out in simulators have been one of the most important investigation method in the development of driver assistance systems for many years. One of their main advantages is the ability to reproduce critical situations as often as required without endangering the driver. The development of highly automated vehicles, especially in urban areas, requires a high degree of interaction with pedestrians and cyclists. In order to better understand and investigate this interaction, a bicycle simulator is currently being built at the DLR Institute of Transportation Systems. Since the possibility of evaluating driver assistance systems or their interaction with other road users also depends heavily on the quality of the driving simulation, a particular focus when setting up the bicycle simulator is on the quality of the underlying simulation modules and the degree of reality perceived by the test persons.

Ms. Martinez Garcia has the task of implementing the final integration of the hardware components into the simulation environment, building on the existing preparatory work. Particularly, this includes work on the hardware as well as the implementation of the corresponding interface implementations. However, the focus should be on the implementation of the dynamic model and the force feedback modules and their parameterization. The selected parameterization should finally be evaluated on the basis of a small study with test subjects.

The task of Ms. Martinez Garcia includes in detail:

- Literature research
  - Dynamic models
  - Physics and mechanics of the bicycle
  - Delimitation of the model for the use on the simulator
  - Work by other research institutions in this area
- Construction and parametrization
  - Modelation of the driving dynamics of a bicycle
  - Statistical evaluation of real cyclist behavior based on infrastructure / vehicle-based measurement data
  - Determination of characteristic parameters
  - Creation of the basic environment for VR in Unreal

    - Integration of the individual software components into an overall system

- Evaluation
    - Creation of a questionnaire
    - Design of parameter sets
    - Implementation of the study and a survey for the test persons with regard to the immersion of the dynamic movements of the bicycle
    - Evaluation of the study using objective (driving behavior) and subjective (questionnaires) criteria

The results of the work must be documented in detail in accordance with the guidelines of the DLR Institute of Transport System Technology and updated and supplemented at regular intervals. Since the work is used as a basis for further work, the results of the investigation are to be recorded in tabular form and / or in a comparable representation. Further details are to be discussed with the supervisor.

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Prof. Dr.-Ing. K. Seifert (TU Braunschweig)	Dr.-Ing. M. Fischer (Supervisor DLR)	Donaji Martinez Garcia (Student)

Sperrklausel

Die Ausgabe der vorliegenden Masterarbeit mit dem Titel „Construction, parameterization and evaluation of a bicycle simulator for a realistic and interactive simulation environment“, ist ausschließlich unter Genehmigung der Institutsleitung zulässig.

Braunschweig, den 16.08.2021

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Eidesstattliche Erklärung

Ich versichere an Eides statt, dass ich die vorliegende Masterarbeit mit dem Titel „Construction, parameterization and evaluation of a bicycle simulator for a realistic and interactive simulation environment“, ohne unerlaubte fremde Hilfe oder Beratung und nur unter Verwendung der angegebenen wissenschaftlichen Hilfsmittel angefertigt habe.

Braunschweig, den 16.08.2021

Donaji Martinez Garcia

A bicycle simulator can be used as a tool for the observation of the behaviors of cyclists and their perceptions of different environments. Through the use of these systems, it is possible to experiment with different possible scenarios without the existence of potential safety problems that could be present in field studies. Furthermore, the performance of research under controlled conditions allows the ability to provide all the participants with a similar experience and therefore collect reliable data about their bicycling experience. It is expected that through the combination of virtual reality (VR) technology with dynamic motion cues, an immersive effect can be achieved, and therefore it is possible to provide an authentic representation of bicycle motion.

The conducted literature research supports the creation of a dynamic model that enables the reproduction of realistic movements of the simulator based on physical parameters. A dynamic model was developed based on this information, and the further integration of all the components of the system is explained. Subsequently, a study was designed to gain knowledge about the acceptance and performance of the simulator by utilizing real-life data.

The results of the developed study assist decision-making during the further design and calibration to provide an immersive riding experience. The subjective criteria allow an optimization of the provided cycling sensation by evaluating the responses from riders when exposed to different driving profiles. The objective evaluation provides enough data to be compared with the behavior of bicycles in real-life situations.

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1. Introduction

Driving simulators represent an important investigation method in the development of driver assistance systems, since they allow the study and reproduction of complex traffic situations under defined conditions, without endangering the driver. The use of simulators provides the opportunity to obtain awareness of risks and contribute to overall road safety, as they can be used for driver training and education (Schulzyk et al., 2007), testing of design, evaluation of environments and entertainment (Kwon et al., 2001).

Studies carried out in simulators allow the possibility of evaluating the interactions between several road users. The development of a bicycle simulator requires the creation of a realistic model, which analyses the cyclist as the subject of study. This would provide important data to help study and understand the cyclist's behavior (M. Shoman & Imine, 2020). The results of the studies depend heavily on the quality of the driving simulation, for this reason, a particular focus when setting up the bicycle simulator is on the quality of the underlying simulation modules and the degree of reality perceived by the test persons.

1.1. Motivation

The development of highly automated vehicles, especially in urban areas, requires a high degree of interaction with other road users such as pedestrians and cyclists. In order to better understand and investigate the interaction between several road users, considering the cyclist as the center of focus, a bicycle simulator is currently being built at the DLR Institute of Transportation Systems. The purpose of the simulator is to provide a semi-realistic simulation in which a human-controlled and human-powered vehicle moves in a virtual environment. This is done to carry out studies that require observing and analyzing the behavior of cyclists in safe and controllable conditions (M. Shoman & Imine, 2020).

For the creation of the bike simulator, it must be considered that the unstable dynamics of the bicycle are combined with the human rider's dynamics (Kwon et al., 2001). Through the use of feedback systems, it is possible to couple the virtual environment with the actions of the rider, such as changes in steer angle, lean angle, step rate or braking force. This makes it possible to react by controlling actuators that influence the steering torque, inclination or step resistance, and therefore create a more immersive experience.

1.2. Objective

The objective of this project is to develop the software and hardware components of a bicycle simulator with the ability to represent traffic situations within a virtual immersive environment, in order to provide riders with a realistic cycling feeling. For this purpose, the implementation of an interface must be performed, which integrates the simulation environment, the hardware components and an existing dynamic model. Furthermore, the force feedback modules and their parameterization must be performed with focus on developing an acceptance study in which test subjects can evaluate the performance of the simulator. The simulation components should be parametrizable in such a way that they can be compared to a real-life experience.

1.3. Structure

For the development of the bicycle simulator, it is necessary to understand the physics and mechanics of bicycles, therefore a literature research with emphasis on dynamic models is conducted in section 2, complemented with information about other institutions that have developed similar systems.

In section 3, the construction and parametrization of the simulator are explained. The modeling of bicycle dynamics is done by determining the required characteristic parameters and the formulas that govern the behavior of the simulator. This is followed by an explanation of the simulation environment and concluding with an integration of all elements into an overall system.

An evaluation of the system is designed in section 4, where an immersion study is designed with different parameter sets that allow the test persons to try different test settings.

Section 5 proposes a validation of the acceptance of the simulator. An evaluation of the results using objective and subjective criteria utilizing the first experimental results is performed, followed by a comparison of the results to real-life driving behaviors.

Finally, section 6 provides a summary, followed by a conclusion derived from the results and an outlook for further development of the project.

Figure 1 presents an outline of the structured thesis elements and the main research questions of each chapter.

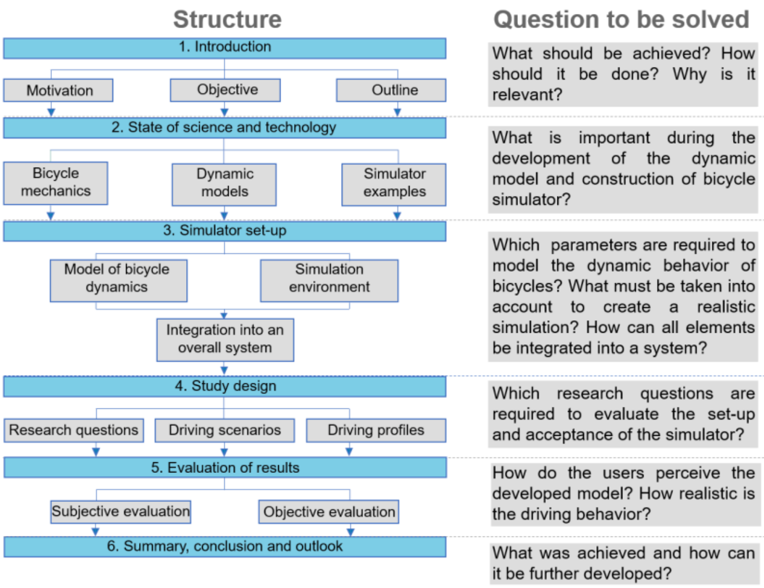

Figure 1. Graphical structure of the thesis outline

2. Theoretical foundations

Bicycle simulators contribute to the development of traffic engineering research and are used for assisting bicycle and road design, training for driving, entertainment and studying the interaction between humans and vehicles (Yin & Yin, 2007). They serve as a tool to analyze the behavior and riding practices of road users in specific situations and record data that can be used to increase rider safety, mobility and efficiency. They allow the identification and reproduction of critical situations and hazards to which cyclists are exposed, in a safe environment, without endangering them (Dialynas et al., 2019). This helps to recognize the environmental elements that influence the cyclists´ behavior and investigate the strategies that cyclists utilize to anticipate risks (M. M. Shoman & Imine, 2021).

For the development of a bicycle simulator, it is important to understand the physical principles of bicycles, especially the forces that influence their movement. This is a challenging task because bicycles can move freely in many directions and therefore have multiple degrees of freedom, they also interact with very different road conditions; furthermore, the interaction between the rider and the bike has a big influence on the balance and stability of the system, and this changes at different velocities (Yin & Yin, 2007). Furthermore, the bicycle simulator must be able to have adjustable dimensions while supporting the load of the rider at every operational mode (Dialynas et al., 2019).

An important fact to understand the dynamic behavior of bicycles is that they are laterally unstable and are only stable while in forward motion under the control of a rider (Astrom et al., 2005). Dynamic models are built by equations that represent the real-life behavior of a system. These models can be used by the simulation to create a realistic environment. The real-time data obtained from sensors and actuators can be used for the calculation of the rider-bicycle dynamics (Yin & Yin, 2007) and the visual representation in the simulation. The interaction between the elements of a bicycle simulator and its operation flow can be seen in Figure 2.

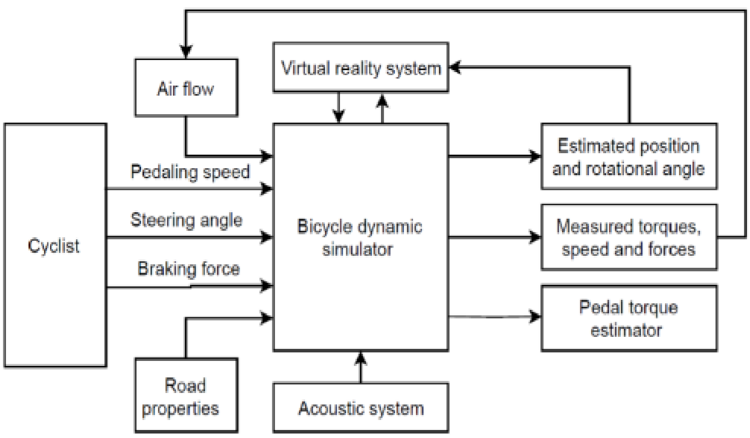

Figure 2. Operating flow of a bicycle simulator (M. M. Shoman & Imine, 2021)

For the study of the rider-bicycle system, several institutions have constructed bicycle simulators with different goals such as replication of a rider's moment, motion generation and haptic feedback, medical rehabilitation, investigation of human factors involved in cycling, and commercially oriented systems that focus on fitness and training (Sun & Qing, 2018). Common elements on bicycle simulators are a modified bicycle, a motion generating subsystem, handlebar and pedal force display subsystems, a visual subsystem, sensors, control computers, and a rider-bicycle dynamic model (Yin & Yin, 2007).

2.1. Physics and mechanics of the bicycle

To build a bicycle simulator, structural design considerations such as required geometry and structural strength must be taken into account (Dialynas et al., 2019). Accurate measurements of a bicycle's physical parameters are required for realistic dynamic simulations and analysis (Moore et al., 2010). Changes in parameters can influence the dynamic behavior of the bicycle. To define the geometry of bicycles, there are some characteristic parameters as seen in Figure 3. The points P_1 and P_2 are the contact points of the wheels with the ground, whereas P_3 is the intersection of the steering axis with the horizontal plane. The angle and shape of the front fork are designed so that P_2 is behind P_3. The letter h represents the height of the center of mass, λ is the head angle, a (also known as rear length l_r) is the distance from a vertical line through the center of mass to P_1, b (also known as length l) is the wheelbase, which is the distance from C_1 to C_2 and c is the trail, which is the horizontal distance between the contact point P_2 and the intersection with the steering axis P_3 with zero steer angle (Astrom et al., 2005). The trail has a big influence on the riding properties of the bicycle, if it is large it improves stability but makes steering less agile. Its typical values are between 0.03 – 0.08 m (Astrom et al., 2005).

