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Review

Systematic Review of Bike Simulator Studies

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Abstract: The bicycle is a promising, human-powered, and emission-free transportation mode that is being increasingly advocated for due to its significant positive impact on congestion and the environment. Despite the growing popularity of bicycles as a sustainable transport mode in the past two decades, compared to the vehicular mode, bicycle facilities have relatively less development, research, and understanding. In recent years, the bike simulator (BS) provides a fairly realistic environment for conducting research in the area of cycling, and it is capable of simulating real-world environments. It has the potential to contribute to the understanding of bicycle facility design and cyclist's behavior. This study is designed to identify and review BS studies, evaluate the study approaches used in the literature, and uncover their gaps and challenges. After reviewing the literature, 83 studies were selected to review as the final database of this study. Furthermore, four approaches were identified in the literature: "application of BS to suggest a mathematical dynamic model/equation for bicycle/bicyclist stability," "incorporation of BS with virtual reality (VR) technology," "application of a BS in safety promotion studies," and "application of BS in medical, psychology, sports management, and other branches of science." This review is expected to assist researchers and decision makers with selecting the most appropriate quantification method based on their goals and study limitations. Compared to the car simulator, fewer studies have been conducted on BSs. Therefore, future research is needed to address the identified challenges in the BS evaluation process.

Keywords: Bike simulator (BS), Bicycling, Multimodal transportation, Virtual Reality (VR), Safety

Abbreviations:
BS: Bike simulator, an efficient tool to simulate bicyclist's behavior in a fairly realistic environment.
VR: Virtual Reality, a technology that simulates vision to end up with a 3D environment in which a user appears to be immersed while browsing through it.
BS&VRT: The incorporation of Bike simulator and Virtual Reality technology as an integrated package.
HUD: Head-up Display, any transparent display that presents data without requiring users to look away from their usual viewpoints.

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1. Introduction

Various types of vehicle simulators – such as automobile, bicycle, flight, tank, and ship simulators – have been developed and widely used for testing a design, evaluating environments, training operators, entertainment, and so on Guiso (1995). Even though many studies have been conducted regarding various driving simulators, few are related to two-wheeled and human-powered simulators such as a BS. The BS consists of a stationary bike and a monitor, analyzing software, and a VR-Design platform. It visualizes biking behavior on different roads and inside a fairly realistic environment. A BS consists of a frame, clamp to hold the bicycle securely, roller that presses up against the rear wheel, and a mechanism that provides resistance when the pedals are turned Trainor (2014). The BS can be interesting for multifarious groups of researchers, bicyclists, and even ordinary people. Such these groups can pedal their way to a better understanding of how drivers and cyclists share the road with one another. The BS is an efficient tool allows researchers to study behavior in situations that might be dangerous to attempt in the real world. Additionally, the BS collects and records key data, such as speed, braking and deviation from the center of the lane. An eye-tracking system determines where bicyclist is looking and for how long. According to the Federal Highway Administration (FHWA). From 2007 to 2019, 9,768 bicyclists have died, and 49,000 bicyclists were injured in traffic crashes across the U.S. FHWA (2021). The year 2018 was the deadliest year for bicyclists with 871 recorded deaths, and 6 percent of all bicyclists killed were under the age of 15 years old. Due to such serious safety problems for bicyclists and the need to reduce injuries and fatalities by better understanding the causes of bicyclist fatalities; identifying and evaluating potential safety improvement measures; and fostering public awareness of bicycle safety matters at the national, State, and local levels, the simulation through BS can be an efficacious approach which help the researchers in this field of study. For the bicycle dynamics calculation and real-time simulation, it is necessary to identify the control inputs from both the rider and the virtual environment Shin & Lee (2002). The virtual environments, such as the ground configuration and condition, can be generated and provided by a visual system. The steering, pedaling and braking torques can be measured directly by using torque sensors attached to the corresponding components. Given the significant application of a BS in previously published studies and as an interesting alternative in response to several challenges such as biking in different environments, awareness of its risks, cyclist safety, etc., this study was designed to synthesize the lessons learned from existing studies that quantified the application of a BS. We implemented a scoping review to identify, screen, and review the existing literature about applying and using a BS. We expect this study to serve as a stop knowledge point and introduce future research avenues to contribute to BS evaluation. The results of evaluating the application of a BS can assist researchers, policy makers, and practitioners with selecting an appropriate evaluation topic based on their objectives. This study is a starting point for other researchers to explore more frequent objectives in applying BSs and present new studies with additional innovations.

2. Materials and Methods

We followed a scoping review methodology proposed by Arksey & O'Malley to: (a) Examine the nature of previous studies on quantifying the impact of BSs, (b) Summarize and document the quantification methodologies in previous research, and (c) Identify research gaps in the existing literature Arksey & O'malley (2005).

In this study, we followed PRISMA 2020 table: a guideline for reporting systematic reviews PRISMA (2020) and we conducted a scoping review since we aimed to identify previous studies reviewing the evidence from previous quantifications on BSs. Scoping review methodology is the first step in a scoping review to identify a research question to be answered. The research question for this review is: "What are the methodologies and gaps in existing research on investigating the potential abilities of BS?" After responding to this question, relevant studies are identified.

We developed a search strategy to retrieve relevant research from four electronic research databases: Scopus, Institute of Electrical and Electronics Engineers digital library (IEEE Xplore), Web of Science, and Transport Research International Documentation (TRID). Reference lists of the retrieved publications were also created. We searched the databases to identify published articles, letters, reports, book chapters, and books using any combination of two sets of keywords ("bike simulator," "bicycling or biking") in their title, abstract, or keywords. Two sets of keywords were considered since bike simulator has been replaced by fixed bicycling or biking in some studies. Hence, bicycling or biking were searched on electronic databases to consider all studies in this field. We included only material written in English due to the burdensome translating process and only considered material published after 1998. We also reviewed the reference lists of the included publications (since 1998 to January 2022) to find any relevant articles the search strategy might have missed. After completing the database, each study was sorted out based on the date of publishing. The primary date found in the database was 1998. It is worth mentioning that BS has been widely utilizing in the academic studies after 2000. Therefore, the studies after 1998 were reviewed in this research.

The first search identified 112 items. Every study was carefully reviewed to determine the aim(s), methodology, outcome(s), and gap(s). The current review attempted to minimize biases wherever possible. Publication bias is a common issue as certain results may be deemed "non-publishable" by reviewers or editors. To minimize the impact of publication bias, we searched the TRID database for "grey" literature, including unpublished papers and research reports. It is obvious that, within any literature review, there is a risk of bias on behalf of those conducting the review. Systematic reviewers have the responsibility to evaluate potential sources of bias and error if these concerns could plausibly influence study results; we tried our best to address and minimize this type of bias and include these concerns even if no empirical evidence exists that they influence study results.

2. Results

The search to find related papers to the topic of this study identified 112 items. Duplicate items were identified using EndNote and removed. Based on the objective(s), gap(s), and content of each study, a particular code was assigned to it. Then, manuscripts with identical topic/content were classified in similar groups. Following the initial search, 19 articles were rejected by a review of titles and abstracts, predominantly for being unrelated to BS topics. After refining the unrelated documents (10 studies), we selected 83 studies for review as the final database in this study. The identification of studies via databases and registers is shown in Figure 1 as a flow diagram.

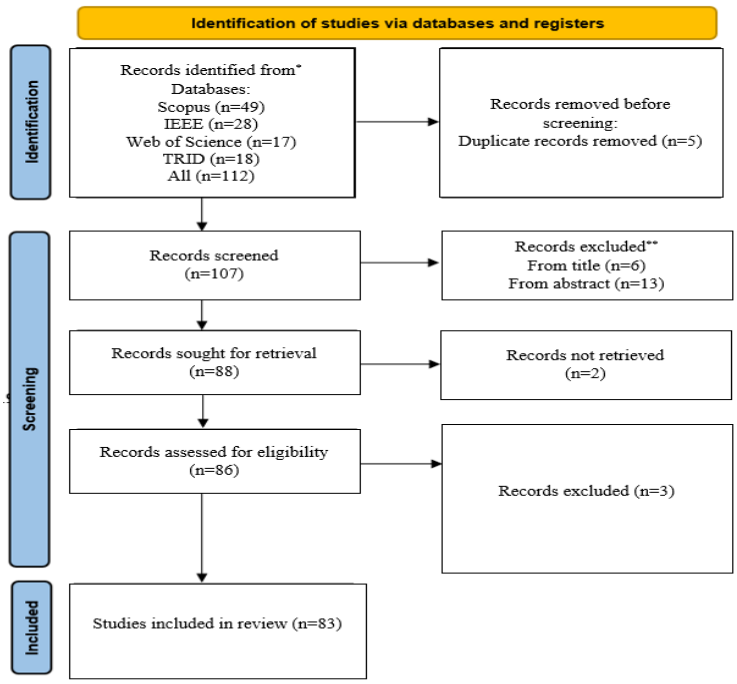

Figure 1. Systematic review process

As of January 2022, the number of publications increased significantly in 2016, and this trend peaked in 2018 with 15 published articles. The applications of BSs were classified into four groups: "suggesting dynamic models or mathematical equations for bicycle stability," "incorporation of BS with VR (VR) technology," "applications in safety promotion studies," and "applications in different fields of science," e.g., medical, psychology, sports management, etc. The number of published articles in the area of BSs is 83 publications over a 24-year period.

3.Four categories of BS studies

3.1. Application of BS in modeling bicycle stability

A simulator is designed to facilitate the simulation of a real-life situation and model a virtual version of it, often for instruction or experimentation in a laboratory environment. This section studied generating different prototypes for a bicycle using a systematic concept generation method, describing the use of an instrumented bicycle and its computational model, and providing mathematical models/equations for bicycle stability. Methods for data collection, analysis, modeling, and simulation of performance parameters for BSs were developed or evaluated in this group of studies.