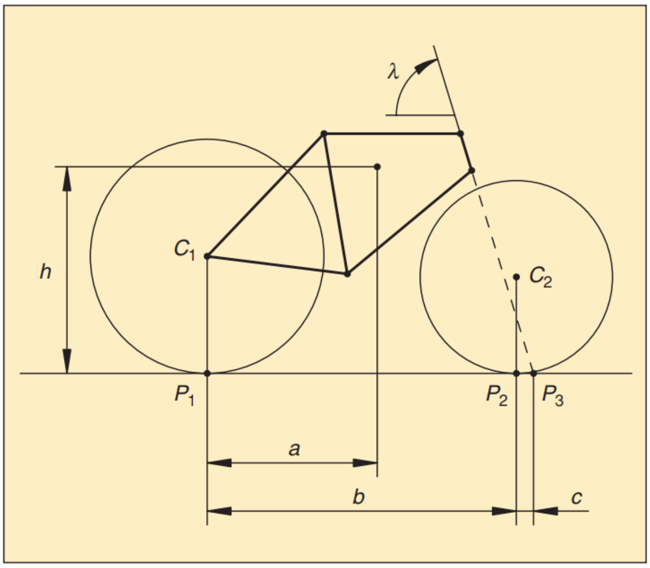

Figure 3. Parameters defining the bicycle geometry (Astrom et al., 2005)

Typically, it is assumed that the bicycle consists of four rigid parts: one frame, one fork with handlebars and two wheels (Astrom et al., 2005; Moore et al., 2010). The influence of other elements on the riding dynamics is omitted. The rider is modeled as a point of mass that can move laterally with respect to the frame as an inverted pendulum (Astrom et al., 2005), creating a lean angle φ (also known as roll or tilt angle) which is positive when leaning to the right.

The rider can also influence the dynamics by applying torque to the handlebars. This generates a steer angle δ which is positive when steering left. These angles are portrayed in Figure 4. The amount of force that can be produced by the rider is influenced by the body posture while cycling (Dialynas et al., 2019), for this reason, it is very important that certain parameters of the bicycle simulator are adjustable.

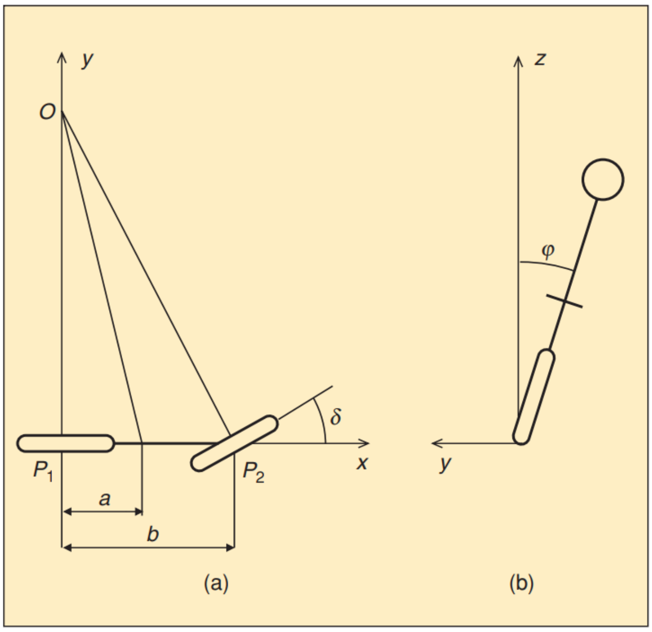

Figure 4. Top and rear view of a bicycle with steer and lean angles (Astrom et al., 2005)

Successful control of a bicycle depends on the forces between the wheels and the ground (Astrom et al., 2005). The understanding of these forces is required to derive a valid dynamic model of the driving conditions. There are longitudinal forces such as acceleration and braking, and lateral forces required for balancing and turning. These forces need to be considered together with the rider´s motion for the development of a dynamic model for the bicycle simulator (Kwon et al., 2001). The longitudinal forces that act on the longitudinal motion of a vehicle in an inclined road can be seen in Figure 5. The red arrows pull in a negative direction and the blue ones in a positive direction.

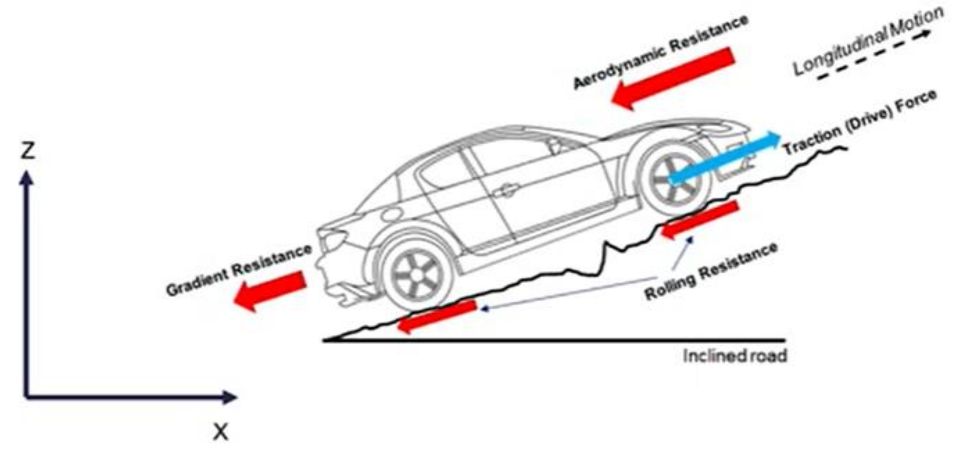

Figure 5. Longitudinal model of a vehicle (Waslander & Kelly, n.d.)

The lateral forces that act on the motion of a vehicle with mass m can be seen in Figure 6. The following parameters influence the lateral motion: steering angle δ, velocity V, distance from the center of gravity to rear wheel l_r (also known as a), distance from the center of gravity to rear wheel l_f, slip angle β, force in y direction of rear wheel F_{yr}, force in y direction of front wheel F_{yf} and angular velocity $\dot{\Psi}$ (also represented with ω and also known as yaw rate).

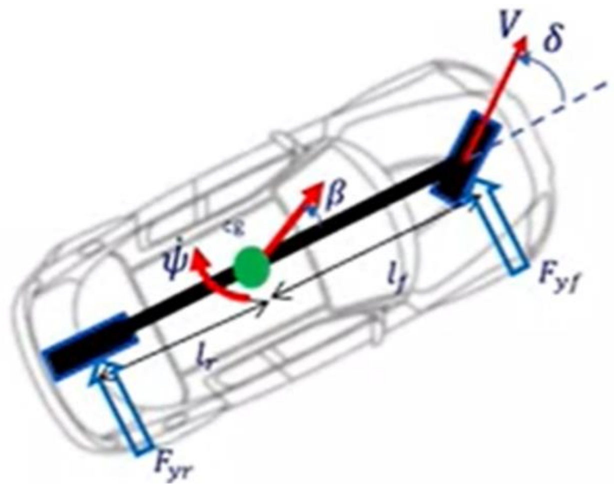

Figure 6. Lateral model of a vehicle (Waslander & Kelly, n.d.)

2.2. Dynamic models

Any mechanical system is created by interconnected subsystems that can be described in an object-oriented manner through constitutive equations complemented with balances of mass, momentum and energy (Åström et al., 2005). A dynamic model is a representation of how the state of a system changes through time. They show the interaction between the involved variables over time. The level of detail depends on the application. Considering bicycle dynamics, the most basic models can be developed with the consideration of geometry, mass, mass location and mass distribution of the bodies, while more complex models also consider friction, stiffness, damping, and special characteristics of humans and tires (Moore et al., 2010). The rider-bicycle dynamic model is the most important component for the development of a realistic interactive bicycle simulator (Yin & Yin, 2007).

There are several approaches to develop a vehicle mathematical model. To develop an exact model, methods of theoretical physics such as Lagrange or Euler can be used (M. Shoman & Imine, 2020). Another option is to reduce computing time by developing a simplified model. Some models have already been developed for bicycle simulators such as the Whipple model, which is constantly found in the literature. It is a detailed non-linear model which provides the ability to analyze the bicycle mathematical model (M. Shoman & Imine, 2020). For the KAIST Interactive Bicycle Simulator (Kwon et al., 2002) the model was divided into a stability and a vibration submodels, where the motion equations were developed using the Lagrange´s equation and for the numerical simulation the Runge-Kutta method was applied (M. Shoman & Imine, 2020). To simplify the calculation of the kinetic energy, the system was divided into bicycle rear and front sections (M. Shoman Imine, 2020).

For the development of a simplified dynamic model, several assumptions must be made. The bicycle is assumed to have ideal rolling and frictionless joints, be laterally symmetric and consist of four rigid bodies: front wheel, rear wheel, frame and handlebar (Astrom et al., 2005; Kwon et al., 2001; Moore et al., 2010). Furthermore, the mass of the whole system is distributed evenly between the two wheels (Astrom et al., 2005). The bicycle rolls over the horizontal plane, the rider has a fixed position and the orientation is relative, the forward velocity of the rear wheel is constant, the trail c is zero, and the steer axis is vertical, which implies that the head angle λ is 90 (Astrom et al., 2005). Further assumptions are that the rider can influence the velocity through the pedals and brakes and that the direction can be changed by using the handlebars and tilting its body (Astrom et al., 2005). As two-wheeled vehicles, bicycles can move in different rotational and translational directions (Kwon et al., 2001), for this reason, the steer angle δ is considered as the control variable, which leaves the lean angle φ as the only degree of freedom (Astrom et al., 2005).

The first step to develop a dynamic model is to analyze the forces and laws of motion that affect an object. For this purpose, the forces that apply to the longitudinal vehicle model need to be considered. As seen in Figure 7, the longitudinal motion of a vehicle with mass m on a road with an inclination angle α is composed by the sum of forces and resistances that act on the vehicle.

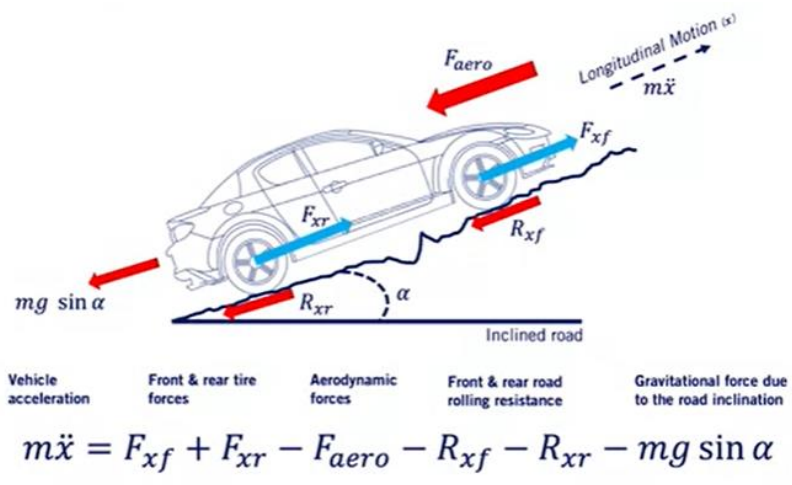

Figure 7. Forces and formula of acceleration of a vehicle (Waslander & Kelly, n.d.)

For the lateral model of the vehicle, the bicycle model with linear tires is utilized under the assumption that the vehicle is a rigid body with the fundamental laws of motion determining its dynamic behavior. This can be identified in Figure 6 and is portrayed in Figure 8, where $F_f = -C_{\alpha,f}\alpha_f$ and $F_r = -C_{\alpha,r}\alpha_r$ are the tire forces generated by a linear tire model acting on the reference points A and B (also called C_1 and C_2 in section 2.1), and the reference point C is the center of gravity. Here, $C_{\alpha,f}$ and $C_{\alpha,r}$ are the cornering stiffness of the front and rear wheel (constant) and considering the rear tire slip angle $\alpha_r = -\beta + \frac{l_r\,\omega}{V}$ and the front tire slip angle $\alpha_f = \delta - \beta - \frac{l_f\,\omega}{V}$, as seen in Figure 9. The angular velocity ω is given by $\omega = \frac{V\delta}{l_r + l_f}$.

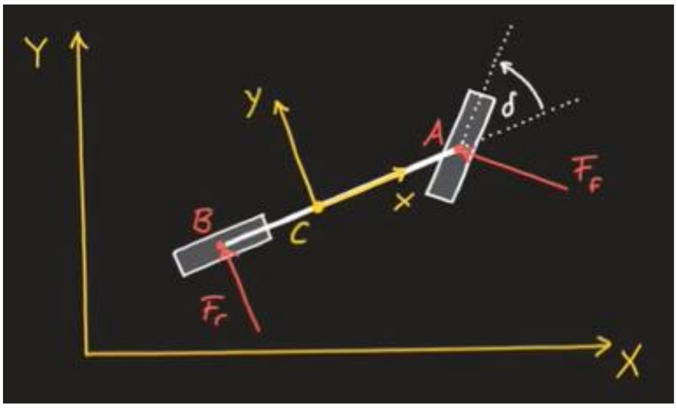

Figure 8. Lateral model of a bicycle with linear tires (Schildbach, n.d.)

The rotational dynamics follow the angular momentum principle. The moment of inertia determines the torque required for a certain angular acceleration about a rotational axis, therefore the moment of inertia I_z about the z-axis multiplied by the angular acceleration $\dot{\omega}$ is equal to the sum of moments about the center of gravity C, therefore $I_z\,\dot{\omega} = -l_r F_r + l_f F_f \cos\delta$.

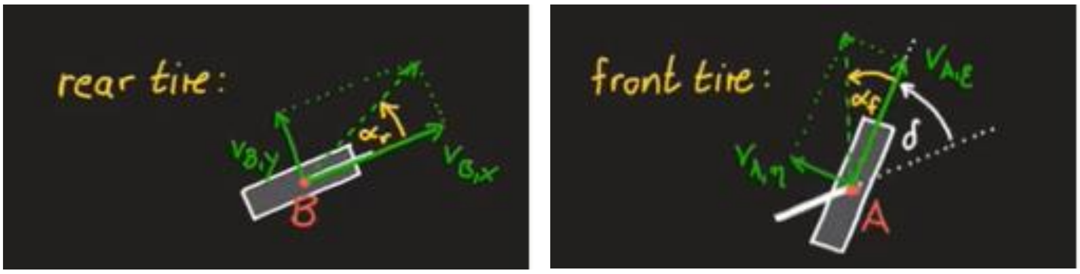

Figure 9. Rear and front tire angles

By applying torque to the handlebars and leaning the bicycle, the driver can control it (Astrom et al., 2005), the simulator reacts to these controls and provides feedback to the rider. The steer angle δ is directly related to the steer torque T. When this torque is applied it influences the path of the bicycle by turning the front wheel in the direction of the applied torque, creating a force that rotates the front fork around the z-axis. The contact forces between the tire and road exert a torque on the front fork that leans the bike and the body of the rider in the x-axis in the opposite direction to which the fork is pointing, therefore if the rider leans its body to the left, the bicycle frame turns to the right, which corresponds to positive lean angle φ (Astrom et al., 2005).

The self-stabilization property of bicycles is highly dependent on the design of the front fork (Astrom et al., 2005). Through the control of the front fork, it is possible to define both the driving direction and the inclination of the bicycle (Astrom et al., 2005). To analyze the behavior of the front fork, the external torque applied to the handlebar is considered as the control variable, rather than the steer angle. The torque of the front fork is defined by

$$T = \frac{acmg \sin\lambda}{b}\, \varphi + \frac{acm \sin\lambda}{b^2}\left(V^2 \sin\lambda - bg\, cos\lambda\right) \delta.$$

The sign of the steer angle δ is negative if $V > V_{sa}$, being

$$V_{sa} = \sqrt{bg \cot\, \lambda}$$

the self-alignment velocity that indicates the velocity at which the bicycle becomes stable (Astrom et al., 2005).

Without the active control of the driver, the bicycle is unstable. The feedback produced by the rider when applying a torque on the front fork stabilizes the bike, therefore the geometry of the front fork must be considered for the development of the dynamic model (Astrom et al., 2005). When the steering wheel is turned, the center of mass of the frame is shifted. Therefore the steering torque $T_\delta = -\frac{mgac \sin\lambda}{b}\delta$ must be considered (Astrom et al., 2005).

A dynamic model developed by the Shanghai Jiao Tong University is explained in the following section.

Interactive Bicycle Simulator – Shanghai Jiao Tong University

With the Newton-Euler method, they developed the formulas for a Rider-Bicycle Dynamic Model (RBDM). When the human driver changes the current status, the sensors installed in the simulator communicate real-time data to the RBDM, which with information from a terrain database calculates the new status. With this output it is possible to react to the rider´s operation by activating the handlebar and pedal force display subsystem, motion generating subsystem, visual subsystem and therefore provide the feelings of force, motion and vision to the rider (Yin & Yin, 2007). The visual representation is calculated using the information of the bicycle velocity from the RBDM, the steer angle, and the terrain database (Yin & Yin, 2007). This workflow can be seen in Figure 10.

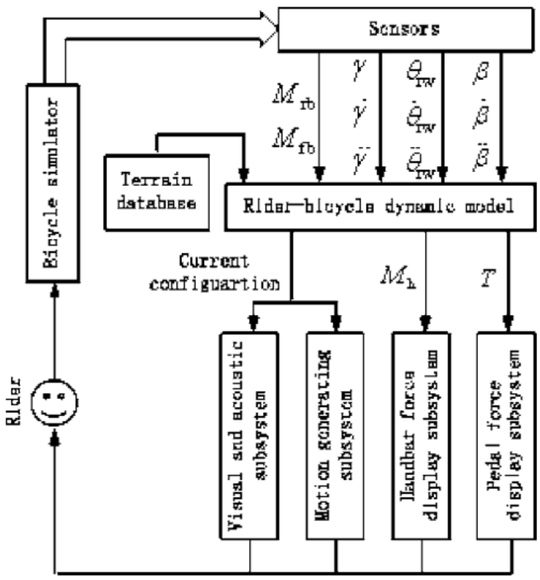

Figure 10. Operating flow of the interactive bicycle simulator (Yin & Yin, 2007)

For the development of the RBDM following assumptions were made (Yin & Yin, 2007):

- The rider-bicycle system is composed of the following five rigid bodies: rear wheel, upper part of the rider, bicycle frame together with lower part of the rider, handlebar assembly, and front wheel.
- The frame and handlebar assembly are symmetric with regard to the rear and front wheel planes.
- The slip angle and longitudinal slip of the tires remain zero because the friction force is strong enough to prevent tires from sliding.
- The influence of pedaling and steering is neglected on the mass distribution of the system.
- The joints are frictionless.
- The rider only leans his/her upper body sideward on the bicycle.

The sensors measure the steering angle β, angular velocity of the rear wheel $\dot{\theta}_{rw}$, lean angle of the rider´s body γ, and the braking torques of the front and rear wheel M_{fb} and M_{rb}. The gradient λ of the slope is obtained from the terrain database. The RBDM calculates all the other variables such as pedaling torque T, steering torque M_h and the angles δ_{rw}, λ and φ_f. These parameters are used by other subsystems to create a realistic environment (Yin & Yin, 2007). For the calculation of the dynamic system utilizing Newton´s equation and considering the whole rider-bicycle system, the following formula must be considered:

$$\sum_{i=1}^{5} m_i a_i = \underbrace{\sum_{i=1}^{5} m_i\, g z_v}_{\text{a.}} + \underbrace{F_{air} x}_{\text{b.}} + \underbrace{(N_r z + S_r x + F_r y) + (N_r z' + S_r x' + F_r y')}_{\text{c.}}$$

This formula considers three main forces:

a. The gravitational forces contribute to the longitudinal and side forces when riding on a slope, with vector z_v being a vertical unit vector that points downwards in the z-axis.

b. The air resistance $F_{air}x$ is only considered to act in the x-axis. It can be neglected at low speed but becomes an important force at high speed (Yin & Yin, 2007). It is given by $F_{air} = \frac{1}{2} C_D A \rho v^2$ where C_D is the drag coefficient, A is the frontal area of rider-bicycle system, ρ is the air density, and v is the speed of air with respect to the bicycle (Yin & Yin, 2007).

c. The reactions between the ground and the elastic tires have an important contribution to the motion of the bike. These interactions are complex and therefore difficult to study, therefore the tires are considered to be rigid and the friction forces are assumed to be large enough (Yin & Yin, 2007).

The RBDM obtains information from the following subsystems. The Pedal Force Display Subsystem (PFDS) simulates the resistance forces that are present when a bicycle is moving forward, these forces include air resistance, ground friction, slope resistance and inertia forces. The Handlebar Force Display System (HFDS) allows the rider to control the motion of the front wheel through the movement of the handlebar. These systems are complemented by a terrain database that collects information about the friction coefficient of the ground and the inclination of a slope (Yin & Yin, 2007).

2.3. Work by other research institutions in this area

Several institutions around the world have dedicated time and resources to the task of developing bicycle simulators with different purposes such as medical rehabilitation, education, study cyclist behaviors, investigating the effect of haptic feedback on the handlebars and bicycle dynamics modeling (Sun & Qing, 2018). There are two types of bicycle simulators, motionless simulators provide only visual feedback, whereas mobile-based simulators complement visual information with real-life movements that can improve the realism (M. Shoman & Imine, 2020). Table 1 shows a compilation of existing bicycle simulators.

Table 1. Existing bicycle simulators

Institution	Name of the project
Korea Advanced Institute of Science	KAIST Interactive Bicycle Racing Simulator System
University of Applied Sciences Bonn-Rhein-Sieg	FIVIS Immersive Bicycle Simulator
University of Missouri - Transportation Research Lab	ZouSim Bicycling Simulator
TU Munich	UR:BAN Bicycle Simulator
Würzburger Institute for Traffic Sciences (WIVW)	WIVW Bicycle Simulator
University of Iowa - Hank Virtual Environments Lab	Bicycling & Pedestrian Simulator Research
University of Coventry	SIMUSAFE
IFSTTAR	Ifsttar's Bicycle Simulator
Shanghai Jiao Tong University	Interactive Bicycle Simulator
TU Delft	TUDelft Bicycle Simulator

The following mobile-based simulators have similar qualities as the simulator to be developed in this thesis.

FIVIS Immersive Bicycle Simulator - University of Applied Sciences Bonn-Rhein-Sieg

The Fivis Project (Fahrradfahrsimulation in der Immersiven Visualisierungsumgebung „Immersion Square" - Bicycle driving simulation in the immersive visualization environment "Immersion Square") was developed primarly by the Institute of Visual Computing at the Bonn-Rhein-Sieg University (Hochschule Bonn-Rhein-Sieg, n.d.). It was designed with the objectives of increasing bicycle traffic education, especially in children, studying the correlation between the visually perceived motion and the physically generated motion, and investigating how physical and stress-related factors affect attention and concentration (Schulzyk et al., 2007). The scenarios portray typical hazardous situations, which allow training to handle such situations and increase the overall attentiveness and alertness.

The FIVIS Simulator uses a Hexapod motion platform with 6-DOF and integrated force feedback control. The bicycle that is mounted on top of the platform is equipped with a variety of sensors that collect data for the simulation, register the forces applied to the pedals, and make it possible to identify the kind of stress that affects the frame, fork and handlebar (Schulzyk et al., 2007). With the use of this information, the FIVIS project verifies if the movements performed by the motion platform represent a real bicycle ride (Schulzyk et al., 2007). A visual simulation environment composed of three perfectly fitting projection screens with an angle of 135° to each other was constructed to examine the impact of visual perception on physical and mental performance under controlled conditions (Schulzyk et al., 2007). The software is composed of the following elements:

1.- Input-Interface: Collects input data from the sensors such as step rate, force, position of the handlebar and inclination of the bike frame.

2.- Output-Interface or force feedback: Transfers the forces calculated by the simulator to the motion platform and the bike.

3.- Physical Simulation: Represents the forces that are applied to the bike in a realistic simulated virtual world.

4.- Mathematical Simulation: Incorporates the differential equations that compose a model of the dynamic behavior of the bicycle.

5.- Logics of training: Controls the simulation based on a fitness scenario. It adapts the simulation´s parameters to motivate and challenge the rider.

6.- Logics of road safety education: Generates manually and randomly every-day traffic situations for different types of road users. The riders must act according to the traffic rules, and react in dangerous situations.

7.- User Interface: Provides intuitive access to all the parameters of the system.

KAIST Interactive Bicycle Racing Simulator System - Korea Advanced Institute of Science

The Korea Advanced Institute of Science (KAIST) developed a simulator system for multi-users that consists of two bicycle simulators in which the user can experience realistic motion sensations. The system integrates a motion generation system, bicycle dynamics, handlebar and pedal resistance systems, a visual simulator, a 3D sound system, and a network structure (Kwon et al., 2002). The simulators can communicate and see each other in the audio-visual experience that they have created. The first simulator was constructed using a six-degree-of-freedom (6-DOF) platform that simulates the motion of the bicycle, complemented with resistance systems able to create active and passive reaction forces (Yin & Yin, 2007).

With the purpose of creating a more advanced interactive racing simulator for multi-users, and after studying the essential issues and integration technologies, the team developed a second simulator, which consists of a four-degree-of-freedom (4-DOF) platform, a real-time visual simulator, an HMD and beam projection system, and a 3D sound system (Kwon et al., 2002). Both simulators can be seen in Figure 11. Furthermore, they developed a network to link both simulators in the virtual world, where the users can race against each other.

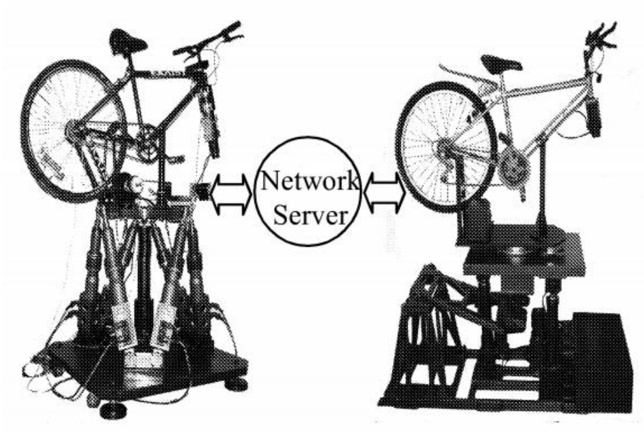

Figure 11. KAIST Interactive bicycle simulator system (Kwon et al., 2002)

With the use of a motion generation algorithm, the simulator system can reproduce real-time bicycle dynamics. The algorithm is based on a nonlinear bicycle dynamic model, accounting for tire flexibility, slip and rider's pedal, handlebars and tilting moment inputs (Kwon et al., 2002). The motion equations were developed by using the Newton-Euler method in which 24 unknown parameters including the rear wheel position, the steering angle, the angular positions of the front and rear wheels relative to the handle fork and the frame, some internal forces and some angles for coordinate transformations (Kwon et al., 2001). For the adjustment of the parameters to improve the rider´s feel of motion, a washout filter was applied and executed synchronously to the bicycle dynamics simulation engine. To protect the dynamic calculations from discrete and delayed road profile data, a low pass filter was used. The dynamics calculator is complemented with a visual simulator and an acoustic system. The data obtained from the motion generation algorithm is sent to the corresponding motion system to be applied and provide a sensation of real motion to the rider (Kwon et al., 2002). The two motion systems are the 6-DOF Stewart platform and the 4-DOF platform. The logic behind the control system can be observed in Figure 12. The data transmitted between clients through the server consist of velocity, road type, direction of handlebar, viewpoint position and normal vector, front and rear wheel positions, and normal vectors (Kwon et al., 2002).