Momentous dynamic models/mathematical equations by using a BS for bike stability are mentioned in the following: a new dynamic model consisting of an electrical motor in the central position that, by means of a bevel gear, transmits the torque to the central hub to investigate the tracking errors was proposed by Abagnale et al. (2016). Arunachalam & Rajesh (2014) suggested a mathematical equation for investigating the stability of foldable bicycles. A method of mixed reality extended by modern industrial technologies to allow natural interaction with virtual prototypes of the BSs was proposed by Beckmann-Dobrev et al. (2015). A mathematical model was implemented by (Pandey, Monteil, Gambella, & Simonetto, 2019)(Pandey, Monteil, Gambella, & Simonetto, 2019)(Pandey, Monteil, Gambella, & Simonetto, 2019)(Pandey, Monteil, Gambella, & Simonetto, 2019)Dahmen et al. (2011) for simulating rides on real courses, providing similar quality measures when comparing field and simulator measurements. Escalona et al. (2018) proposed the mathematical equations to generate a simple computer graphics animation of bicycle riding. In another study, a mathematical model was suggested by He et al (a). (2005) to investigate the bicyclist's stability and vibration behavior. A new dynamic model was suggested by He et al (b). (2005) for BSs consisting of motion generation, and force reaction, dynamics simulation, and visual/audio systems. In addition to previous studies, a new rehabilitation training system (consisting of a dynamic model) was developed by Jeong et al. (2005) to improve equilibrium sense control by combining virtual reality technology with a fixed exercise bicycle. A new dynamic model to validate the integrated power-assisted BS was proposed by Kakutani & Furusho (2004) They suggested an integrated prototype that was able to investigate power-assisted bicycle. Kim et al. (2017) developed a heuristic dynamic model to evaluate the user experience of virtual systems. They modeled the user experience of virtual bikes by VR technology. In another research project, Kooijman et al. (2008) suggested a model study to consider many physical aspects of a real bicycle such as the flexibility of the frame and wheels, play in the bearings, and precise tire characteristics. One of the first proposed BSs was introduced by Kwon et al. (2001) KAIST Interactive BS (Korean BS) consists of a bicycle, a Stewart platform, magnetorheological handle, pedal, resistance system to generate motion feelings, real-time visual simulator, and a projection system, sub-controllers, and an integrating control network. A dynamic model that couples the bicycle roll and steer in a realistic manner was proposed by Lee et al. (2017) and it also allowed studying the effect of balance on the rider's higher-level cognitive decisions. Schwab & Recuero (2013) described and used a BS prototype that can help understand the synergy among the parts intervening in the active stabilization process in cycling. An affordable BS prototype with proper longitudinal and lateral stability Snapika et al. (2018) that simulates the form of indoor cycling was presented.

To increase the efficiency of BSs, new methods were proposed by the following researchers. In all reviewed methods, a particular structure or architecture is presented that can increase the efficiency of the BS. This issue is clearly discussed in studies such as Englund et al. (2016): Ginters et al. (2014): Jamin et al. (2019). Shin and Lee (2002) proposed the control inputs from the rider as well as the virtual environments for the calculation of bicycle dynamics in a bicycle simulator. Simulating the impression of geometry and road surface characteristics – such as radius of curvature, road adhesion, and unevenness of road profile – was studied by Shoman & Imine (2020) based on which a dynamic model was developed. Finally, a 6-degrees-of-freedom (DOF) platform that is controlled by linear actuators and a microcontroller was proposed by Yap et al. (2016) who successfully formulated the kinematics equation. The aforementioned studies propose different physical concepts of the BS. In each of these studies, the degree of freedom and dynamic features of a BS have been changed to suggest the new structure for the BS.

After reviewing the aforementioned studies, we conclude that a BS can be used to model the physical motions of the human body. Therefore, spatial geometric equations have been defined to model the stability of bicyclists. To sum up, the first application of the BS is limited to the process of presenting such models or mathematical equations.

3.2. Incorporation of BS with VR technology

Virtual reality (VR) refers to a computer-generated simulation in which a person can interact within an artificial three-dimensional environment using electronic devices with a screen or gloves fitted with sensors Mitchell (2020). The VR can be a 360-degree immersive experience, in which computer-generated graphics help create things as close to reality as possible. The majority of researchers attempted to integrate the application of a BS with the VR technology. Incorporating the BS and VR as an integrated package helps the researchers gain more realistic data. The VR's most immediately recognizable component is the Head-mounted Display (HMD), which can be applied to simulate the performance of bike riders in different situations. The most important studies in the field of BS and VR technology integration (BS&VRT) are mentioned below:

VR technology was used by Bogacz et al. (2020) to contribute to a better understanding of the implications of the choice of the experimental setup by comparing the cycling behavior between two groups of participants. The first group controlled the maneuvers using a keyboard and the other group rode an instrumented bicycle. Some studies examined unique applications of a BS&VRT Bottone et al. (2015): Carraro et al. (1998): Kikuchi (2011): Kakutani (2004): Katsigiannis et al. (2019): Al-Kefagy (2019): Padmini et al. (2019): Schulzyk et al. (2009). The 2-DOF mechanism on a dynamic platform driven by changing the cable length and its application to VR for bicyclists in virtual environments was presented by Chen et al. (2007) Their prototype could interact between the bicycle and VR system and integrate exercise with entertainment. Dahmen & Saupe (2009) concentrated on the simulation of endurance sports with an emphasis on competitive cycling with BS&VRT. The goal of Gao et al.'s work was providing a simulator system that enables race bikers to improve their performance in training Gao et al. (2005). In another study, Hernández–Melgarejo et al. (2020) integrated physical VR and control behavior systems to compose a virtual bicycle simulator. They designed and implemented a VR bicycle system based on a functional-based mechatronic design approach. An immersive bicycle simulation platform and VR technology for several applications in the areas of biomechanics, sports, traffic education, road safety, and entertainment was proposed by Herpers et al. (2009) Their prototype consists of special immersive visualization systems to simulate biking in a real-world environment. All the aforementioned studies were tested in a laboratory environment.

The following studies are instances of new integrated systems that have been suggested to promote the performance of BS&VRT. Studies like Horne et al. (2018): Jia et al. (2006) proposed new techniques to improve the performance of a BS&VRT. A calibration procedure was proposed by Horne et al. that uses general equations and techniques to calibrate speed measurements and improve the consistency of experimental data. Jia et al. (2006) evaluated the role of the human-computer interaction system as the key technology of a virtual bicycle simulator.

Researchers, e.g., Keler et al (2020) and Nazemi et al. (2018) used BS&VRT to evaluate novel traffic control strategies on existing transport infrastructure depicted in VR environments. In addition, Nazemi et al. (2018) used BS&VRT to evaluate the effects of environmental properties and road infrastructure design on cyclists' perceived safety. This study investigated the combination of immersive VR and an instrumented cycling simulator for in-depth behavioral studies of cyclists. Researchers, e.g., Ouden (2011) used a BS for physical rehabilitation purposes. BS&VRT has been used to train children and help them get used to being on a bicycle. Children's cycling has been studied less than adult cycling. Therefore, additional studies should be conducted because children have been considered as one of the groups for whom education can positively affect their behavior in adulthood.

An example of a well-done study regarding the bicyclists' behavior on different pavements was performed by Rakhmatov et al. (2018) They designed a data-collection bike that captures the vibrations induced at the handlebar and the cycling velocity for different tire pressures. The level of tire pressure, the weight of bicyclists, and the role of pavement in the reaction of bicyclists was investigated. By studying the behavior of cyclists, Schramka et al. (2017) investigated how different street design configurations and traffic levels impact perceived cycling stress levels, cognitive reactions, and mobility behavior. The role of environmental elements to investigate how cyclists adapt their behavior (e.g., speed, safety, gaps, steering, etc.) was evaluated by Shoman & Imine (2021) They adjusted their riding practices as they interacted with other road users and anticipated risks in hazardous riding situations. In another study, Ullmann et al. (2020) used the integration of BS&VRT to provide rare qualitative factors (such as stress, perception of time, and attractiveness of the environment). They utilized an audiovisual VR bicycle simulator to allow the user to ride in a virtual urban environment. The aforementioned studies were conducted with adult cyclists. Finally, the exercise and entertainment purposes of a BS&VRT were studied by Tang et al. (2018) and Yap et al. (2018) who investigated the entertainment role of BSs. Overall, the number of studies regarding incorporating VR and BSs has risen in recent decades, reflecting increasing interest by researchers. Incorporating VR and BS provides a fairly realistic environment for the participants of the research, and they can efficiently adapt to the simulated environment when riding a BS.

3.3. Application of BS in safety promotion studies

When a crash occurs between a vehicle and a bike, it is the cyclist who is most likely to be injured. By law, bicycles on the roadway are vehicles with the same rights and responsibilities as motorized vehicles. Over 1,000 people were killed in bicycle crashes in 2018 and over 300,000 ended up in the emergency room. In the U.S. in 2017, over eight times more men were killed in bicycle crashes than women Grover (2020). One notable application of BSs is in safety promotion studies. Researchers have studied the interaction of bicycles with other vehicle types, plans to increase bicyclist's safety, and the most hazardous situations for bicyclists. Different cyclist's behaviors and cyclist-enhanced safety schemes can be evaluated when they interact with the road and other vehicle types. "The role of bicyclists under different conditions" and "the role of the road and its characteristics" are two critical properties involved in increasing or decreasing cyclist safety.

The following studies investigated the role of the bicyclist in the occurrence of crashes. A novel approach consisting of a unique bicycle simulator equipped with sensors capable of capturing the behavior of bicyclists was suggested by Englund et al. (2016) to model the visual distraction of bicyclists. Ghodrat Abadi et al. (2019) suggested a high-fidelity full-scale bicycling simulator that examined the interaction of bicyclists and trucks near Commercial Vehicle Loading Zones (CVLZ) in urban areas. They investigated the influence of engineering treatments on bicyclist performance.

Additionally, a factorial design with three levels of pavement markings (white lane marking, solid green, and dashed green), two levels of signage (no signs and warning signs), and three levels of truck maneuvers (no truck, parked trucked, and exiting truck) was developed. Kaß et al. (2020) evaluated and investigated cyclists' behavior during dynamically evolving interactions. Furthermore, they measured the dynamic behavior patterns. The research focused on external human-machine interface (eHMI) as a communication interface of automated vehicles.

Researchers such as Lindström et al. (2019) evaluated how radar sensors and technologies common in automotive vehicles can be transferred for use on bicycles. A bicycle simulator was used for testing and evaluation. Moreover, high-risk scenarios and requirements were identified, followed by identified design challenges and design activities. To facilitate road safety for children, Matviienko et al. (2018) explored the use of multimodal warning signals to increase their awareness and prime action in critical situations. A BS linked to these signals and the results showed that the participants spent significantly more time perceiving visual than auditory cues. A better understanding of bicyclists' perceived safety and their preferences for currently unavailable and/or unknown facilities was studied by Nazemi (2020) who used different survey methods ranging from verbal descriptions of facilities to surveys including images and videos. There is evidence that some aspects of cyclist performance when interacting with the road environment can be investigated by using a BS. O'Hern et al. (2017) concentrated on the cyclist spatial position measures to investigate the bicyclists' interaction. They assessed the validity of the participants' performance using a BS, compared to riding on road. In line with former research, O'Hern et al. (2018) examined how bicycle lane width and perceptual countermeasures can influence cyclist speed and position. Researchers such as Powell (2017) concentrated on the injuries caused by bicyclists and motor vehicle crashes. They used a particular BS to provide a virtual environment and reduce crashes by safely investigating the interaction between bicycle riders and traffic, particularly when bicyclists were crossing streets. Sawitzky et al. (2020) studied the effects of new infrastructural concepts and technologies, such as a head-up display (HUD) for cyclists' potential crash possibilities brought by automated vehicles, and smart, connected traffic, on actual cyclist road safety. Some researchers studied the hazard of biking on sidewalks. Suzuki (2013) is a good example, concentrating on a particular BS that is available for analysis of the safety and influence on other transport modes.

Using BSs and VR technology for assessing bicyclists' safety was studied by Tsuboi et al. (2018). They proposed methods to improve the awareness of bicycle riding safety by experiencing virtual accidents in a virtual space. The study helped the participants learn desirable and safe bicycle riding behavior. The role of bicyclists in injury or fatal crashes was assessed by Warner et al. (2017) They concentrated on the right-hook crash, which is a crash between a right-turning motor vehicle and an adjacent by-moving bicycle. They evaluated driver behavior in collisions that occur during the latter green phase (the second portion of the green signal phase, after the initial vehicle queue has cleared) at signalized intersections with a bicycle lane and a shared right-turn lane.

Researchers like Brown et al. (2017) and Yamaguchi et al. (2018) investigated the role of the road and its characteristics on bicyclists' crashes. Alternative pavement markings were investigated by Brown et al. for bicycle wayfinding and proper bicycle placement at signalized intersections. Yamaguchi et al. proposed an innovative method to detect road hazards using sensors attached to a bicycle. The built-in sensors send the speed and front-wheel angle information to the control unit. The proposed system allows for dangerous situations to be easily and repeatedly created with no danger to the bicyclists.

The popularity of biking has drawn researchers' attention to finding methods for protecting bicyclists on public roads. Bicyclists (and pedestrians) are frequently classified as "vulnerable road users." The biking community, however, is not comfortable regarding the safety of these two groups Cynecki (2012). Bicyclists are susceptible to serious injuries, and special attention should be paid to the safety of this group Ragland (2012). The elevated risk of injury to bicyclists when they encounter motor vehicles makes it important to identify and implement strategies to protect cyclists on the road. There is some evidence that bicycling has increased in recent years Jacobsen et al. (2009). However, even with widespread encouragement, many will be deterred from biking if they do not feel safe.

Overall, many studies used a BS to simulate the behavior of bike riders under different environmental conditions and on different road types. Therefore, researchers can take advantage of BSs to conduct new projects that encourage cyclists' safety when interacting with vehicle traffic.

3.4. Specific applications of BSs

BSs can be applied for conducting studies in other fields of science such as medicine, psychology, sports management, etc. We chose to conduct a scoping review since we aimed to identify previous studies regarding the specific applications of BSs in various research fields. The application of BSs in medical science has been investigated in studies, e.g. Batcir et al. (2021): Kim et al. (2006): Jamin et al. (2020): Mittelstaedt et al. (2018). The application of BSs in psychology has been studied by Gratkowski et al. (2017): Matsumura et al. (2018): Yin & Yin (2006). Two examples of applying BSs in mechanical engineering studies are Soma et al.; and Yin & Yin (b). Soma et al. (2012): Yin & Yin (2007). Applications of BSs in transportation engineering include Fernández et al. (2018): Ginters et al. (2017): Herpers et al. (2008): Hurwitz et al. (2019): Keler et al. (2018): Keler et al. (2019): Kaths et al. (2019): Mizoguchi (2015): Sun & Qing (2018). In addition to the aforementioned studies, BSs have been used as equipment to study the stability and motion of astronauts Coombe (2011). The application of BSs in sports management science Youn (2014) has also been studied in the recent years.

In some studies, particular sensors were installed on the bike simulator to provide greater user involvement and comfort. A virtual bike simulator (SimBike) that used nonconventional motor, sensory, and sensorimotor devices to provide greater user involvement and comfort was proposed by Almeida et al. (2020) Their research recreated the activity of riding a bicycle by exploring the possibilities of electronic devices, such as making curves with the handlebar or body weight, pedaling, and braking, among others. They used particular sensors to investigate how the devices in SimBike contribute to the user experience in the virtual simulator, including the level of immersion, realism, and cyber-sickness symptoms. This resulted in improvements to make the simulator suitable for all types of users, regardless of their characteristics such as weight and height. The mechanism of perception of the natural speed which affects the adopted speed was investigated by Caro & Bernardi (2015). An experiment was carried out on a BS in which three pieces of sensory information were separately manipulated: the speed of the image, the resistance to pedaling, and airflow. The results showed that, "airflow" has no effect. This indicator should be better evaluated especially by conducting more accurate models. Additionally, the small variation of the speed suggesting that the pedaling rate plays a preponderant role in the control of speed. Rittenbruch et al. (2020) designed a toolkit that enabled flexible transitions between ideation and out-of-the-box thinking, prototyping, and immediate evaluation. The results addressed to what extent the toolkit can help workshop participants ideate novel bicycle user interfaces, specifically interfaces that relay time-critical information about potential hazards. As well, the results revealed how this toolkit can combine with a lightweight bicycle simulator, and simulated hazards can be used to evaluate different designs and elicit rich feedback.

A rising interest in sustainable modes of transportation has increased demand for the design and implementation of bicycle facilities. A BS requires interfaces for bicycle speed, braking, and steering angle as well as a visual interface. After providing these facilities, it will be possible for researchers to take advantage of BSs in their own studies. The reviewed studies are summarized in Table 1. Each study was reviewed in detail, and the main achievements were mentioned. Additionally, all reviewed studies in Table 1 were graphically determined based on the published year in Figure 3.

4. Discussion

As of January 2022, 83 publications over a 24-year period have been published. Figure 2 shows the percentage of four groups included in this review, and Figure 3 shows the frequency of number of articles published in each year. It is obvious that due to the relatively high cost of BS equipment and the need to use simulator software for synchronization with that equipment, less effort has been made to conduct studies using BSs.

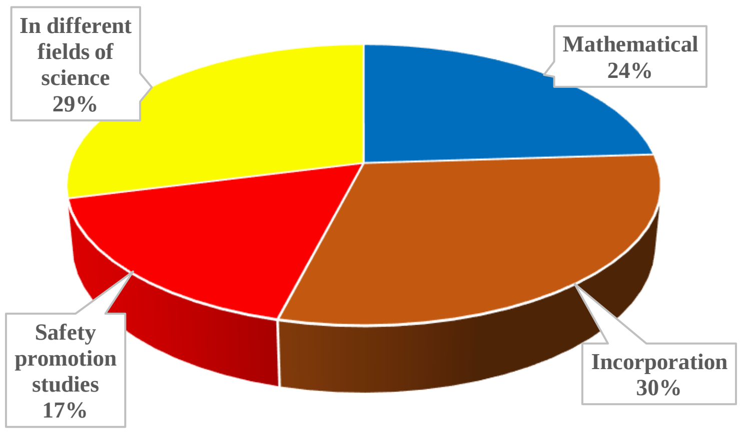

Figure 2 Figure 2. Percentage of the studies included in this review

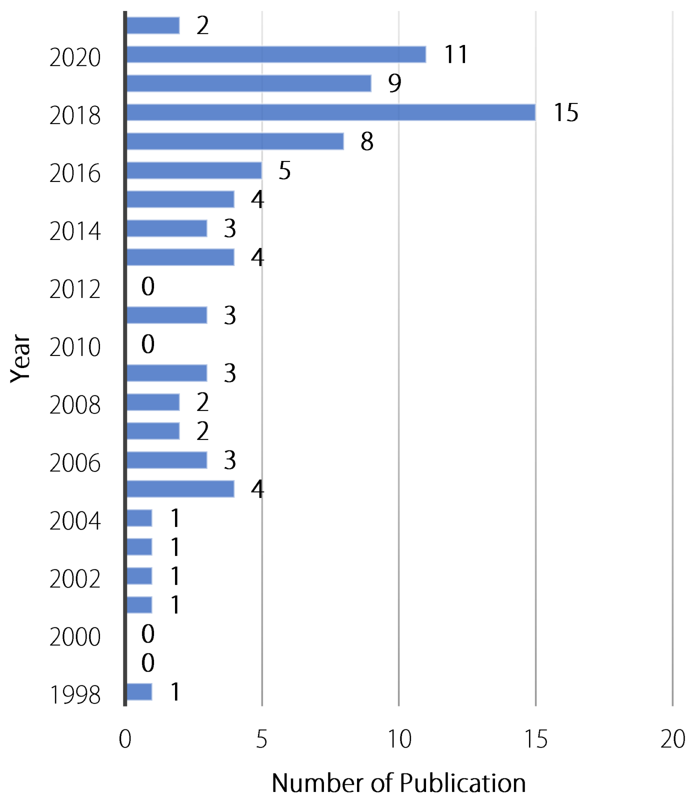

Figure 3. Publication dates of the studies included in this review

5. Practical Applications.

This study is comprehensive research regarding the BS applications. BS is an efficient tool for simulating the behavior of bicyclists under different conditions. Various cycling conditions can be addressed on the software which coordinate with BS to record behavioral changes of bicyclists when they pedal. Simply put, the findings could be useful for diverse majors especially sport physiology and sport performance because multifarious sensors can be installed on BS to record the bicyclist's physical changes like heart palpitations, changes in the cornea of the eye when pedaling fast, the number of changes in the cyclist's angle of view, and the number of distractions on roads with multiple traffic signs. The applications of the BS are not limited, and it is possible to be applied in various types of studies.

This review has two limitations. First, this study systematically reviewed all published studies regarding the BS, and we did not compare the methods and gaps among the current studies. Second, we examined the BS evaluation methodologies and gaps qualitatively and relatively. Future research should be conducted to provide a more accurate comparison between the methods or gaps by conducting quantitative analyses. In light of the comprehensive literature review, we tried to interpret the important gaps in this study, but identified approaches have some shortcomings and limitations that need to be addressed. First, the incorporation of BSs and traffic simulation studies can benefit from ground truth data to verify their assessments and study findings. Second, the reliability of the gathered data is an important issue in BS studies. The contents of the designed questionnaire, refining the participants' answers, their correct understanding of the questions, and the participants' properly working with the BS during data collection are important matters. Despite these limitations in previous studies, the progress of studies in the field of BSs is admirable, and many of the gaps in initially published research have been resolved over time by the relentless work of other researchers and practitioners.

The following topics can provide valuable studies in the future: "simulating the interaction of bicycles with other transport modes, especially connected and autonomous vehicles," "risk analysis of biking," "bicyclist longitudinal motion modeling," and "investigation of the possibility of further coordination between the physical components of the BS with the designed VR technology," all of which are notable topics that can be simulated and investigated in future studies.

6. Conclusions

This study implemented a systematic review to synthesize the applications of BSs. We assessed the identified qualitative approaches and uncovered the gaps and challenges in the BS evaluation process. Applications of bike simulators (BSs) were classified into four groups, including "suggesting dynamic models or mathematical equations for bicycle/bicyclist stability," "incorporation with VR technology," "applications in safety promotion studies," and "applications in different fields of science" (e.g., medical, psychology, sports management, etc.). The results can be used as a guideline for future research to select the appropriate method based on the study's objectives and limitations. This review showed that previous studies carry certain shortcomings, and further investigation is required for a reliable evaluation of bike simulator research. The gap(s) of each research was determined in Table (1), and the readers of our study can refer to it to figure out the principal shortcoming(s). Insomuch the gap(s) was recognized, future research is required to better understand and evaluate BS applications while addressing the gaps in the existing methods and the challenges in BS evaluation. After reviewing 83 studies, the limitations – such as small sample size, budget, using car sensors inside a bike simulator, considering small networks, ignoring road characteristics such as pavement, different weather conditions in simulation software, lack of attention to longitudinal and lateral movement of the bicyclists, changing the bicyclist's behavior in the face of different traffic conditions and confrontations with pedestrians, and providing strategies to prevent the participant from having headaches during the simulation session – can be enumerated.