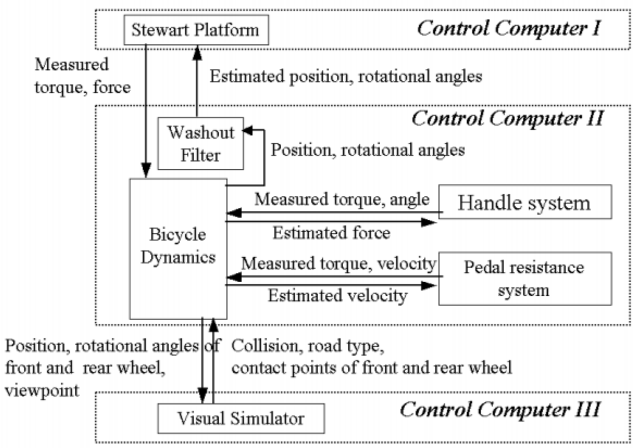

Figure 12. Input and output signals of the control system (Kwon et al., 2001)

The dynamics calculator receives and processes information from a handlebar reaction force system and a pedal resistance system that generates motion feelings. These are haptic devices that imitate the road conditions, by using background vibrations, to provide a more realistic feeling. To model these conditions, the handlebar reaction forces and rolling resistances are measured for real bicycles on different road conditions such as asphalt, grass, bricks and soil. These conditions are not considered for the development of the dynamic model because it would make it difficult to solve, therefore the bicycle dynamics results without road conditions and a road condition profile are superposed and compared with the experimental results (Kwon et al., 2002). It is assumed that the rolling resistance between the wheels and the road is proportional to velocity (Kwon et al., 2002). The pedal resistance system calculates the pedal resistance force by using a rolling resistance model with variations for different road conditions. The handlebar reaction forces can be calculated by analyzing the measured handlebar torque. Using this information from the first model, a more precise model was developed, as seen in Figure 13.

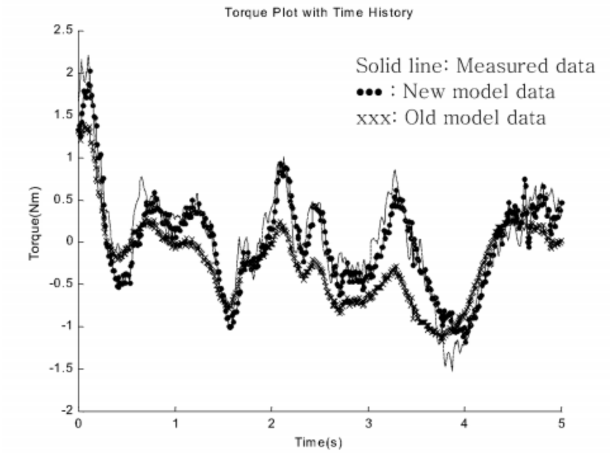

Figure 13. Torque plot for different models (Kwon et al., 2002)

The dynamic model can calculate the location of the bicycle based on the rider´s input and geographical information from the visual database (Kwon et al., 2002). Using the information from the location of the front and rear wheel locations, as well as the location of the user, the visual simulator creates images and sends information such as contact points of the wheels with the ground, normal vectors and road conditions to the dynamic model (Kwon et al., 2002). Auditory perception highly complements visual perception to provide information to the rider of its location and position in space. To improve the sense of reality, a virtual reality system with 3D sound effects was implemented. The acoustic system uses the relative position of an observer, object ID and ground conditions to create realistic sounds. The system uses 3D vectors in relative coordinates between the rider and the virtual sound source, which are delivered as UDP (User Datagram Protocol) packages. The output is calculated using a VBAP (Vector Base Amplitude Panning) algorithm. To further process the information and generate a 3D effect, an HRTF (head relative transfer function) filter is applied to the sound source before it is delivered to the rider. It obtains the viewpoint vector of the rider from the HMD (head-mounted display), which is then transformed with the 3D vector in relative coordinates (Kwon et al., 2002).

3. DLR bicycle simulator set-up

The purpose of the bicycle simulator is to generate realistic circumstances to enable the study of the driving behavior of cyclists. The simulator constructed at the DLR Institute of Transportation Systems is composed of the hardware components shown in Figure 14.

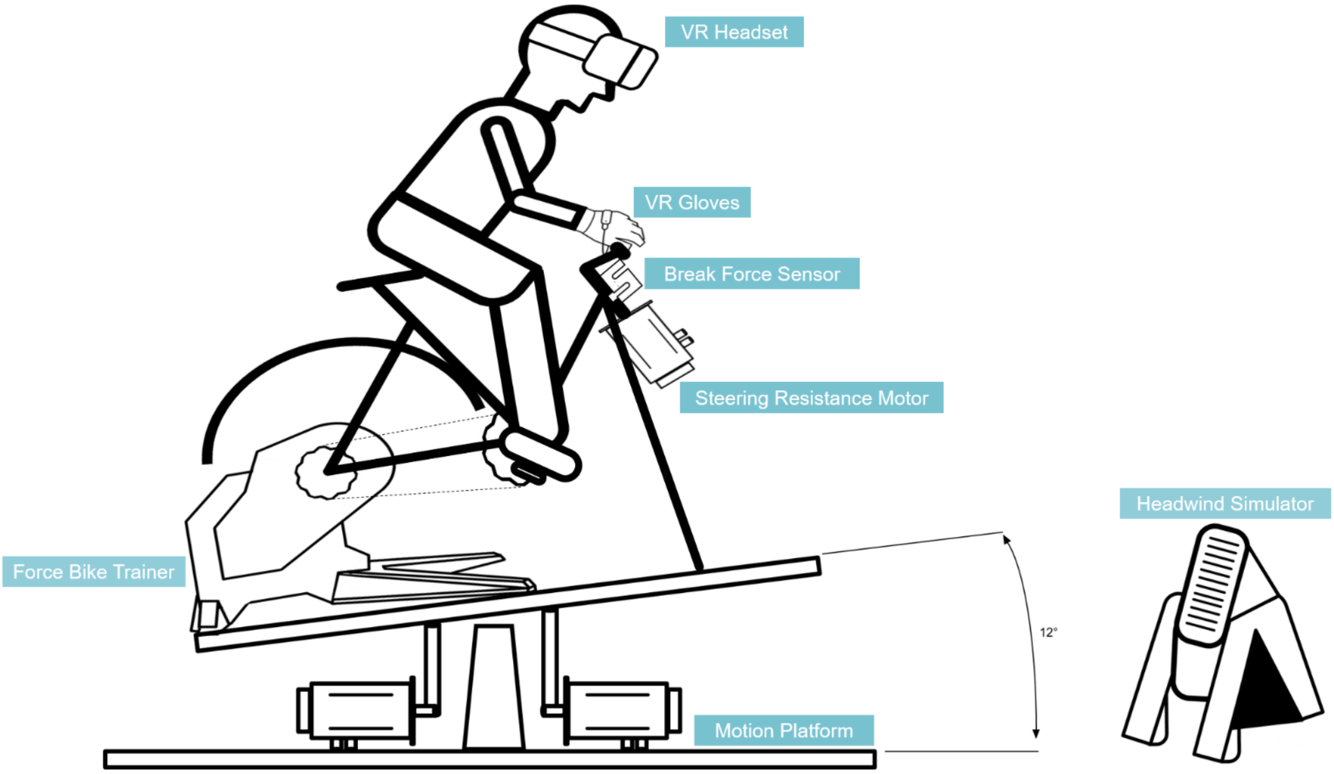

Figure 14. Hardware components of the bicycle simulator

The simulator was built using a stationary bicycle frame with adjustable seat and handlebar height in order to fit different-sized riders. To generate motion, the bicycle is mounted on a motion platform with two degrees of freedom that reproduces the pitch and roll movement, with the purpose of simulating road inclination and lean angle. The platform allows the simulation of external forces acting on the bicycle and different road surfaces. A headwind simulator is used to recreate the airflow that cyclists experience while riding and therefore aid immersion at different velocities. The speed of the fan is proportional to the driving speed. The airflow can help reduce motion sickness and increase comfort because the users are generating heat energy while riding. The real-time visualization is reproduced on a HMD (Head-mounted display) that shows dynamic images of a virtual world in VR (Virtual Reality). The VR gloves track the movements of the hands and display them in the simulation within the cyclist´s field of vision.

The simulator allows the cyclist to interact with the visualization and receive haptic feedback through the use of the handlebar, the force bike trainer and the motion platform. These elements must simulate the driving and steering forces and provide torque feedback. The handlebar is a haptic steering device connected to a motor that replaces and simulates the motion of the front wheel and generates force feedback by reproducing the steering resistance. Realistic torque feedback enhances rider control and prevents excessive rotation of the handlebar (Dialynas et al., 2019). This motor can measure the position of the handlebar to calculate the steering angle. The second force feedback device is a force bike trainer which replaces the rear wheel and registers the cycling velocity. It is connected with the pedal, chain, and chain pulleys of the bicycle. This element is able to simulate inertia and create realistic resistance of road conditions such as road friction, air resistance, gradient and gravitational forces. Two force sensors are used to measure the force with which the brake handle is pulled. One of the brakes is used to reduce the movement of the bike trainer by pressing the rear wheel and therefore restricting its rotation.

The motion data is particularly important to maximize the immersion in the virtual environment because it provides the tools to control the simulation with real-life information of the physical behavior of cycling situations. A model-based control approach is utilized to simulate the motion of the bicycle. The following computer model was designed to process the information and generate the feedback required by the hardware and other applications involved in the simulation environment.

3.1. Model of the driving dynamics of a bicycle

The objective of the dynamic model is to understand the reactive forces that influence an object and provide a realistic representation of the movement behavior of a bicycle. The model communicates with several components and performs cyclic processing in the background of the dynamic calculations at each sampling time. It receives information from the sensors and the visualization, and provides data for other applications such as motion cueing, which parametrizes and prepares feedback to be sent to the visualization and the actuators. This process is depicted in Figure 15.

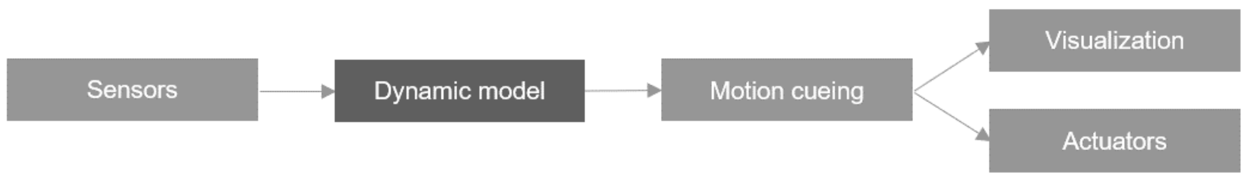

Figure 15. Block diagram of the embedding of the dynamic model

The dynamic model observed in Figure 16 was developed with the formulas provided in Chapter 2.2. The model receives force input from the diver regarding pedaling, steering and braking. With this information, it calculates the following quantities: speed, acceleration, cornering, steering and braking. This model does not consider the leaning motion measured by the motion platform. This is planned to be done for the further development of the simulator.

The calculation of the driving dynamics is divided into 4 main steps:

1. Velocity. This module receives information from the force bike trainer, the visualization and the brake force sensors. As output, it delivers the sum of the total resistance and the speed that is portrayed in the simulation.
2. Steering. It receives the steering angle measured by the steering motor and with the simulation speed calculates the steering angle, speed angle, angular velocity and angular acceleration.
3. Wheel forces. By using the steering angle, speed angle, angular velocity, the front and rear tire forces are calculated.
4. Torque. Information about the wheel forces, steering angle and angular acceleration is processed to calculate the torque that the steering motor requires to provide a realistic driving feeling.

The constant bicycle parameters required by the dynamic model with its default value and name of the variable in the code can be found in Table 2, whereas Table 3 shows the physical variables utilized in the dynamic model with the name of the variable in the code and it indicates if it is an input or an output for the dynamic model.