Supplementary Materials: The main contribution and achievement of our research was determined in Table (1). The aforementioned studies were carefully reviewed, and the objective(s), methodology, outcome(s), and gap(s) were highlighted. Due to the number of reviewed studies, Table (1) was included at the end of this study. Table 1: Systematic Review of BS' Application

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TABLE 1 Systematic Review of BS' Application

The first application of BSs: Suggesting dynamic model or mathematical equations for bicycle stability				
Author Name	**Objective**	**Methodology**	**Outcome**	**Gaps**
Abagnale et al. (2016)	• Designing a new model of power-assisted bicycle (pedelec prototype), consists of an electrical motor in the central position that, by means of a bevel gear, transmits the torque on the central hub	• Using the optimal pedelec torque control (OPTC). The proposed control method is based on a torque control designed via an optimal approach to achieve multi-objective performances regarding the external disturbance input, control signal magnitude, and velocity tracking error	• Providing reduced tracking errors and good robustness, • Improving the performance of model over classical pedelec assistance systems	• The design of several control strategies by means of a hardware in the loop procedure should be evaluated
Arunachalam et al. (2014)	• Generating different concepts for a foldable bicycle product • Proposing the mathematical equation and conceptual model for foldable bicycle	• A systematic concept generation method • Describing a systemic approach to material selection and FEA justification during embodiment design phase • Using Pugh concept selection chart	• The design has been evaluated with existing designs using Pugh chart/numerical scoring methods • The DHM technology has been used to check the human comfort like knee clearance, hand reach, foot reach, etc. The selected materials during embodiment design stage have been validated by FEA analysis under static and dynamic loading conditions	• A conceptual and embodiment design of a foldable bicycle only has been considered
Beckmann et al. (2015)	• Usage of a new technology called Smart Hybrid Prototyping (SHP) on urban bike mobility (a hybrid bicycle simulator) • Describing a development process using SHP in order to design and validate PSS (Product Service Systems). PSS combine products, services, and infrastructure to fulfil individual customer needs	• The Plug-IN VR methodology was used to identify the following system requirements: interaction, usability, perceptibility concerning the level of user experience and functional, visual and haptic validation to ensure significant results during SHP4PSS evaluation	• Proposing "an Android app for mobile devices integration," "the hybrid bicycle prototype as hardware device," "the virtual environment and a bicycle simulation within Unity 3D"	• Usability studies and other PSS evaluation activities have not been considered during this paper • The proposed model is only a concept model. The new proposed approach should be tested in a real-world environment
Dahmen et al. (2011)	• Developing and evaluating performance parameters in road cycling on real tracks • Conducting a simulation included real height profiles and a video playback that was synchronized with the cyclist's current virtual position on the track	• Using field data obtained on mountain tracks and comparing it with the state-of-the art mathematical model for road cycling power, established by Martin et al. in 1998	• Implementing the mathematical model on an ergometer for simulating rides on real courses • Providing similar quality measures when comparing field and simulator measurements	• This study incorporated slopes, but not high speeds, which would test for accuracy of the model regarding higher order terms of the speed • Downhill sections have not been considered in their proposed simulator
Escalona (2018)	• Describing the use of an instrumented bicycle (the experimental setup) and its computational model for multibody dynamics	• Using the mathematical equation sets consists of "multibody model of the bicycle," "Kinematic simulation of the bicycle" and "equations of motion of the bicycle"	• Generating a simple computer graphics animation of the bicycle ride	• Experimental validations of the model and the kinematic simulation have been developed for the position, velocity and acceleration. It is worth noting that, no validation is included for the inverse dynamic analysis
Ginters et al. (2014)	• Providing a bicycle inter-modality simulation case (a simulator has been created to find a useable solution for bicycle station and track building location in the city of Skopje, North Macedonia)	• Using double cycled policy crafting model and providing the statistical data	• Proposed simulator ensures validation of potential activities by using multi-agent systems (MAS) simulation	• Enhancing and statistical validation of simulation model has not been considered in the proposed model
He et al. (2005)	• Developing an interactive bicycle simulator • Proposing an innovated completed mathematical model of a bicycle (bicycle's stability and vibration behavior)	• Using an innovated completed mathematical model of a bicycle (consists of 2 sub-models)	• Doing experiments to validate the proposed mathematical model • Evaluation of the tilt torques and pedal torques of the rider • Processing the road profile data in the bicycle simulator system	• Using inaccurate methods to evaluate the tilt torques and pedal torque of the rider
He et al. (2005)	• Proposing the collective structure of a bicycle simulator which consists of motion generation and force reaction system, dynamics simulation system, visual/audio system	• Using the interactive bicycle simulator (new type of interactive entertainment tool which is constructed by multimedia, mechanics and computer technologies)	• A discussion of the system integration	• A brief description of the function and key technologies of each subsystem of the BS
Jamin et al. (2019)	• Presenting a new approach – the so-called time-shift multiscale cross-distribution entropy (TSMCDE)	• Analyzing biomedical data • Using multiscale cross-sample entropy (MCSE), multiscale cross-distribution entropy (MCDE), and time-shift multiscale cross-sample entropy (TSMCSE) • Recruiting the participants (Twenty-four subjects divided into two groups (12 subjects each))	• Providing a link, this link may exist between complexity and the age and physical state of a population • TSMCDE leads to a better differentiation of the two groups than MCSE, MCDE, and TSMCSE	• Application of TSMCDE was not well explained. It should be tested on other types of data and on larger datasets to prove its usefulness and its efficiency
Jeong et al. (2005)	• Developing a new rehabilitation training system to improve equilibrium sense control by combining virtual reality technology with a fixed exercise bicycle	• Using 20 normal healthy adults as test subjects • Evaluating and analyzing several factors including path deviation, cycling time, cycling velocity, center of pressure	• Improvements not only in controlling balance and weight shift but also in the overall cycling capabilities such as cycling speed	• The size of sample (number of participants) is small in the investigation of the influence of the different parameters on equilibrium sensory control • The measure of effectiveness indicator regarding the new proposed training system has not been suggested
Kakutani & Furusho (2004)	• Proposing an integrated performance simulator that supports efficient	• Modeling the theoretical conditions as closely as possible to real conditions and	• Validating the integrated power-assisted bicycle simulator	• The correlation process between pedaling torque and the velocity of each

	research and development for a power-assisted bicycle	reproducing the conditions on the equipment simulator • Using the experimental evaluation method	• Modeling the performance of the power-assisted bicycle with respect to the elasticity of a torque sensor, and considering the correlation between pedaling torque and the velocity of each component using the computer simulator	component using the computer simulator has not been explained in detail
Kim et al. (2017)	• Deriving a model or framework to evaluate user experiences (UX) of virtual reality (VR) systems, especially, VR indoor bikes • Proposing a comprehensive evaluation model of UX, which consists of four factors: usability, affect, user value, and feeling the presence	• Developing a questionnaire	• Developing a looselycoupled framework or model to evaluate UX of virtual systems and a specific model to evaluate UX of virtual bikes	• Despite the model being sufficiently capable of evaluating reality on VR bikes, it may be exposed to some limitation on the evaluation of other VR systems • The results depend on the subjective judgements that users made for each element on the questionnaire
Kooijman et al. (2008)	• Presenting an experimental validation of some modelling aspects of an uncontrolled bicycle	• Using the numerical simulations on a three-degree-of-freedom benchmarked bicycle model	• The model appeared to be fairly accurate for the low-speed low-frequency behavior	• The effect of flexibility of the frame and wheels, play in the bearings, and precise tire characteristics have been excluded
Kwon et al. (2001)	• Presenting key technologies and system integration issues of the KAIST interactive bicycle simulator (Korean BS) • Developing a bicycle simulator to study essential issues and integration technologies in order to develop more advanced interactive simulators	• Using the system integration process (communication and synchronization among the scenes, the motion of the platform manipulator, and the reaction of the handlebar and pedal resistance systems)	• Introducing the motion generation system, the bicycle dynamics, the handlebars and pedal resistance systems, the visual simulator, and the system integration technique, which are essential technologies of the KAIST interactive bicycle simulator	• The inherent unstable dynamics of the bicycle have not been well considered
Lee et al. (2017)	• Developing a simulator that allows studying the effect of balance on the bike rider’s higher level cognitive decisions	• Using the unity game engine to render the virtual bicycle in the visual environment. The engine supports output to a standard monitor, multiple monitors, or a head-mounted display	• Initial tests showed behavior subjectively resembles the Whipple model (the Whipple model uses linearized equations of motion to describe the bicycle stability in terms of roll angle and steer angle)	• The bicycle simulator is still under development • Involving balance behavior for a small group of participants given the observed realistic steering dynamics, and therefore, realistic handlebar haptic feedback
Schwab & Recuero (2013)	• Construction, describing, and utilizing a bicycle simulator, in which the rider controls a monitored handlebar and receives realistic visual feedback and haptic feedback torques on the handlebar from the computer model of the bicycle	• Using the mathematical equations of motion for BS	• Understanding the synergy among the parts intervening in the active stabilizing process in bicycling	• When the haptic feedback torque on the handlebar was turned off, the rider was unable to stabilize the lateral motions of the bicycle. In this paper the need for haptic steer torque feedback in cycling is implicitly mentioned • It was better to add realistic pedal resistance, enhancement of the visual feedback, and adding realistic sceneries
Snapika et al. (2018)	• Providing a solution to build a high-end bicycle simulator with a motion platform which simulates physical forces and the street • Simulating the real-life bicycle ride situations as a scenario with a virtual environment	• Providing a Block diagram consisting of the following parts: -bicycle with sensors -controller for interface -unity software -keyboard press event -game mode screen	• Implementing a bicycle simulator with the lowest cost and using different components for efficiency purposes	• In this study, a dynamometer was used for generating voltage by rotation of the wheel. The generated voltage can be used as backup without wasting the energy and it can be given to the battery charger. This procedure has not been explained well
Shin & Lee (2002)	• Identifying the control inputs from the rider as well as the virtual environments for calculation of bicycle dynamics in a bicycle simulator (estimation of rider’s reaction force)	• Using both analytical and experimental methods	• The simulator rider's reaction force can be well estimated from the control forces of the motion system and that the motion system gives a good tracking performance irrespective of the perturbation from the simulator rider	• The controller showed unknown performance in estimation of the reaction force and tracking control under the presence of perturbation representing rider's reaction
Shoman & Imine (2020)	• Presenting an experimental validation of the bicycle simulator (improving the dynamics of the bicycle model and simulating the effects of road geometry and surface characteristics)	• Using the experimental results	• Improving the dynamics of the bicycle model and simulating the effects of road geometry and surface characteristics such as radius of curvature, road adhesion, and unevenness of road profile	• The effect of these characteristics on user behavior to improve the safety and stability of bicycles, particularly in bad weather conditions, has not been considered • Estimation of the vertical displacement and side slip angle has not been presented
Yap et al. (2016)	• Design and development of a 6-degree-of-freedom (6-DOF) motion platform to simulate the Velodrome track cycling	• Using the mathematical model (a set of inverse kinematics model and converting into a programming system in order to control the movement of the platform)	• The kinematics equation has been successfully formulated • The dimensions required for the desired movements of the prototype have been well determined	• The accuracy of the prototype has not tested well

TABLE 1 Systematic Review of BS's Application (Cont'd)

The second application of BSs: Incorporation of BS with virtual reality (VR) technology				
Author Name	**Objective**	**Methodology**	**Outcome**	**Gaps**
Bogacz et al. (2020)	• Comparing cycling behavior in VR between two groups of participants in similar immersive scenarios – the first group controlling the maneuvers using a keyboard and the other group riding an instrumented bicycle	• Collecting electroencephalography (EEG) data to compare the alpha wave amplitudes and assess the engagement levels of participants in the two settings • Conducting a between-subject comparison of the behavior in two samples	• The ability of VR to elicit behavioral patterns in line with those observed in the real world • Indicating the importance of the experimental design in a VR environment beyond the choice of audio-visual stimuli	• None of the participants took part in both treatments • Lack of considering the neural data, the role of the road and pavement features
Bottone et al. (2015)	• Proposing an algorithm consisting of a filter that averages past values and current values to reduce jitter and then uses trigonometric functions to convert 2-axis accelerometer data into an angular velocity	• Inviting 40 to 50 participants to ride the VR BS and finding the conscious and subconscious part of participant's brain when they're riding the BS	• Everyone who rode the simulator talked about how weird it was because they knew it wasn't real but they felt like it was. This is a result of that conflict between the subconscious and conscious processes in the brain	• Lack of good tracking equipment, some sort of rig that would allow participants to tilt the bike when someone was going around a corner or up a hill
Carraro et al. (1998)	• Describing the bicycling simulations enabled by Peloton[1]. • Discussing the role of VRML in the system's implementation, focusing on how its virtual worlds are generated from topological data, how cameras and third-person viewpoints are managed, and how unconventional input/output devices are incorporated	• Explanation of Peloton architecture. Illustrating the main components of Peloton, which is composed of a client for each user and a centralized server	• Briefly described Peloton, a multi-user sports simulator. Users can view the simulated world by several third-person viewpoints, which provide a collection of changing viewing angles. Peloton's virtual bicycle rides are now augmented by pedestrian movement by virtual landscapes	• Peloton's simulation environments differ significantly from large, long-lived communal spaces[2]. Peloton simulation sessions involve only a few people and have limited duration, Peloton users' rendezvous by sharing a session, not by meeting in a common virtual world location • The proposed architecture for Peloton's simulation is complex. Ordinary people can't easily understand its hierarchical relationships between different elements
Kikuchi & Tsubata (2013)	• Developing the virtual reality bike (VR Bike) with a cylindrical MR fluid brake to facilitate the moderate aerobic exercise for users who cannot do real cycling	• Conducting the validation tests	• Describing the system integration of the VR Bike and control of its pedal resistance based on the virtual reality environment • Developing a pedal torque controller with a PIC microcomputer, and a visual controller with a PC	• The developed controller can't adequately perform pedal torques on the basis of the conditions (with/without air resistance and rolling friction, on flat/slope road) of the bike in the virtual world
Chen & Huang (2007)	• Proposing an interactive BS of 2-degrees-of-freedom (DOF) mechanisms with a dynamic platform driven by changing cable length and its application to virtual reality for the rider in the virtual environments	• The bike motion equations and road conditions in virtual bike driving have been calculated and analyzed by using numerical methods and software of virtual reality. • Using statistical manners, 3D model, road condition, bike motion equations, and an option of SDK (Software Development Kit)	• The bike motion equations and road conditions in virtual bike riding have been calculated and analyzed by using numerical methods and software of the virtual reality	• The extra DOF of yaw angle motion is needed to improve the performance of the interactive bike simulator between the rider and virtual reality system
Dahmen et al. (2009)	• Designing a simulator to facilitate the measurement of training parameters in a laboratory environment, to familiarize cyclists with unknown tracks, and to develop models for training control and performance prediction	• Developing the methods for data acquisition, analysis, modeling and visualization of performance parameters in endurance sports with emphasis on competitive cycling	• Providing software that incorporates the virtual gear into the gradient so that the cyclist feels a correct resistance while the flywheel exceeds the minimum rotation velocity in all realistic uphill scenarios	• Lack of extending the palette of physiological measurements (oxygen consumption, ECG, lactate, etc.) and implement models for these parameters
Gao, Sun & Jia (2005)	• Presenting the design and implementation of the VR-BWS bicycle simulator. The VR-BWS takes the bicycle as the carrier of human-computer interaction, and integrates sensor technology, three-dimensional modeling, collision detection and multimodal interactive technologies such as stereo displaying	• Using the participator experiences in a virtual environment	• The feeling that a participator experience in a virtual environment with the aid of the VR-BWS bicycle simulator is just like that of the real one	• Digital Signal Processing (DSP) control technique and three-dimensional modeling should be explained in detail. It means that the best domain (time domain, spatial domain, frequency domain, or wavelet domain) which best represents the essential characteristics of the signal and the processing to be applied to it has not been explained well.
Hernández et al.(2020)	• Design and implement a virtual reality bicycle system based on a functional based mechatronic design approach • Integrating a physical system, a VR system, and a Control Behavior System to compose a virtual bicycle simulator	• Using conventional or sequential design strategies • Implementing an approach that allows synergistic integration along the development process, integrating the involved disciplines concurrently	• The performance of instrumentation elements, control strategies, and feedback mechanisms, to provide the user with an immersive experience in the virtual environment	• The cybersickness aspect and quality of experience was considered with more detail in this research. • Since it is not possible to have a confident quantitative analysis with a questionnaire and a small sample, it's necessary to develop a suitable study on presence and immersion from an affect detection approach
Herpers et al. (2009)	• Development of an immersive bicycle simulation platform for several applications in the areas of biomechanics, sports, traffic education, road safety and entertainment (FIVIS project)	• Providing a special immersive visualization system, a motion platform and a standard bicycle with sensors and actuators, as well as a surround sound system	• The FIVIS simulator provides a realistic training and exercising environment for traffic education and stress research	• Applied resolution requires powerful graphics hardware. Therefore, the proposed simulator in this study is expensive and needs special hardware.
Horne et al. (2018)	• Proposing a speed calibration procedure to increase the validity of the simulator results, by using an independent bicycle computer for comparing the simulator speed	• Calibrating the procedure based on different traffic and vehicle's parameters, e.g., The effect of tire pressure and the physical speed of the wheel	• The calibration procedure uses general equations and techniques that can be applied to other bicycling simulators to calibrate speed measurements and improve	• Sensitivity analysis of dependent and independent variables regarding speed calibration has not been done in detail. It was assumed that the two variables of tire

[1] A sports simulator that uses the Virtual Reality Modeling Language (VRML) to create virtual environments for athletic training and competition

[2] The VR technologies which have been produced by famous IT companies. These systems are designed to create widely available spaces that may be simultaneously shared by many users.

			the consistency of experimental data worldwide	pressure and speed rate change with each other and the other variables are constant
Jia Q et al. (2006)	• Evaluating the role of the human-computer interaction system as the key technology of a virtual bicycle simulator	• Research about the structure of the interactive system (integrating the technology of force feedback, transducer, DSP control, bump detection and multicenter)	• A new project that combines virtual reality with human-computer interaction has been presented	• Requiring new methods to integrate the technology of force feedback, transducer, DSP control, bump detection and multicenter
Kakutani (2003)	• Proposing an integrated performance simulator that supports efficient research and development for a power-assisted bicycle	• Using the theoretical conditions which can experimentally evaluate qualities of the power-assisted bicycle	• Modeling the performance of the power-assisted bicycle with respect to the elasticity of a torque sensor • Considering the correlation between pedaling torque and the velocity of each component • The experimental results support the validity of the integrated power-assisted bicycle simulator	• The procedure of correlation between pedaling torque and the velocity was not explained in detail. It means that the elasticity of a torque sensor was used to measure deformations, forces and pressures. It had to be determined how this elasticity can measure the conflicting requirements of stiffness for all forces imposed to the bike simulator and torque components.
Katsigiannis et al. (2019)	• Proposing and evaluating a physical exercise system comprised of a smart-exercise-bike and a virtual reality platform that allows the users to engage in physical exercise while immersed within a virtual environment	• Using the Simulator Sickness Questionnaire (18 participants) • Physiological responses in terms of electrocardiography (ECG) and galvanic skin response (GSR) signals	• While the examined quality settings did not affect simulator sickness scores, the levels of prior experience with virtual reality technology were shown to have a statistically significant impact on simulator sickness	• A slow familiarization period could be allocated in order to allow users to become accustomed to the virtual reality system before engaging with it for long periods of time
Keler et al. (2020)	• Using a bicycle simulator to conduct studies with test subjects, evaluating novel traffic control strategies on existing transport infrastructure depicted in Virtual Reality (VR) environments	• Two studies were conducted and their quantitative (trajectories of the test subjects) and qualitative (questionnaire responses) results were analyzed	• The introduction of a Green Wave for cyclists can expand the cycling capacity and has a positive impact on the flow of cycling. • Comparing the widened one- and two-directional bicycle highway segments (3.0 m width per direction) with existing conditions (1.6 to 2.0 m), clarified that there is an increase in average speeds of test subjects of 0.37 to 0.62 m/s	• Providing a perceptual evaluation of proposals doesn't provide well-done quantitative estimates of their impacts on traffic efficiency and safety for the various types of road users by the direct analysis of collected trajectory data
Al-Kefagy and Sava Pokrajac (2019)	• Creating a virtual reality environment in which a bike user interface can be tested and evaluated • Implementing physical interaction inputs that can control the bike in virtual reality • The simulator should have the ability to perform unusual test cases in VR that otherwise cannot be tested in real life	• Proposing 3 levels of methodology consisting of "Research, Development and Evaluation." -Research: three different methods were used to triangulate the research data (Interview with stakeholders, Literature study and pre-study) -Development: Covering the minimum requirements set by the stakeholders and providing a functioning prototype -Evaluation: explanation of the metrics, e.g., effectiveness, efficiency and satisfaction of the conducted data	• Responding to the following **questions**: 1- Will the motion sickness be overwhelming and ruin the overall user experience? 2- Will the user be deceived by the stimuli in the VR and lose balance in real life? 3- Will the resolution be sufficient so that the details in the bike's interface are visible enough? 4- How well does the interaction in virtual reality correspond to real-life interaction?	• No unusual test scenarios were tested • Due to the imposed time limitation of 20 weeks and the limited availability of the VR eye tracking headset HTC Vive Pro eye, machine learning and eye tracking have only been discussed • Some technical problems regarding software and hardware components due to security reasons
Nazemi et al. (2018)	• Investigating the combination immersive virtual reality (VR) and an instrumented cycling simulator for in-depth behavioral studies of cyclists • Evaluating the effects environmental properties and road infrastructure designs on cyclists' perceived safety • Providing evidence that cyclists' behavior and perceptions in VR are very similar to reality and that VR, combined with a cycling simulator, is suitable to communicate (future) cycling facilities	• Preparing a questionnaire for 40 participants, mainly university students who were recruited for the experiment. The participants were asked to cycle approximately six times for 90 seconds. After that the respondents cycled through five different virtual environments, with five different types of cycling facilities (treatments)	• The average speed of the participants changed between scenes with different bicycle facilities, with the highest value for the segregated bicycle path. The braking and head movement activities also changed within each scene, where they occurred significantly more before arriving at the intersections	• The locked steering which confines riding to a straight line • The lack of interaction between the participant (as the cyclist in VR) and other road users, due to technological limitations • Detailed models weren't constructed to investigate the relationship between cycling behavior and the proximity to pedestrians and vehicles
Ouden (2011)	• Inventory of bicycle motion for the design of a bicycle simulator	• Using an "analytical methodology" consists of the question: What are the requirements for a bicycle in terms of, for example, steer torque, steer angle, lean angle, etc.	• Providing a set of requirements for the actual construction of a bicycle simulator	• This article was just about how to build a BS
Padmini et al. (2019)	• Implementing the virtual reality platform into a physical world (merging a physical environment with the virtual reality platform) • Providing an outdoor experience in indoor paddling and cycling exercises	• Using the hardware and software facilities (game engine, platform of BS, sending signal sensors to the user's cell phone by means of bluetooth, special gadget to control the virtual attributes inside the VR platform)	• Designing the compactness, ease of installation and cost effectiveness of a VR platform with the aid of a BS	• Lack of considering the effect of multiple virtual environments • Inclination and declination could be incorporated into system • Hill climb experience was not considered in this study
Rakhmatov et al. (2018)	• Proposing a data-driven vibrotactile rendering system for indoor exercise bicycles	• Using the data-driven model (a two-dimensional vector of cycling velocity and tire pressure as inputs of the model) • Using a data-collection bike that captures vibrations induced at the handlebar and the cycling velocity for different tire pressures	• The participants were able to successfully discriminate and identify simulated virtual road surfaces	• The effect of pavement type for generating road surface texture models has not been considered
Schramka et al. (2017)	• Presenting a cycling simulator implemented using consumer virtual reality hardware and additional off-the-shelf sensors • Developing a robust hard- and software framework which is able to track all essential parts of the bike	• Retrieved data from digital motion processors is sent over Bluetooth to a render machine running unity3D • By processing this data, a bicycle is mapped into virtual space	• Measuring how different street design configurations and traffic levels impact perceived cycling stress level, cognitive reactions and mobility behavior	• Measuring how different street design configurations and traffic levels impact perceived cycling stress level, cognitive reactions and mobility behavior • The lack of physical forces that increases the probability of getting motion sick • The downhill drive problem. A definitive solution has not been proposed to this problem