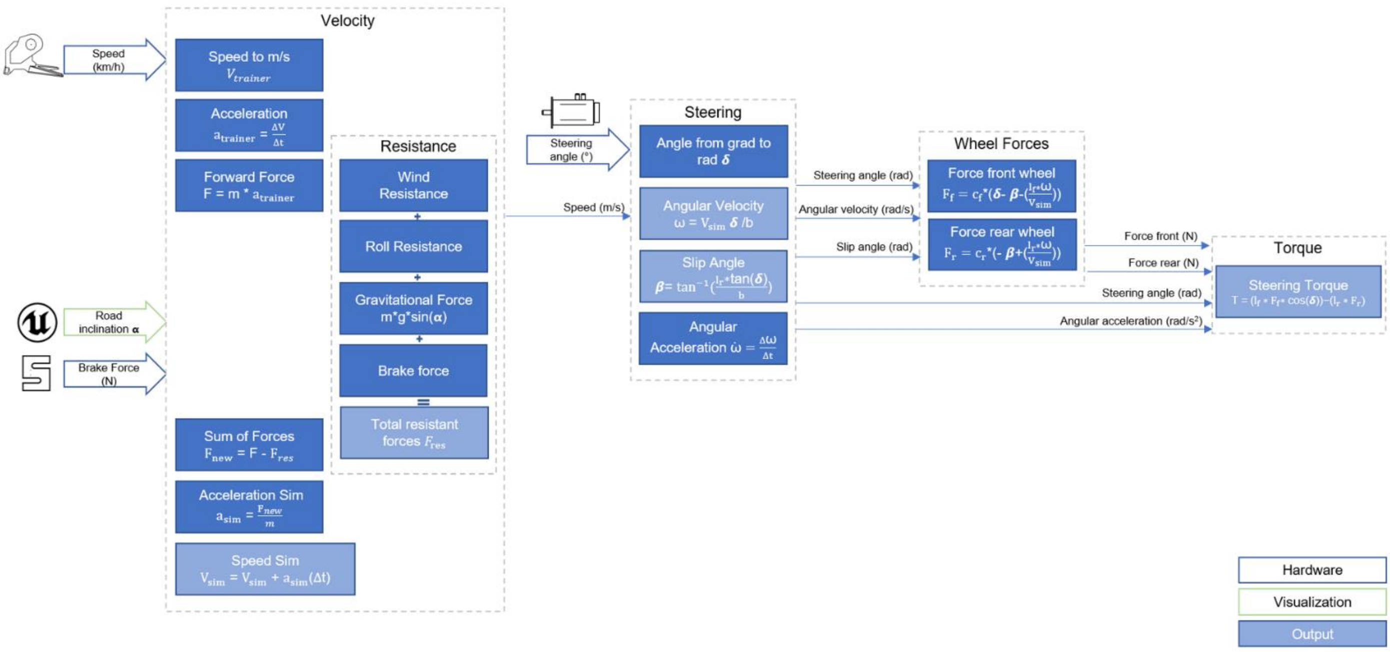

Figure 16. Dynamic model of the bicycle simulator

Table 2. Constant parameters of bicycle

Symbol	Parameter	Variable name	Default value
m	Total mass of the system	vehicleMass	100 kg
b	Wheel base	bikeLength	1.2 m
l_r	Length center of mass to rear wheel	lengthRear	0.6 m
l_f	Length center of mass to rear wheel	lengthFront	0.6 m
c_f	Cornering Stiffness Front Wheel	corneringStiffnessFront	156
c_r	Cornering Stiffness Rear Wheel	corneringStiffnessRear	156
g	Gravity	gravity	9.81 m/s^2

Table 3. Parameters of the dynamic model

Symbol	Parameter	Variable name	Input/Output
$V_{trainer}$	Trainer speed	forwardVelocityTrainer	I
$a_{trainer}$	Trainer acceleration	trainerAcceleration	I
F	Forward force trainer	tireForwardForceTrainer	-
F_{res}	Total resistant forces	resistance	O
F_{new}	Sum of forces	forceSum	-
a_{sim}	Simulation acceleration	vehicleAccelerationSimulation	-
V_{sim}	Simulation speed	forwardVelocitySimulation	O
δ	Steering angle	steeringAngle	I
V_x	Velocity in x	velX	O
V_y	Velocity in y	velY	O
ω	Angular velocity	angularVelocity	O
β	Slip angle	slipAngle	O
$\dot{\omega}$	Angular acceleration	angularAcceleration	-
F_f	Force front wheel in y direction	forceFrontWheel	-
F_r	Force rear wheel in y direction	forceRearWheel	-
T	Steering torque (Resistance)	steeringTorque	O

The calculations obtained from the dynamic model are transferred to other operational components of the simulator. After processing the physical variables, visual and haptic feedback is delivered to the cyclist through the hardware components, including the VR visualization. This allows the synchronization of the virtual and physical environments with the goal of simulating real bicycle motion.

3.2. Integration of the components into an overall system

The bicycle simulator should activate the following sensory systems of the cyclist: visual, proprioceptive, vestibular and auditory (Dialynas et al., 2019). Interfaces that activate these sensory systems are required to increase immersion into the virtual environment. Visual information is a very important factor for the perception of objects (Kwon et al., 2002). The simulator provides visual feedback for the rider by using the simulation software Unreal Engine 4. This allows the creation of 3D scenarios, as seen in Figure 17, while simulating realistic physic behaviors using the data received from the dynamic model.

Figure 17. Visualization of the driving scenario in Unreal Engine 4

The physical inputs of the rider are displayed realistically in the visualization through the use of a VR headset, which enables a graphical representation that covers 360° of horizontal vision. This technology also allows tracking of the motion of the user´s head and eye movements. This provides important data of the user´s behavior about the impact of the simulation on physical and mental performance. Two of the main disadvantages that need to be taken into account while using VR lenses are the presence of simulator sickness and the fact that the user cannot see the real world. This must be taken into account for the design of the simulator and of security measures to protect the user.

Figure 18. Visualization of the bicycle in Unreal Engine 4

To activate the proprioceptive sensory system, haptic feedback is created by processing the data exchanged between the mechanical construction, the simulation software and the visualization. As the rider manipulates the haptic devices (handlebar and pedals), the location and state of the bicycle are updated due to the constant communication between all the elements of the simulator. The virtual bicycle is rendered on the graphical interface as displayed in Figure 18. The reactive forces calculated by the dynamic model are sent to the hardware components as well as the visualization. This includes the motion platform, which enables the stimulation of the vestibular sensory system by simulating leaning, inclination and braking behaviors.

The motion cueing module is in charge of providing the rider accurate vestibular and proprioceptive feedback by providing realistic motion cues and vibrations, as the ones that would be present in real manoeuvers. It is an interface between dynamic model and simulator which is designed to increase immersion and therefore enable a better driving sensation, considering the capabilities and physical limits of the hardware elements.

Auditory perception increases the immersion as it aids the rider to orient itself in space and identify the elements of its surroundings. Unreal Engine allows the use of dynamic 3D noises either from the bicycle itself such as pedaling and tire noises on different surfaces, as well as ambient noises from other road users like cars or pedestrians.

The integration into an overall system with the goal of maintaining the human in the loop is achieved through communication and synchronization between all elements of the bicycle simulator. These elements, shown in Figure 19, include the mechanical construction, the simulation software and the VR environment.

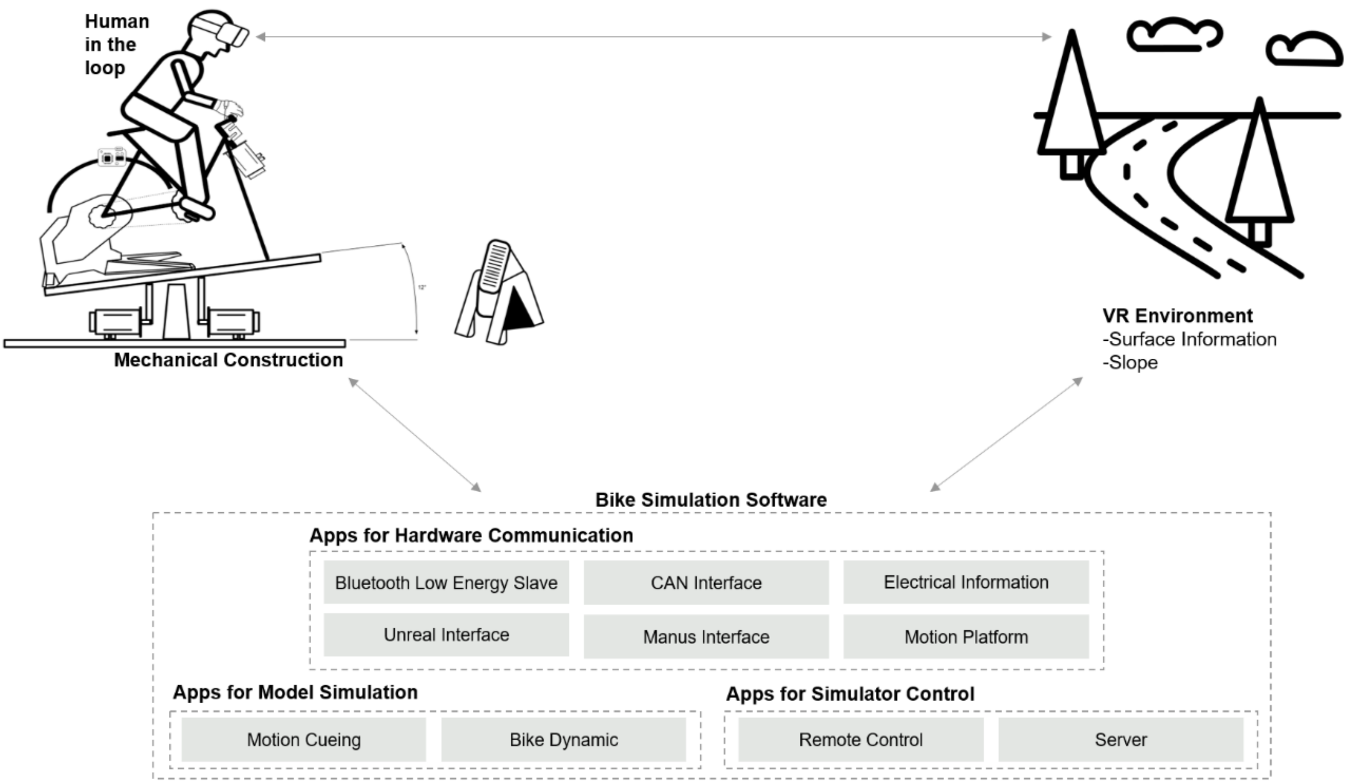

Figure 19. Concept and simulation software of the bicycle simulator

The virtual reality environment integrates geographical data using a 3D terrain generation software for real-time environments. To improve the sense of reality, the slope and surface information is communicated to the active motion system creating a closed-loop integration of all the elements of the simulator. This highly complements the hardware components and provides information to the rider of its location and position in space.

The real-time synchronization of the VR visualization with the hardware information is crucial for the creation of a highly immersive experience. To achieve this, the cyclical communication between the control elements needs to happen in periods that are short enough. The computing environment of the bicycle simulator consists of three software subsystems: hardware communication, model simulation and simulator control. The task of this thesis was to integrate and develop the apps for model simulation, which are the motion cueing and bicycle dynamics.

The integration of all the components of the simulation software enables the collection of simulator and rider performance data that can be used to evaluate and improve the simulation environment. This information includes speed, braking, acceleration, location, steering angle, yaw rate, lean angle and eye movements. This data can be used for a first evaluation of the acceptance of the simulator, seen in Figure 20, whereas the results can be used for fine-tuning of the parametrization of the motion cueing.

Figure 20. Side and front view of the bicycle simulator

4. Study design

The bicycle simulator is designed to provide a realistic driving sensation that enables the study of people´s behavior and perception under different cycling circumstances. The use of VR as a research tool combined with the bicycle simulator supports a human-centered approach, enabling the assessment of subjective perceptions and preferences of cyclists surrounded by different environments (Nazemi et al., 2019). To evaluate the responses and preferences of the drivers, the simulator must create similar motion conditions as the ones felt while riding a real bicycle.

With the focus of identifying simulator characteristics that do not fit a real-world behavior and are therefore not accepted by the users, a study to evaluate the bicycle simulator and collect information about the riding behavior was designed. The study aims to evaluate the bicycle simulator, in particular the driving dynamics, mechanics and motion cueing in the form of predefined driving profiles, via the recording of acceptance. This information can be used to upgrade the simulation model and improve the calibration of the simulator based on the feedback of cyclists.

The following research questions arise:

RQ 1: Are the differences between the driving profiles perceived?

RQ 2: Which driving profile provides a better driving sensation?

RQ 3: How high is the acceptance of the simulator?

RQ 4: Does the simulation set-up correspond to the behavior of a real bike?

To answer these questions and test the features of the simulator, an experiment was designed with a total duration of 90 minutes, including enough time for a pause between scenarios and to fill in the questionnaires. The driving time was different for all users, it was planned to be between 30 – 60 minutes. The target was to evaluate 20 complete data sets of persons of any gender older than 18 years that ride a bicycle regularly (at least once a month). The recruited users were required to cycle in a virtual environment, where the possibility to have any accidents did not exist. They could maneuver with the handlebar, pedaling, braking and leaning behaviors.

To start the experiment and get familiarized with the driving sensation, a training session of around 3 minutes was performed, in which the participants were instructed to cycle through an urban environment while performing small tasks such as braking and turning in both directions. After the training phase, the participants were asked to cycle along four different scenarios on a short bicycling course generated with the geographical information and the appearance of the road, signs, and markings of a research crossroad in the city of Braunschweig as seen in Figure 17. The specifications of each scenario are depicted and explained in Table 4. The length of each ride was of around 2 minutes and the scenarios were performed in random order.

Table 4. Explanation and representation of the driving scenarios

Scenario	Description	Graphical representation
1-A	Driving straight ahead and stopping at the traffic light with crossing vehicle	
1-B	Driving straight ahead and stopping at the traffic light with a vehicle driving straight ahead	
1-C	Driving straight ahead and stopping at the traffic light without a vehicle	
2	Turning to the right and avoiding a construction site without a vehicle	

The first three scenarios (1A, 1B, 1C) have the same course configuration but vary in the amount of interaction between the participant and a vehicle. In the last scenario, the rider must avoid a construction site and has no interaction with other road users. Each rider is required to drive through the five (training + 4 scenarios) environments two times with different driving profiles. During the study, the following independent variables were manipulated:

1. Driving task: driving straight ahead and stopping at the traffic light vs. turning to the right and avoiding a construction site
2. Interaction: vehicle crossing, vehicle driving straight, no vehicle
3. Driving profile: profile A and B

The driving profiles were designed to evaluate the mechanics and dynamic behavior of the simulator. Two parameters of the motion cueing module were varied. These are listed and explained in Table 5.

Table 5. Characteristics of the parameters of the driving profiles

Parameter	Description	Profile A	Profile B
Yaw Rate	Factor between the calculated yaw rate, coming from the dynamic model and the applied yaw rate in the virtual reality visualization	0.5	1
Roll	Factor between the measurement of the slope from the motion platform and the virtual reality visualization	2	1.5

The yaw rate (or angular velocity) and the leaning angle (roll angle) exist in both the physical as well as the virtual environment. The rider can control these through movements of the handlebar and motion platform, which are displayed through the visualization. The synchronization between the physical and the virtual environments needs to be adjusted to improve the realism considering the physical performance of the simulator and the visual replication of the information. Therefore, feedback from the study participants is essential for the calibration of the physical and virtual movements of the bicycle.