Schulzyk, Hartmann & Bongartz (2009)	• Designing a real bicycle simulator that is able to generate any desired traffic situation within an immersive visualization environment	• Developing a method in order to compute the bike's mechanical behavior that corresponds to the visualized traffic and the reaction of the driver • Using a UDP protocol for the transmission of the information	• Conducting a special system that facilitates a range of completely new applications in the field of safety at work, the area of neuropsychological research, and road safety education	• Neuropsychological applications have not been explained in detail
Shoman & Imine (2021)	• Presenting the new features implemented in the bicycle simulator developed by the Perceptions, Interactions, Behaviors and Simulations Lab for road and street users (PICS-L) at Gustave Eiffel University	• An experiment involving 36 participants who rode the simulator for around 600 meters with full control on the handlebar, pedals and brakes has been conducted	• Responding to the following issues: 1) The environmental elements to which cyclists adapt their behavior (i.e., speed, safety gap, steering, etc.); 2) How cyclists adjust their riding practices as they interact with other road users; 3) How cyclists anticipate risks in hazardous riding situations, and what strategies, equipment or behaviors they employ to cope with those risks	• The effect of cyclist behavior and the interaction with the infrastructure and other road users has not been considered
Tang et al. (2018)	• Developing a virtual cycling simulator for exercise and entertainment purposes, and for promoting the cycling activity (the case study is the university gymnasium in the Chinese University of Hong Kong)	• Proposing the architecture of the virtual cycling simulator. The hardware of the simulator includes a bike platform, an actuation unit, a sensing unit, and a display unit • The software communicates between the hardware and controls the necessary motions of the hardware	• The university gymnasium was simulated by this BS • The dynamic changes of the virtual environment including the resistance of different land profiles and decelerating can be simulated well by this BS	• More outdoor cycling elements such as wind and sunlight effects could be included in the system to increase the realism of the cycling experience
Ullmann et al. (2020)	• Presenting a virtual reality bike simulator as part of sustainable urban space and traffic planning to provide rare qualitative factors (such as stress, the perception of time and attractiveness of the environment). • An audiovisual VR bicycle simulator has been presented	• Using the observation/Participant Observation • As well, using Unity 2018.3.11 as VR engine to connect the bicycle interface to the HTC Vive HMD and the virtual environment with its static and dynamic content	• Presenting an interactive audiovisual VR bicycle simulator that allows users to explore and evaluate virtual environments	• Optimizing and evaluating this virtual reality bicycle simulator in terms of realism to gain valuable qualitative and quantitative data on cyclists' behavior characteristics and requirements in urban spaces
Yap et al. (2018)	• Proposing a spatial immersive track cycling simulator • Simulating the velodrome track cycling in the VR environment and synchronizing with a 6-degree-of-freedom motion platform	• 50 students as participants were selected to try the developed spatial immersive track cycling simulator/ asked to complete a questionnaire survey regarding the spatial immersive track cycling simulator	• Based on the questionnaire results, a majority of the students have accepted the current prototype of the spatial immersive track cycling simulator as a training tool	• The effectiveness of this simulator in raising the performance of the athletes is uncertain

TABLE 1 Systematic Review of BS's Application (Cont'd)

The third application of BSs: Application of BS in the safety promotion studies				
Author Name	**Objective**	**Methodology**	**Outcome**	**Gaps**
Brown et al. (2017)	• Investigation of alternative pavement markings for bicycle wayfinding and proper bicycle placement at signalized intersections	• Using a bicycle simulator and post-simulator survey with 27 participants (case study a network of 37 intersections with characteristics similar to intersections in Columbia, Missouri)	• The second proposed marking (based on MUTCD definition) with a green circle performed better with respect to visibility and delineating the bicycle route. Based on Analysis of variance (ANOVA) results, the considered MOEs (consisting of four MOEs: Average elapsed time for the simulation run, Surrogate for the relative perception-reaction time of the signage or marking, Relative distance to the signage or marking when the rider started to hand signal, and Average number of missed transitions such as not following the signage or marking and going the wrong way) were statistically investigated, and the second proposed marking had the better performance	• Small sample size (27 participants); two of the 27 participants were not able to complete the experiment because of motion sickness. • Other MOEs could be considered such as lighting conditions, different pavement types, different colors of pavement, and bicyclists' level of experience.
Ghodrat Abadi et al. (2019)	• Evaluating the behavioral interaction between bicycle lanes and commercial vehicle loading zones (CVLZ) in the United States by BS (to preempt increasing conflicts between truckers and bicyclists)	• Developing the virtual environment using simulator software packages, including Internet Scene Assembler (ISA) • Inviting 48 participants • The bicycling simulator collected data regarding a participant's velocity and lateral position	• Truck presence does have an effect on bicyclist's performance, and this effect varies based on the engineering and design treatments employed. Truck maneuvering had the greatest impact by decreasing mean bicyclist velocity and increasing mean lateral position	• Near-miss real-world events have not been considered • Detail of crash data is necessary to determine what factors contributed to a crash, such as travel direction and relative position of the parties
Kaß et al (2020)	• Measurement of cyclists' riding behavior during dynamic interactions with automated vehicles (Investigating the potential benefits of eHMIs (external human-machine interfaces) as a communication interface of automated vehicles)	• In a bicycle simulator study, 20 participants (10 men, 10 women) encountered different interaction scenarios with an automated vehicle that either had the maneuver intention to brake or continue driving • The comprehensibility of the eHMI was measured with a special occlusion method	• The eHMI led to more effective and efficient behavior of the cyclists when the automated vehicle braked • The eHMI provoked safety-critical behavior during three interactions when the vehicle continued driving	• More scenarios regarding the interaction between automated vehicles and bicyclists could be simulated • The sample size is very small • The proposed behavioral parameters could be supplemented by further measurements • The method could be complemented by self-reported measurements, such as usefulness, trust, or satisfaction
Lindström et al (2019)	• Exploring how radar sensors and technology common in automotive vehicles can be transferred for use on bicycles. A bicycle simulator was planned to be used for test and evaluation.	• Analysis of traffic accident injury statistics. Two workshops were conducted involving experts within mobility and traffic safety to develop knowledge and collect ideas related to functions, interactions, problems and solutions of a device for increasing the situational awareness for a bicyclist in traffic	• It explored bicycle radar as a means of improving bicycle safety and bringing ADAS (Advanced driver-assistance systems) technology from the vehicle industry to the bicycle domain	• The new analytical methods based on heuristic algorithms in software should be presented to consider different aspects of the user interaction in this simulator, including sensor modalities, different messages and different encoding of messages • They didn't explain how temporal and spatial vibration patterns on this HMI (human-machine interaction) could be used to provide information to the bicyclist about the direction and the level of danger • The project used commercial off-the-shelf radar sensors commonly used for cars
Matviienko et al (2018)	• Using multimodal warning signals to increase children's awareness and prime action in critical situations by developing a bicycle simulator • Investigating how visual, vibrotactile, and auditory feedback situated in the helmet and bike can be used to convey warning signals for children	• Recruiting 15 children (7 female) aged 6-18 (M = 9.2, SD = 1.9) years, who had between 2-9 years of cycling experience (M = 4.67, SD = 2.02)), all of whom had normal or corrected vision without color blindness and no hearing problems • Conducting a brief interview with each child to better understand issues they faced while cycling	• Participants spent significantly more time perceiving visual than auditory or vibrotactile cues. Unimodal signals were the easiest to recognize and suitable for encoding directional cues • Unimodal signals were better for encoding directional cues and multimodal signals for urgent immediate actions especially in the two most common car-to-cyclist collisions	• Children faced problems noticing and interpreting traffic signs on the road, which must be evaluated • Deriving a set of on-bicycle and helmet locations for multimodal feedback applicable for warning representation
Nazemi (2020)	• Investigating the capabilities and limitations of immersive 360-degree virtual reality (VR) for bicycle research to study bicycle facility preferences, perception of safety of bicyclists, and bicycling behavior	• 150 Singaporeans participated in this experiment and were asked about bicycling attitudes after bicycling in five different environments with an instrumented bicycle in VR	• The results identified thresholds at which the majority of the participants could recognize speed and distance variations between two subsequent scenes in VR	• Limitations of the applied VR technology such as lack of interaction between different road users and the bicyclist • Lack of diverse skill set to create the virtual environments for travel behavior • Even though the sample had a good gender balance, it was not representative of the Singapore age population and is likely subject to some response bias • Due to restrictions with regards to VR immersion duration to avoid motion sickness and mental overload, short bicycling courses were designed resulting in short ride time per bicycling environment • The ability to steer was not activated in this study and conflicts with other road

				users were not allowed, which had an impact on safety perceptions
O'Hern et al. (2017)	• Assessing the behavioral validity of participants using a newly developed bicycle simulator with respect to a range of cycling performance measures collected both using the cycling simulator and on-road	• Recruiting 26 participants ranging in age from 18 to 35 years (M = 25.0, SD = 4.8). Absolute validity was established for measures of spatial positioning including average lane position, deviation in lane position and average passing distance from curbside parked cars	• Finding evidence to suggest that aspects of cyclist behavior can be investigated using the bicycle simulator • The simulator was capable of eliciting similar behavioral responses among the group of participants compared to on-road cycling	• Validation of cyclist head movements may need to be conducted in a more controlled environment, potentially using a test-track to create consistent and controlled environments for participants • Validating the study for more complex behavioral performance measures such as gap acceptance and cyclist reaction times
O'Hern et al. (2018)	• Conducting a study in Australia to understand how cyclist behavior can be influenced by variations in road design aimed to improve safety • Examining how bicycle lane width and perceptual countermeasures can influence cyclist speed and position	• Recruiting 27 participants ranging in age from 18 to 39 (M=24.2, SD=5.7) • Using a statistically significant data method (Post-hoc testing) to observe the influence of bicycle lane width on cyclist lateral position	• Providing fundamental information about how cyclists choose to position themselves when riding in bicycle lanes in a validated virtual reality environment • Regardless of the width of the bicycle lane, cyclists tend to ride toward the center of the lane	• Effect of road design to improve cyclist safety should be investigated in detail
Powell (2017)	• Providing a virtual environment by a BS to study and reduce fatal and injury accidents between bicyclist and motor vehicles by safely investigating the interaction of bicycle riders and traffic, particularly for bicyclists crossing streets	• Designing the hardware elements for an electro-mechanical bicycle simulator in an immersive virtual reality environment	• Describing the simulator design • Validating various physical experiments measuring the system inertia, the time delay of the electrical components, and the overall system performance	• Proposing the measure of effectiveness • Proposing sensitivity analysis among dependent and independent variables
Sawitzky et al (2020)	• Studying the effects of new infrastructural concepts and technologies such as head-up displays for cyclists • Investigating how children can be better prepared during traffic safety education for cycling • How the general public responds to novel warning systems displayed on a HUD (Head-up displays)	• Using a mixed reality simulation	• Children who train for hazardous situations can recognize and react to dangers faster • Introducing proposed bicycle simulator setup, either used with a VR headset, combined with a physical bike, or with a game-like control on a PC	• Some of BS features are still under development (Cyclist safety service, smartphone, smartphone connection, HUD prototype) • Evaluating new warning systems for cyclists and developing modules for traffic safety education
Suzuki (2013)	• Study about cycling on sidewalks and its hazards (case study Japan)	• Examining various road designs and traffic situations to develop better bicycle facilities	• Developing a new cycling simulator ("Morics") which is available for analysis on the safety and influence to the other modes	• Lack of the detailed design guideline of bicycle facilities
Tsuboi et al. (2018)	• Making people learn desirable riding manners for a bicycle, and improving their skills to increase safety by using bicycle riding training systems based on virtual reality technologies	• Conducting an experiment by the following steps: Step 1: Preliminary questionnaire Step 2: Training explanation Step 3: Actual training Step 4: Post questionnaire	• Improving the effectiveness of bicycle riding training by improving the reality of the training system • Introducing a proper feedback system for training system users	• Due to the limitations of the VR devices, some users experienced VR sickness during their training, and the discomfort narrowed their field of vision • Did not conduct an experiment with children in this study
Warner et al. (2017)	• Analyzing a right-hook crash (a crash between a right-turning motor vehicle and an adjacent by-moving bicycle) • Evaluating the effectiveness of four types of engineering countermeasures: regulatory signage, intersection pavement marking, smaller curb radius, and protected intersection design at modifying driver behaviors	• Designing a second experiment to test various design treatments and controls in a simulated driving environment under specific environmental conditions • Examining and analyzing motorist behavior – including the right-turning motorists' visual attention, crash avoidance behavior, and potential crash severity – in response to four different categories of possible right-hook crash treatments	• All gathered treatments had some positive effects on measured driver performance with respect to the right-turn vehicle conflicts	• Due to limitations of the eye-tracking system equipment and calibration procedures, individuals wearing glasses were unable to participate unless they had contact lenses that provided them with adequate driving vision • Lack of considering the fatigue effects which can cause the participant's performance to decline over time during the experiment • Statistical power of the analyses; limited statistical power was observed which could be due to the limited number of observations
Yamaguchi et al. (2018)	• Proposing a method to detect road hazards using sensors attached to a bicycle in a prior conventional study • Proposing a bicycle simulator capable of tilt angle control that runs in a three-dimensional (3D) virtual space; the built-in sensors send the speed and front-wheel angle information to the control unit	• Using a BS to gather training data for machine learning, requiring the bicycle to travel over hazardous areas repeatedly	• A new tilt angle was calculated by the control unit and the information was sent to an AC servo motor to achieve this new tilt angle. This system allows for dangerous situations to be easily and repeatedly created with no danger to the rider	• They didn't explain why a fixed type of bicycle simulator is not suitable for gathering hazard data • More evaluation is needed regarding the "rotation center tracking method"

TABLE 1 Systematic Review of BS's Application (Cont'd)

The fourth application of BSs: Application of BS in different fields of science				
Author Name	**Objective**	**Methodology**	**Outcome**	**Gaps**
Englund, Nilsson & Voronov (2016)	• Presenting a novel approach consisting of a unique bicycle simulator equipped with sensors capable of capturing the behavior of the bicyclist to modeling visual distractions of bicyclists	• The methodology is based on a cyber-physical bicycle simulator developed for the experiment • The data is used to model the self-assessed distraction level and a variable selection procedure is used to find the distinguishing variables	• With a few observable variables, it is possible to use machine learning to model and predict the distraction level of a bicyclist • The bike can measure the most descriptive variables remotely, e.g. a vehicle with radar, Lidar and camera sensors	• The difficulty of verify the models and their relevance compared to the behavior in a real traffic environment • The engagement from the test person is also one limitation for simulators
Batcir et al. (2021)	• The effects of bicycle simulator training on an anticipatory and compensatory postural control in older adults • Investigating whether an alternative PBBT[3] program that provides perturbations during hands-free bicycling in a sitting position, geared to improve trunk and arm reactive responses, can be transferred to reduce fall risks and improve balance function among pre-frail older adults	• In a single-blinded randomized-controlled trial, 68 community-dwelling pre-frail older adults were randomly allocated into two intervention groups • The experimental group received 24-PBBT sessions over 12 weeks that include self-induced internal and machine-induced external unannounced perturbations of balance during hands-free pedaling on a bicycle-simulator system, in combination with cognitive dual-tasks	• Older adults are able to respond effectively to increasing levels of unannounced perturbations during stationary bicycle riding • Generalization of balance skills acquired by exposure to postural perturbations in a sitting position • The individualization of perturbation training to older adults' neuromotor capacities in order to optimize training responses and their applicability to real-life challenges	• Because of the lack of specificity in the tilting perturbation model, the authors find no effects of the intervention • Trainers were trained to follow the pedaling intensity according to the training program to control endurance component in the two intervention groups, but although the bicycle resistance was set equally, it might be difficult to monitor the speed of pedaling for each participant
Fernández et al. (2018)	• Presenting a simulator for analyzing bike-sharing systems • Several user generation distributions have been configured • The simulator was specifically designed with the aim of evaluating incentive-based rebalancing strategies	• Assessing algorithms that try to balance the number of available resources (bikes/slots) at a bike-sharing system	• The proposed BS can be used to assess a specific bike-sharing system infrastructure (station locations, size, etc.) before deploying it by testing how the proposed infrastructure behaves to a given expected demand	• Graphical interfaces to assist users to create configurations • Adding further quality measures (e.g., time a station is empty, extra distance walking by users, etc.) • Designing incentive-based algorithms and testing them with the simulator
Kim et al. (2006)	• Development of a virtual-reality training system based on an exercise bicycle and a personal computer for rehabilitation of motor functions and balance capability in elderly patients	• A series of experiments were conducted with three different visual feedback conditions: without visual feedback of balance information; with visual feedback of weight shift; or with visual feedback of the center of pressure	• The improvement of balance capability on the bicycle • The system might be used as a balance and motor function rehabilitation system with further objective measurements of balance ability of the patients in longer terms	• Only three parameters entered to model from the BS: the pedaling speed, the direction of the handles, and the location of the center of pressure on the supporting base of the bicycle
Ginter et al. (2016)	• Understanding which bike path network would be more efficient and important for municipalities and cyclists	• Using the multi agent-based (MAS/ABM) simulator VeloRoutes • The MAS/ABM occupancy simulation model can be specified by two components: data and algorithm	• VeloRouter enables continuous occupancy assessment on the planned routes, which are determined by the amount and quality of context captured data in PostgreSQL database; in this way the Occupancy Simulator is trained to increase the assessment credibility	• The use of semantic analytics and visualization results in a manner that corresponds to the user's perception, although more parameters were examined and investigated
Gratkowski (2017)	• Presenting an experimental setup • The main part of the setup is a BS consisting of a classic Dutch-style bicycle frame mounted on a commercially available ergometer • The pedal resistance is controllable in real-time by custom software and the pedal position is continuously tracked by custom Arduino-based electronics using optical and magnetic sensors	• Using the Brain Cycles setup, a modified version of the power BS, which was developed for data acquisition, analysis, and visualization of performance parameters in endurance cycling	• The presented experimental setup provides means to directly record basal ganglia activity not only during cycling but also during other movement tasks in patients • It can help clarify the mechanism by which cycling may have therapeutic benefits	• The suddenly appearing obstacles effect on the behavior of patients has not been well studied • The Power bike's ability to play videos synchronized to pedaling • Comparing the Visuomotor processing during walking on a treadmill and cycling on an ergometer
Herpers et al. (2008)	• The objective of the FIVIS project was to develop a bicycle simulator able to simulate real life bicycle ride situations as a virtual scenario within an immersive environment	• A 6 DOF motion platform has been integrated into the system design; the platform is known as a Hexapod or Stewart Platform together with the mounted bicycle • The mechanics of the bike are transformed into components of modelling software that support the solution of the underlying differential equations	• Developing a physical simulation model for a virtual world • FIVISim, the FIVIS simulator software, coordinates the sensor input, performs the visualization and controls the motion platform	• It is unclear so far how an operator would react if the perceived velocity is higher or slower than the expected physical velocity • Very little is known with respect to the range in which humans accept the visually perceived velocity in relation to the expected physical one
Coombe (2011)	• Design and build of a system that can operate in an artificial gravitation environment and utilizes VR technology with Google Earth and NASA World Wind • Considering a heuristic BS as a medical tool for astronauts and could potentially be a solution for bone density losses that would debilitate astronauts on extended duration missions	• Creating a software program (incorporates GoogleEarth, NASA World Wind and Instant Player) • Using theoretical results	• Creating a testing platform consisting of an exercise bike with the same functionality as the space-faring system to allow testing of the program and validity of the space bicycle simulator concepts	• The motion sickness effect has not been evaluated well
Hurwitz et al. (2019)	• Proposing a speed calibration procedure to increase the validity of the simulator results, by using an independent bicycle computer for comparing the simulator speed	• The calibration procedure uses general equations and techniques that can be applied to other bicycling simulators to calibrate speed measurements and improve the consistency of experimental data worldwide • Calibrating the wheel speed input between real-world and virtual bicycling will increase the validity of the bicycling simulator • Wheel speed was calibrated by an independent bike computer	• Provides framework for transportation researchers to measure steering latency • The speed ratio, or the simulated speed divided by the bike computer speed, was used to evaluate the influence of tire pressure and gain factor	• Evaluating acceleration or deceleration would be difficult using the current bike computer due to data resolution, as the system only records data every 10 seconds • Does not address the possibility of applying the proposed procedure in this study to other bicycle simulators, developing a procedure to analyze the calibration of steering input by observation of visual latency, and validation studies to match simulator performance to field experiments