For the study, the participants had to answer a series of questionnaires about their demographical information, cycling background and experience using virtual reality. The following dependent variables were collected before, between and after the trials through the use of questionnaires:

- Acceptance (Acceptance scale - Van der Laan)
- Realism (One-dimensional scale, two open questions)

In addition, symptoms of simulation sickness were recorded by using:

- Simulator Sickness Questionnaire (SSQ)
- Fast Motion Sickness Scale

At the end of the experiment, the test persons went through a post simulator survey to grade their experience when using the simulator.

Further information recorded from each participant includes driving speed, yaw rate, deceleration, inclination angle, as well as hand, eye and head movements. This information, specially the driving speed and yaw rate can be compared with real-life information from sensors placed at the research intersection in Braunschweig collected by the Institute for Vehicle Technology (Institute für Fahrzeugtechnik - IfF) from the Technical University of Braunschweig.

The implementation of the study, the recorded data and the surveys for the test persons concerning the immersion of the dynamic movements of the bicycle help assess possibilities for calibration measures to improve the performance and safety of the simulator. These results will be analyzed in the following section.

5. Evaluation of results

In order to evaluate the performance and acceptance of the bicycle simulator combined with virtual reality, several test scenarios were conducted in a simulated environment. A small sample of 24 persons including 11 females (mean age = 29.18, SD = 4.85) and 13 males (mean age = 29.77, SD = 5,08) participated in this experiment with a mean cycling experience of 22.5 years and an average of 139.7 km cycled per month. As seen in Figure 21, only 17% of the participants had never used VR lenses before, whereas 46% had used them more than 10 times. The persons were asked about their sensitivity to motion sickness in previous experiences, and as shown in Figure 22, 4% declared significant sensitivity, 12% moderate, 46% slight and 38% reported no sensitivity to motion sickness.

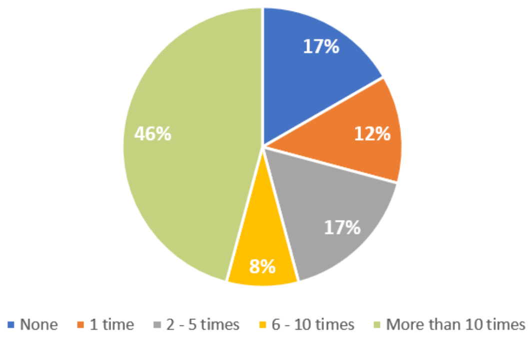

Figure 21. Experience using VR technology

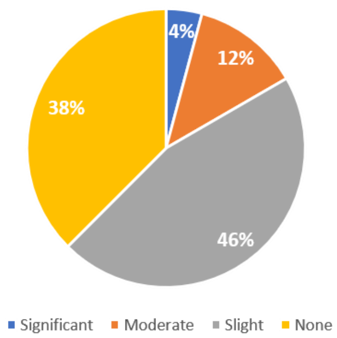

Figure 22. Sensitivity to motion sickness

Out of the 24 participants, three women had to stop the tests due to strong motion sickness symptoms, therefore the results presented in this section were collected from questionnaires answered by 21 participants. These questionnaires provide subjective information about the perception and judgment of the test subjects after riding the bicycle in virtual reality. The analysis of the collected data provides answers to the research questions proposed in this thesis.

5.1. Evaluation of results using subjective criteria

RQ 1: Are the differences between the driving profiles perceived?

To solve this question the order of the driving profiles was varied, therefore half of the participants performed the experiment with order AB and the other half with the order BA. After the end of the whole experiment, the users were asked to evaluate which profile provided a better driving experience. The results seen in Figure 23 show a variation in the perception of the differences between driving profiles. After driving with the order AB, 46% of the cyclists reported that they found “rather part 2” provided a better driving sensation, whereas none of the users reported this feeling after driving with the order BA. Furthermore, 18% reported that they did not notice the differences between the driving profiles after riding with AB, this was reported by 50% after riding with BA.

A deeper analysis than the one provided by this theses is required to identify the origin of these differences, but the fact that there are perceived differences after driving with a different order can be observed in the results. This can also be a consequence of the small size of the sample and would require a bigger experiment to be proven.

The fact that most users (82% by AB and 50% by BA) indicated that part 2 provided a better driving experience can be justified with the fact that they got used to the feeling of the simulator and learned with time how to control the system and how to behave while driving it.

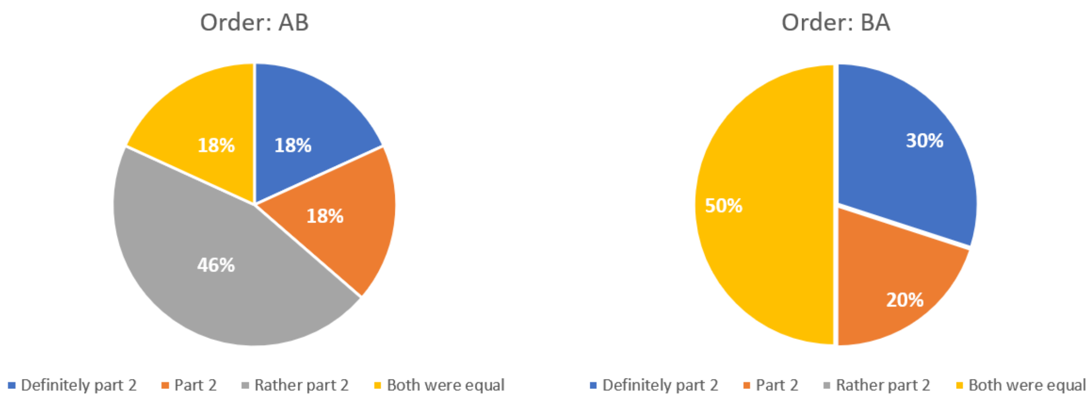

Figure 23. Evaluation of the driving experience with both driving profiles in a different order

The next step is to identify if the users experienced a different driving sensation while driving with each profile, even if they did not notice the difference between those. To evaluate this, the following question arises.

RQ 2: Which driving profile provides a better driving sensation?

A simulator sickness questionnaire (SSQ) was performed after each training and after each experiment section. The analysis of this questionnaire provides crucial information about the state of the participants after cycling with different profiles.

The results of the SSQ for the training phase, depicted in Figure 24, show that after driving with profile A on the training section, the users experienced up to 60% slight and moderate general discomfort, sweating and stomach awareness. About 20% slight and severe fullness of the head and about 30% slight, moderate and severe vertigo. Around 20% slight and moderate fatigue and headache, and nearly 10% slight eye strain, difficulty focusing (eyes), salivation increase, blurred vision and dizziness with eyes open. The users reported no difficulty concentrating or burping.

The results after cycling through the training phase with profile B show an increase in the severe (yellow) symptoms in general discomfort, sweating, nausea and stomach awareness. It is also clear, that generally the appearance of slight (orange) and moderate (gray) symptoms increased while driving with this profile. The results report over 70% slight, moderate and severe sweating, up to 60% slight, moderate and severe general discomfort, about 40% slight and moderate fatigue and vertigo, and around 40% slight, moderate and severe nausea and stomach awareness. Around 20% slight and moderate difficulty concentrating, and nearly 20% slight headache, eye strain, fullness of the head and dizziness with eyes open. The users reported up to 10% slight difficulty focusing (eyes), salivation increase and blurred vision, and no burping.

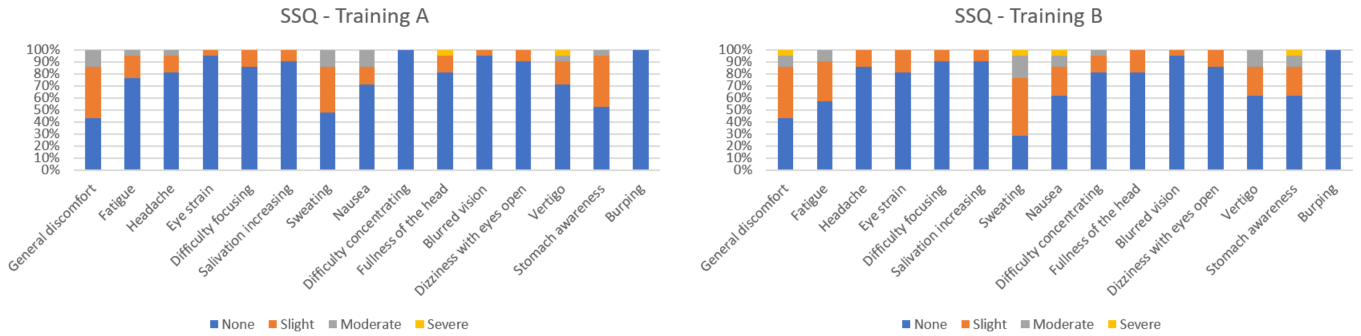

Figure 24. Results of the simulation sickness questionnaire for the training phase of the experiment for profile A (left) and profile B (right)

The results of the simulator sickness questionnaire performed after driving the block of four scenarios with each profile are shown in Figure 25, where it can be seen that the users also experienced fewer simulation sickness symptoms while driving with profile A, and that the severity of these symptoms was lower. The symptoms that changed the most were for example fatigue, which was around 40% slight to moderate in profile A but almost 60% in profile B. Sweating in profile A was indicated to be slight to moderate in 70% of the cases, whereas in profile B it was indicated to be slight, moderate and severe in 80% of the cases. Vertigo and stomach awareness stayed by the same percentage, but more moderate and severe cases were reported. The percentage of nausea is 10% lower by profile B than by profile A and it has a similar relation between slight, moderate and severe cases. A deeper analysis would be required to examine if this effect has a relation

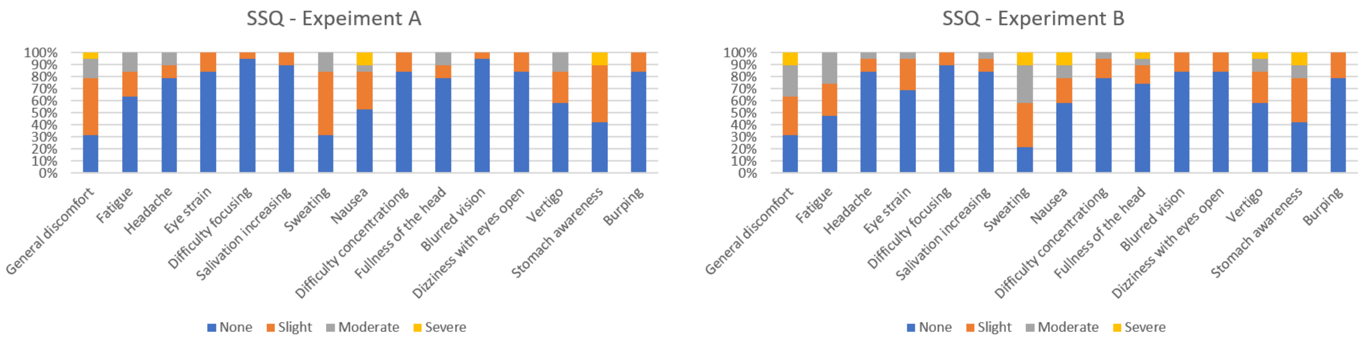

Figure 25. Results of the simulation sickness questionnaire for the experiment phase for profile A (left) and profile B (right)

to the order in which the participants performed the study. The increase of cases and severity in almost every section supports the assumption that profile A provides a better driving sensation than profile B.

The results of the fast motion sickness scale, summarized in Table 6 complement these results. To collect considerable data for each bicycling environment, the participants were asked after each scenario how strong were all the symptoms of motion sickness summarized together on a scale from 1 – 20. The results show that the average of symptoms felt while driving profile A was significantly lower than the average symptoms experienced in profile B.

Table 6. Results of the fast simulation sickness scale

Scenario	Profile	
	A	B
1A	3,43	4,52
1B	4,00	4,95
1C	4,09	4,75
2	3,66	4,14

RQ 3: How high is the acceptance of the simulator?

For the assessment of acceptance of the bicycle simulator to evaluate if the system is appealing to the cyclists, the scale shown in Figure 26 was presented to the cyclists after being exposed to each profile. The users had to assess each of the 9 criteria according to their experience after using the simulator. For the evaluation of the results, the criteria are coded from -2 to + 2 from left to right, whereas items number 3, 6 and 9 are mirrored and are therefore coded from +2 to -2.

1	Useful	-2	-1	0	1	2	Useless
2	Pleasant	-2	-1	0	1	2	Unpleasant
3	Bad	2	1	0	-1	-2	Good
4	Nice	-2	-1	0	1	2	Annoying
5	Effective	-2	-1	0	1	2	Superfluous
6	Irritating	2	1	0	-1	-2	Likeable
7	Assisting	-2	-1	0	1	2	Worthless
8	Undesirable	-2	-1	0	1	2	Desirable
9	Raising Alertness	2	1	0	-1	-2	Sleep-inducing

Figure 26. Acceptance scale (Van Der Laan et al., 1997)

The analysis of the results seen in Figure 27 shows that the users had a tendency to find the system useful, assisting and that it raised awareness. Lower scores, but still positive were received for good, nice, effective, likable and desirable. The users reported that the simulator was slightly unpleasant, this can be due to the exposure to virtual reality display together with moving hardware, and the lack of calibration of the motion cueing, which is one of the main goals of the study. The general positive ratings show that the users accepted the simulator, however, fine-tuning must take place in order to provide a pleasant experience.

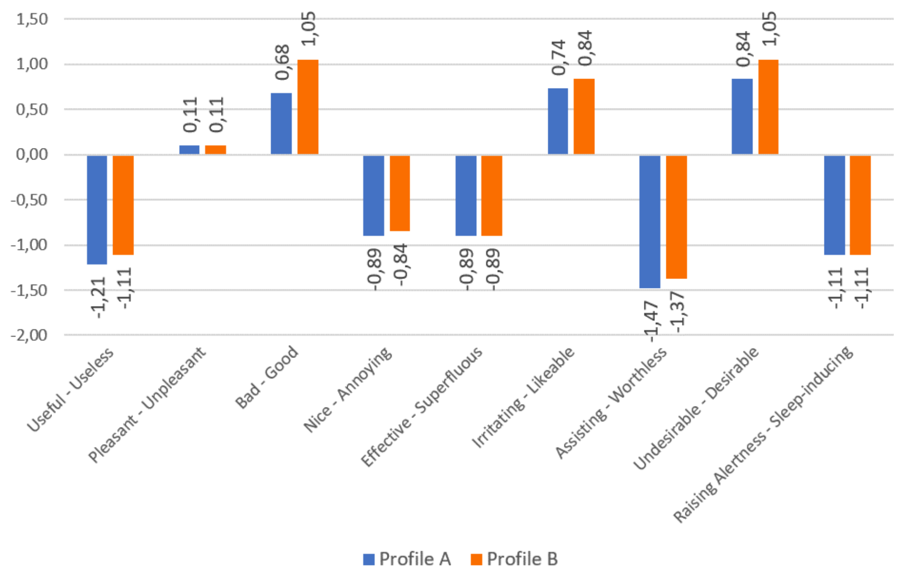

Figure 27. Acceptance ratings of the bicycle simulator

An overall judgment of the usefulness and satisfaction of the system can be performed by calculating the average of items 1, 3, 5, 7 and 9 for the usefulness score and items 2, 4, 6 and 8 for the satisfaction score. The users evaluated the system with an absolute value of the average of 1.07 in the usefulness score and an absolute value of 0.59 in the satisfaction score, which reflects a good acceptance of the simulator as they provided positive ratings. A low score of satisfaction can depend on whether the system restrains the free choice of the participants and therefore forces them to act in a certain manner (Van Der Laan et al., 1997), it also depends on the unpleasant feelings that the simulator causes due to a lack of calibration.

The probands were asked on the postsimulator survey to evaluate the realism of the simulator on a scale from 1 to 10, where they graded it with a mean score of 5,6 with a standard deviation of 2,5. A more realistic experience would provide a better physical riding feeling, therefore, a first step to performing a fine-tuning of the simulator is to perform a comparison with real-life data. This will be done in the following section.

5.2. Evaluation of the study using objective criteria

To analyze the performance of the cycling sensation it is necessary to evaluate quantifiable evidence of the behavior of the simulator. This allows a validation of the developed model and further calibration with the objectives of creating a realistic riding experience and generating accurate data on further studies. The realization of experiments in a controlled environment provides enough information to be analyzed under constant conditions, and judge if the simulated environment evokes the same behavior as a real-world situation. The following research question allows a comparison with real-life data to evaluate the cyclist´s behavior based on infrastructure-based measurement data and hence, carry out a performance calibration to eliminate unrealistic responses.

RQ 4: Does the simulation set-up correspond to the behavior of a real bike?

To evaluate this, the Institute for Vehicle Technology (Institute für Fahrzeugtechnik - IfF) from the Technical University of Braunschweig provided data collected at the research intersection about the behavior of bicycles measured with a laser sensor. The speed and yaw rate obtained from the collected data will be compared with the information calculated by the dynamic model and motion cueing of the simulator, as seen in Figure 28.

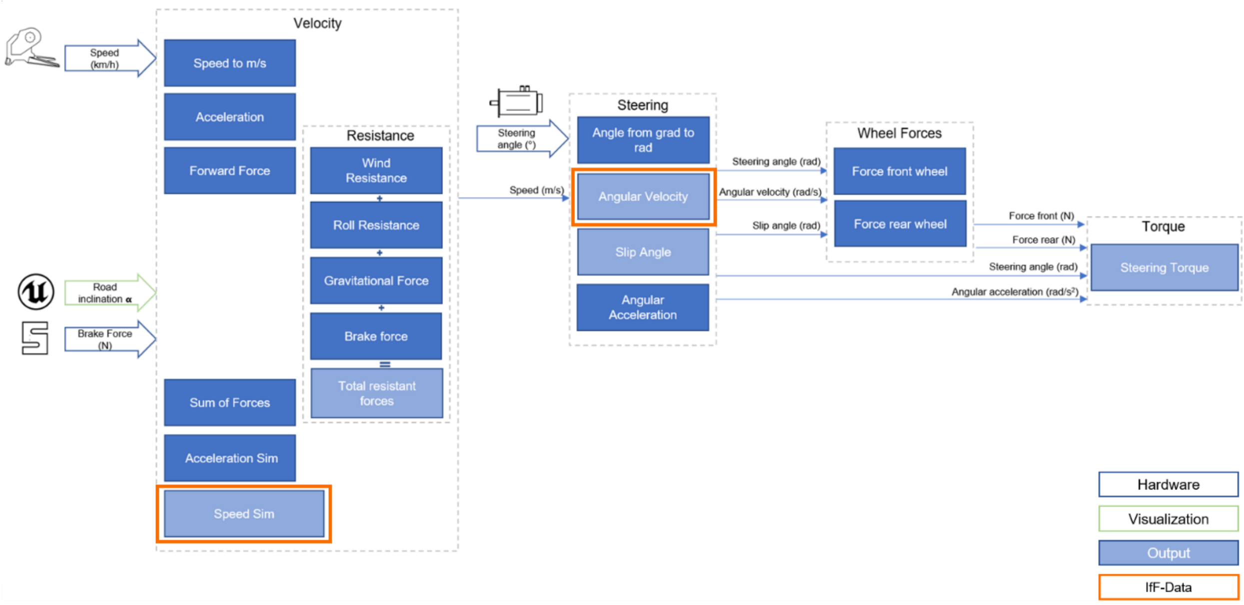

Figure 28. Data to be compared between the simulator and real-life information

The results of the data analysis corresponding to the absolute forward velocity (also known as speed) and angular velocity (also known as yaw rate) profiles of real bicycles are examined in this section with the purpose of adjusting the software and hardware components to improve performance of the simulator. The provided data cannot be examined for specific routes, therefore the information recorded during the experiment of all driving scenarios was combined for the comparison with the real data.

Absolute velocity

The speed profile of 1439 bikes recorded on the research intersection can be seen in Figure 29. This image shows the velocities between 0.3 m/s (1.08km/h) and 15 m/s (54 km/h). The lower limit was done to eliminate the elements that were not in motion, and the upper limit was to eliminate data sets from invalid classifications, such as motorbikes etc. As seen in the picture, the average driving velocity was of 3.728 m/s (13.420 km/h) and most of the elements were moving between an interval of 0.3 m/s (1.08km/h) and 8m/s (28.8km/h).

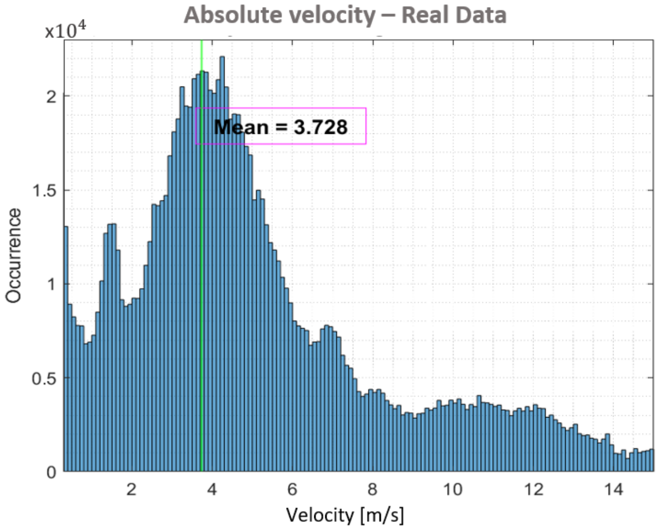

Figure 29. Absolute velocity profile of real-life data

Figure 30 display the recorded absolute velocities higher than 0.3 m/s after performing several tests with 4 different scenarios with each driving profile, as explained in Chapter 4. These graphs show that the highest velocity driven by the cyclists was around 5 m/s (18 km/h) with a mean of 2.561 m/s (9.22 km/h) and 2.663 m/s (9.59 km/h).

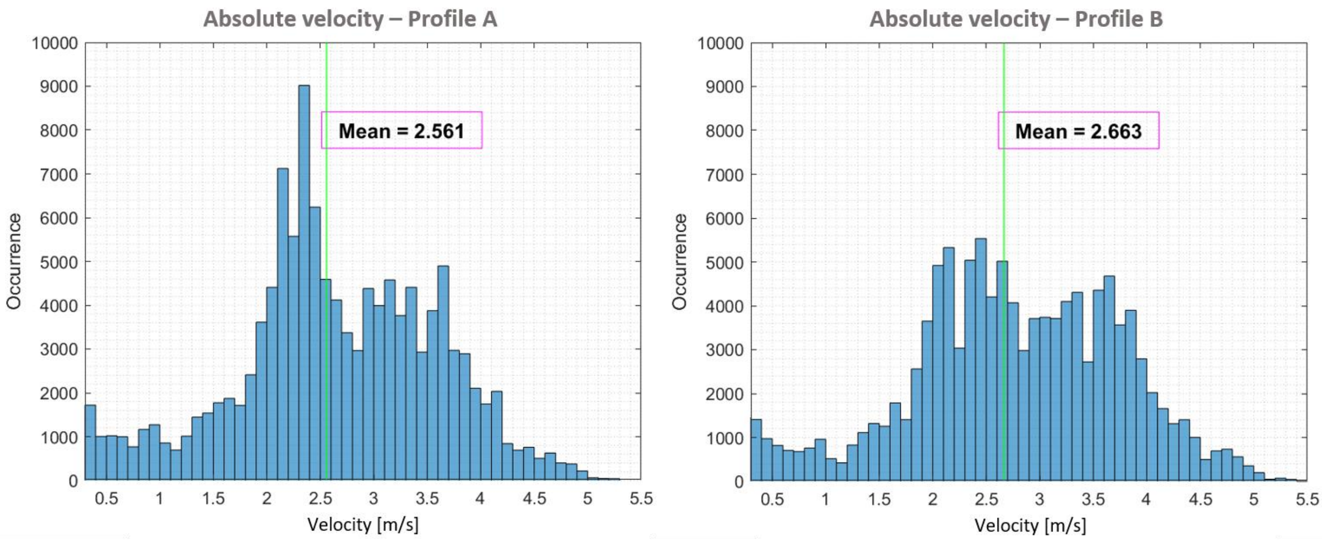

Figure 30. Absolute velocities of driving profile A (left) and driving profile B (right)

For this experiment, the velocity received from the bike force trainer was the same velocity used for the simulation, considering only the braking force as resistance. It can be noticed that the velocities received from the bicycle simulator are approximately 1 m/s (3.6 km/h) lower than those obtained from the real data. A possible factor that affects these values can be the lack of usage of the bike gears during the study. This could be solved by adjusting the mechanics and allowing gear shifting. Another possibility for providing more realistic speed conditions is to dynamically adjust the resistance of the force bike trainer, creating this way a virtual gear. Generally, an update of the hardare capabilities to measure at higher frequencies and with a higher resolution must be performed. These options would require further calibration for the model to deliver higher accuracy. Another possible option that must be considered is the feeling of motion sickness while driving in a moving simulation, which could be a reason why the probands did not drive faster. This must also be further examined.

Angular velocity

The angular velocity within an interval of -0.5 rad/s to 0.5 rad/s of actual bicycles measured in the research intersection is shown in Figure 31. In this graph, it can be noticed that the average angular velocity is 0.009 rad/s. This high amount of values near zero indicates that most of the bicycles were driving straight. The further values indicate different steering operations, with the positive values indicating a turn to the right and negative values to the left.

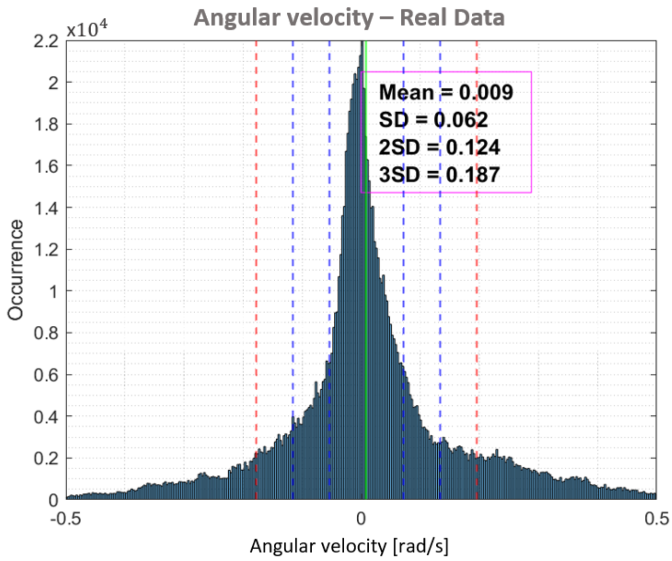

Figure 31. Angular velocity profile of real-life data

The movement of the handlebar controls the yaw rate, which is then processed by the dynamic model and motion cueing and is sent to the visualization. As explained in Chapter 4, the motion cueing factor “yaw rate” modifies the value registered by the dynamic model. This factor was 0.5 for profile A and 1 for profile B. This means that the angular velocity from the dynamic model is multiplied by 0.5 in profile A and then sent to the visualization. This process can be observed in Figure 32.