[3] Perturbation-Based-Balance Training (PBBT) is a promising approach to reduce fall rates by improving reactive balance responses

Jamin et al. (2020)	• Analyzing the influence of age in the ability to ride a bike on a virtual straight line with the perspective to be able to identify diseases in a geriatric population	• Processing time series defined as the deviation from the center of the virtual path	• The proposed approach is able to reveal different learning and adaptation skills in the two populations	• This study can be useful to help the geriatricians in their diagnoses
Keler et al. (2018)	• Proposing one option for experiencing microscopic traffic flow simulations from a first-person perspective visualization as one interacting traffic participant on a non-moving physical bicycle • Introducing a procedure for implementing a bicycle simulator for testing various scenarios in three-dimensional environments	• Proposing the connecting methodology of the data acquisition and processing within the bicycle simulator hard and software (Connection between the results of BS and heuristic MATLAB SIMULINK code)	• Analyzing present problems of traffic and built infrastructural elements • Inspecting planned scenarios with variations in traffic compositions (participants and modes) and built infrastructure (inclusion of new design elements)	• It was better to test the usefulness of the presented device with more scenarios
Keler et al. (2019)	• Evaluating a traffic control strategy implying countdown timer displays for bicyclists with one device being permanently installed in Munich (Germany) by (1) extracting cyclist trajectories from video observations before and after the installations, and, (2) introducing a bicycle simulator scenario via a map design approach	• Using video trajectory extraction methodology • Using a questionnaire	• The findings of the bicycle simulator study for evaluating different countdown timer displays helped improve the immersion and hardware efficiency of the whole system	• Numerous questions of the questionnaire focused on realism in performing specific maneuvers, such as accurate stopping at or before the stop lines • Other aspects of bicyclist's behavior were not well considered
Kaths et al. (2019)	• Identifying and separating the desired movement of more flexible road users who do not follow lane discipline, such as bicyclists, from movements made as a reaction to other road users or obstacles	• An approach was developed and presented for connecting three environments: observations from an intersection in the real world, a SUMO traffic simulation and a DYNA4 simulation of the road environment	• The bicycle simulator was developed as a tool for investigating the tactical behavior of bicyclists (e.g., response to a red traffic light).	• Systematic errors can be detected by comparing velocities, particularly at curves, from bicyclists in real and VR space • Acceleration's effect has not been determined well (more tests are needed to investigate it) • The results of validation studies
Matsumura et al (2016)	• Proposing a method that uses speech analysis to measure fatigue • Developing general-purpose fatigue measurement system	• Preparing a method that uses the following fatigue measurement indexes: -fundamental frequency -average power -time period	• Significant results of a CVa-a variation coefficient (acceleration plethysmogram) were obtained • The proposed method effectively measures fatigue better than a conventional method	• Failing to obtain significant results by another conventional method
Mittelstaedt et al. (2018)	• Considering the effects of Cybersickness in VR usage by BS	• Participants were instructed to ride a virtual bike across a virtual island and used either a head-mounted display (HMD) or a large TV screen for VR presentations and a bike ergometer or a gamepad for motion control • Cybersickness in three different conditions, each with 20 participants, was assessed on multiple occasions during and after VR immersion	• Higher sickness scores with the HMD than in the large screen condition • No differences between the means of control were observed • Additional correlation analyses revealed significant relationships between the sickness scores with past motion sickness history	• The authors could not confirm that a more realistic motion control (bike ergometer) induces less cybersickness than more generic means of motion control (gamepad) • More research is needed on why display types induced different levels of cybersickness within VR and why these differences disappeared in the post-immersion assessment
Mizoguchi & Yamanaka (2015)	• Making clear the performance of the developed bicycle simulator with widescreen from the viewpoint of real perception reappearance of speed and distance	• The evaluation of road facilities and information scheme were determined based on comparing the lab study and real world	• Speed in BS tends to be felt slower at about 50%, distance in BS tends to be felt shorter at about 50% than a real situation, but time perception in BS seems to be compatible to the real world	• Sight distance for signage becomes short due to the low resolution of display
Soma et al. (2013)	• Designing a semi-automatic stabilizing control for the bicycle as the long-term purpose	• A mechanical simulator to simulate circling bicycles has been developed with a pendulum system, and effectiveness of a stabilizing control has been verified with the simulator	• The authors have proposed a power-steering system for electrically assisted bicycles in their previous works • The power steering system can support the steering of riders; it has the possibility to stabilize a bicycle with two children semi-automatically	• The balance of a two-person bike is more difficult • The issue of the stability of this type of bike over long distances was not mentioned
Sun & Qing (2018)	• Evaluating the availability of a bicycle simulator to contribute to the understanding of bicycle facility design and bicyclist behavior • Presenting the details of the ZouSim bicycle simulator development and the tradeoffs associated with various design decisions, such as the choice of a steering sensor and graphical display	• Using an automated collection of simulator performance measures such as bicycle trajectories	• The software development process for the ZouSim bicycling simulator • Calibrating the simulator using field videos improved the visual fidelity of the simulator	• Existence of some limiting factors such as the inability to replicate bicycle leaning for turning or the assumption of a flat grade • Human participants error (who make wrong turns)
Yin & Yin (2007)	• Presenting a set of novel force display devices for the interactive bicycle simulator for indicating the human-bicycle contact forces at handlebars and foot pedals	• Using experiments and practical application to construct force display devices	• The developed RBD model (rider–bicycle dynamic model) and the constructed force display devices are effective in capturing and displaying the information on forces	• A more comprehensive equation and solution schemes will be better for conducting a control model of the of the presented rider-bicycle system
Yin & Yin (2006)	• Implementation of the interactive bicycle simulator with its functional subsystems to bring riders a realistic cycling feeling	• Providing the rider-bicycle dynamic model • The Newton-Euler method was adopted to formulate this model.	• Simple and effective devices were constructed and driven by the outputs of the rider-bicycle dynamic model, and these devices were successfully applied to the interactive bicycle simulator	• No clear explanation for choosing the Newton-Euler method for this research

Youn & Choi (2014)	• Concentrating on the "SporTainment" concept with a realistic bike simulation • SporTainment is a compound of the words 'Sports' and 'Entertainment' and it possesses the meaning of sports and entertainment simultaneously	• Proposing the hierarchical architecture to connect a virtual game environment and BS (connection between the bike module, its sensors and reappearance device)	• Application of consumer's emotional feedback technology • It maximizes the feeling of existence and immersion of the consumers • The presence of the user was increased by developing a realistic bike simulation	• New methods to combine emotional effects and reappearance devices in the bike simulation will be needed
Almeida et al. (2020)	• Recreating the activity of riding a bicycle by exploring the possibilities of electronic devices, such as making curves with the handlebar or body-weight, pedaling, and braking, among others • Identifying how the devices in SimBike contribute to the user experience in the virtual simulator, including the level of immersion, realism, and cybersickness symptoms	• Conducting an empirical evaluation of the proposed simulator, aiming to identify if the proposed devices contributed to the user's presence and the reduction of cybersickness symptoms. Tests were performed at the laboratory	• The implementation of the acceleration proved to be satisfactory • The handlebar attenuation by bicycle speed offers good precision and latency and its concept seeks to provide greater comfort to the user and greater involvement in the simulator • Improvements to make the simulator suitable for all types of users, regardless of their characteristics such as weight and height	• Improve the balance's calibration algorithm and procedure • Track user's hand positionsements in haptic response, reducing latency and better transmitting the sensation of contact with the ground • Improve immersion by adding more sound effects, such as the sound of the bicycle's chain and other events related to haptics feedback
Caro & Bernardi (2015)	• Determining the role of the different sensory information available (the mechanisms of perception of the natural speed which affect the adopted speed)	• Recruiting several participants for a laboratory experiment	• The speed of the picture and the resistance to pedaling affect the speed adopted by the participants, while the manipulation of the airflow has no effect • The small variation of the speed adopted regarding the stimuli suggests that the pedaling rate, as an internal feedback, plays a preponderant role in the control of their own speed	• Based on this research, "Air flow" has no effect, and this indicator should be better evaluated, especially by more accurate modeling

Rittenbruch (2020)	• Presenting a physical computing toolkit that supports the rapid exploration and co-design of on-bicycle interfaces • Understanding how to support and facilitate co-design processes that allow participating cyclists to safely explore different on-bicycle notification mechanisms and modalities	• Assessing the toolkit by analyzing video recordings of two group design workshops and 12 individual design sessions	• Results from the first set of design workshops (Study I) addressed to what extent a toolkit can help workshop participants ideate novel bicycle user interfaces, specifically interfaces that relay time-critical information about potential hazards • Results from the second user study (Study II) revealed how a toolkit in combination with a lightweight bicycle simulator and simulated hazards can be used to evaluate different designs and elicit rich feedback	• Integrating hazard events will pose additional challenges to the design of notification mechanisms • The simulator only offered a single generic type of bicycle •