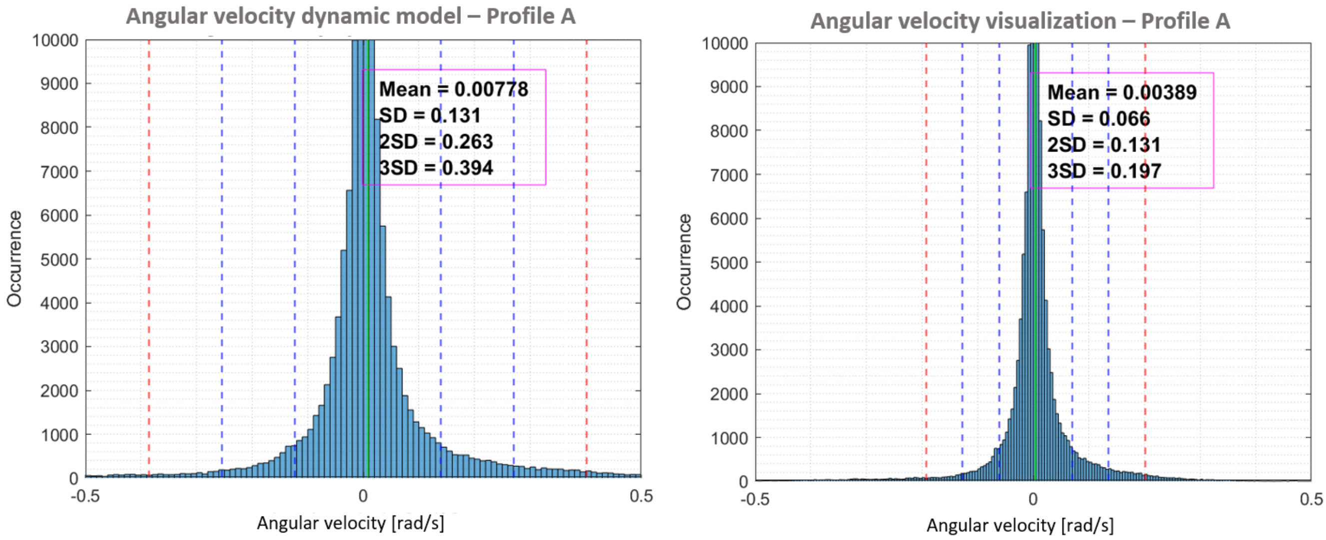

Figure 32. Angular velocities of profile A corresponding to the dynamic model (left) and the visualization (right)

The average angular velocity recorded by the dynamic model mimics the behavior of real bikes. Since in RQ2 it was concluded that driving profile A provided a better driving sensation, these graphs show that smaller angular velocities make the user more comfortable. This might be due to the fact that while driving a bicycle, the bike might move with a higher average angular velocity but the head and point of view of the driver stays in a more stable position and does not necessarily turn with the same yaw rate as the bike. Another possibility is that fast movements in VR generate a feeling of dizziness and insecurity while driving.

Figure 33 shows the angular velocity of both the visualization and dynamic model for profile B, which are the same since the yaw rate factor for profile B was 1. The mean of 0.004 rad/s indicates that the drivers were more cautious by steering and performed smaller movements with the handlebar.

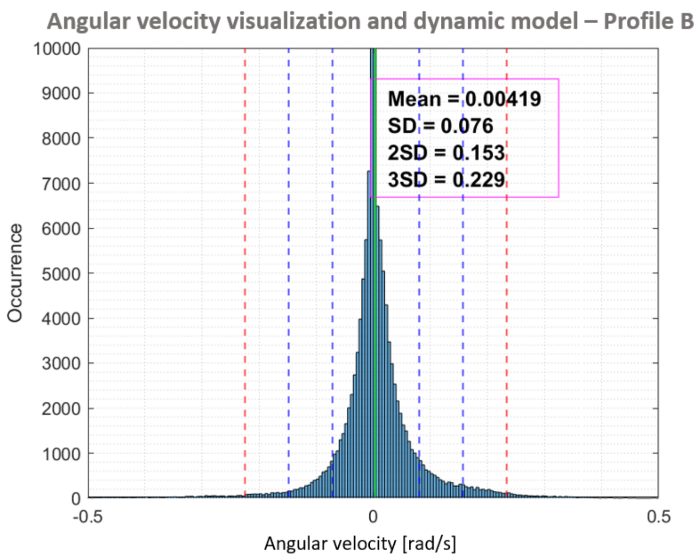

Figure 33. Angular velocity of profile B

The values of profile B are more similar to the values of the visualization of profile A, which were processed by the motion cueing. This might indicate that the drivers felt more comfortable and safe with smaller changes of the yaw rate in the visualization. The reason why riders preferred profile A might be that the changes of angular velocity are not so sensible as in profile B. For the further fine-tuning of the simulator, it would be suggested to test with different values of the angular velocity factor values that are around 0.5 to evaluate if a better driving sensation can be provided and simulation sickness can be avoided.

These analyses show that the parameters of the simulator require optimization for the velocity and yaw rate profiles of actual bicycles to be replicated and therefore provide a real feeling of cycling. The response action of the drivers must be considered as even though they have full control of the handlebar, pedals and brakes, their only visual feedback is the visualization. This can easily cause an increase in motion sickness since the expected feedback does not fit with what they are experiencing in the visualization. The real-life data provide a good base to accurately adjust the parameters of the simulator and therefore provide realistic feedback to the cyclists. The results can also be used to improve the hardware dependencies to accomplish similar movement values like the ones from the research intersection. It is expected that an increase in the realism of the simulator will cause a decrease in motion sickness symptoms and it is assumed that this will have an impact on the acceptance of the users.

6. Summary

Bicycle simulators enable the study of cyclists' responses to possible real-life scenarios without endangering them. With the use of these systems, it is possible to research the rider´s behaviors and possible conflicts while interacting with other road users such as vehicles, pedestrians and wheelchair users. The controlled setting surrounding the simulator offers the ability to provide the same riding conditions for all the participants and therefore collect reliable behavioral data. The bicycle simulator developed at the DLR Institute of Transportation Systems intends to provide an immersive experience through the use of virtual reality (VR) technology combined with realistic motion cues.

A systematic research was conducted to support the development of the dynamic model and motion cueing module based on background information about the dynamic behaviors of bicycles. This information provides a basis for the development and validation of the bike simulator. An overview of similar existing systems is provided, where the components and interfaces required for the development are identified.

Based on this information, a model of the driving dynamics was created with the main goal of providing an immersive experience. For this to be possible, compatibility, communication and synchronization between all the elements are essential. The hardware and software components of the system were integrated with the purpose of maintaining the human in the loop. The hardware components are used for the creation of a driving sensation supported by a visualization that takes place on a scenario based on real data.

A study for the evaluation of the simulator was designed using the derived knowledge as a basis. The goal of the study was to acquire information about the acceptance and performance of the simulator. This information supports decision-making for the process of fine-tuning and therefore provide a stable and realistic riding experience. The recorded data was analyzed by using subjective to understand the perceptions of the drivers and objective criteria to compare the behavior of the simulator to real-life data. By having two driving profiles, it is possible to evaluate which parameter generates a better response of the drivers, and use this information as feedback to better calibrate the simulation to reflect realistic bike performance.

6.1. Conclusion

This work aimed to perform an initial evaluation of the functions of the simulator for further calibration and development. To properly assess the human-machine interaction, the simulator must generate realistic motion cues when fed with real forces supplied by the cyclists. A realistic sense of cycling enables a better evaluation of subjective behaviors while driving in different situations. This test environment presents the opportunity to recreate the same conditions for every participant, which provides reliable and consistent data. In this case, the data was used to evaluate the perceptions, preferences and acceptance of the ridders after being exposed to the simulator. Accurate values are essential for the execution of any study, therefore information about real-life traffic situations was used to analyze the realism of the behavior of the simulator and to present measures for the further development of the simulator based on the received feedback.

The results of the questionnaires show that the simulator was accepted by the participants but requires further calibration to provide an immersive experience. It must be considered that the preferences are based on an individual level, but the fact that most of the users experienced lower simulation sickness while driving with profile A, indicates that this parameterization provided a more pleasant experience. The comparison with real-life data showed that the behavior of the simulator must be improved in order to eliminate unrealistic responses.

A bicycle simulator combined with VR technology and real-life infrastructure data is a research tool that allows the automated collection of performance measures both from the system as well as from the users. This set-up provides an alternative for performing tests concerning the reactions that are present within the interaction between cyclists and automated vehicles.

To optimize the performance of the system, improvements in the motion cueing and the visualization must be done with the goal of eliminating oversensitivity or undersensitivity of the components. The synchronization between the physical and the visual environments needs to be very precise to reduce motion sickness symptoms and therefore improve the acceptance of the simulator. These corrections in the physical and visual performance would have an impact on the perception of realism for a large number of participants.

6.2. Discussion

The system developed in this thesis was designed to provide a physical feeling of bicycle riding combined with a virtual reality environment. All the components were integrated with the focus of providing the right sensory cues during the implementation of studies based on the cyclist´s perspective. The simulator delivers haptic, vestibular, visual and acoustic motion cues to provide the users a realistic environment. This is done by using a motion cueing module which is the interface between the dynamic model and the simulator that aims to simulate the movements of a real bicycle by considering the mechanical possibilities and limitations that the hardware components provide.

Although the integration of the system was successful, several things must be improved for the simulator to provide a realistic and pleasant experience. The simulation of the driving dynamics requires further calibration in order to behave accurately and therefore provide the right motion cues to the rider. This calibration can be performed constantly by comparing the results of the system to real-life data and evaluating how the users feel while cycling.

The reactive forces that are sent to the handlebar and force trainer should be fine-tuned to provide a realistic torque and velocity respectively. Generally, it was observed that the bike trainer did not provide a satisfactory behavior due to a lack of control possibilities which include the insufficiency to provide a reliable connection and the deficiency to replicate real braking operations. Therefore, the search for a component that has better compatibility with the simulator is suggested.

The movements of the platform should be adjusted to correctly stimulate the vesicular system. This includes leaning behaviors, as well as the reproduction of the acceleration and braking procedures. The exploration of parameters that provide a better riding sensation within the physical limits of the platform is required. This must be implemented by considering the motion sickness symptoms that a virtual reality environment can generate. This can be done by adjusting parameters in the motion cueing algorithm or directly by calibrating the platform by using the software provided by the manufacturer. During the performed study the participants barely used the possibility to lean and therefore it is difficult to make a statement about the roll factor presented in Chapter 4. To further develop this behavior it is necessary to experiment with the spring rate with which the motion platform pulls back to the center and the transmission of this behavior to the visualization. A possibility to allow the users to get used to the feeling of leaning would be to create a training phase in which the users experiment with the physical behavior of the simulator without the VR lenses, and therefore understand what is possible and which are the physical limits of the simulator.

The following changes and improvements can be performed for the parameterization of the dynamic model and motion cueing. The factors that can be implemented and calibrated are speed transmission, step resistance factor, damping of the handlebar, braking force transmission and resistance factor that includes inclinations and rolling resistances.

The experience of the users while using virtual reality combined with motion algorithms must be observed. For the design of every further study, it must be considered that the combination of these factors can induce motion sickness and mental overload, even if the users are not reporting any symptoms. For this reason, the duration of each driving scenario should be designed to be short and the number of tasks should be designed to avoid overwhelming the participants, furthermore, the status of the participants should be constantly monitored.

Regarding the performed study, it is possible that the small sample size did not provide statistically representative results. Furthermore, the participants were all relatively young and therefore it is difficult to assess the impact of the simulator in a more generalized population. The study of the behavior in different cycling environments would provide a broad understanding of the requirements and perceptions of the users.

These improvements would support the creation of a unique system with which it is possible to accurately evaluate the cycling experience of different riders and evaluate the impact of the simulator on their conditions while using it.

6.3. Outlook

Based on the information reported in this thesis, it is possible to further develop and calibrate the bicycle simulator created at the DLR Institute of Transportation Systems. The literature research provides the basic knowledge required to experimentally acquire data for fine-tuning. The analysis of this data can be performed subjectively with the help of probands that evaluate the conditions of the system or objectively with the use of real-life data.

Once the calibration of the simulator is performed, it will be possible to implement human-centered studies to obtain reliable data about the behavior and preferences of individuals, including their reactions and interactions with other road users. This will be performed in a safe environment that provides the same driving conditions for all the participants.

With this basis, future experiments should be performed to evaluate the acceptance and realism of the simulator after the calibration was performed. This will lead to the opportunity to provide enhance the cycling experience for accurate data collection in a realistic bicycling environment.

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List of Abbreviations

a	Rear length (also l_r)
b	Wheelbase length (also l)
c	Trail
C	Center of gravity
$C_{\alpha,f}$	Cornering stiffness front wheel
$C_{\alpha,r}$	Cornering stiffness rear wheel
DOF	Degrees-of-freedom
F_{yf}	Front-wheel force in the y-direction
F_{yr}	Rear-wheel force in y direction
h	Height of center of mass
HFDS	Handlebar Force Display System
HMD	Head-mounted display
HRTF	Head relative transfer function
I_z	Moment of inertia about the z-axis
KAIST	Korea Advanced Institute of Science
l	Wheelbase length
l_r	Rear length
m	Mass
PFDS	Pedal Force Display Subsystem
P_1	Contact point of the wheels
P_2	Contact point of the wheels
P_3	Intersecion of steering axis with horizontal plane
RBDM	Rider-Bicycle Dynamic Model
RQ	Research question
SD	Standard deviation

SSQ	Simulator sickness questionnaire
T	Steering toque
UDP	User Datagram Protocol
V	Velocity
VBAP	Vector Base Amplitude Panning
VR	Virtual Reality
V_{sa}	Self alignment velocity
α	Inclination angle
α_f	Front tire slip angle
α_r	Rear tire slip angle
δ	Steer angle
λ	Head angle
φ	Lean angle
ω	Angular velocity (also $\dot{\Psi}$)
$\dot{\omega}$	Angular acceleration

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