Bicycle Accident Prevention using Sensors and Automotive Systems

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ABSTRACT

Road safety for bike riders has become more relevant in many countries. An increase in cyclists has been observed since the introduction of the electric bicycle. Even today, bicycles have little or no intelligent systems onboard and relatively little research has been done on such methods. We propose to deliver a literature survey based on the cycling accident causes, available methods and a comparison with systems used on cars. Besides the literature research a simulation is made based on the findings from the literature research. This research is concluded by an evaluation on the found methods, simulation and a detailed consideration on sensors. This paper should provide more insight of what causes bike safety issues, the systems that are currently available, and potentially more sensors that could improve cycling safety. Concluded that sensors in combination with a vehicle-to-vehicle system can contribute to cycling safety.

Keywords

Sensors, Bicycle, Machine Learning, Roads, Safety, Traffic, Cyclist, Smartbike, Literature Research, Simulation

1. INTRODUCTION

The number of road fatalities for bike riders is increasing worldwide, due to the increasing number of cyclists. An analysis conducted by Statistics Netherlands (CBS) showed that the number of traffic deaths has decreased more sharply among motorists than among cyclists over the past two decades. The number of accidents involving cyclists has decreased relatively little in recent years. Between 1999 and 2019, passenger car occupant deaths dropped 60 percent, while cyclist fatalities only fell by 11 percent.[61] In 2017, the number of fatal accidents among cyclists in the Netherlands was even higher than fatal car accidents. The difference in percentage between automobiles and bicycles is huge. According to this analysis we should pay more attention to bicycle safety as well.

The causes of accidents on the bicycle may differ from those of the car. A number of studies showed that the most common mechanism of injury were single bicycle crashes which made up two thirds of all injuries [10]. It follows that accidents were mainly caused by the cyclist himself. Hence, we need to revise current systems on bicycles or develop a new method in order to ameliorate safety for bike riders. The most common safety feature used in traffic are sensors.

Sensors are useful because they can observe things that we as humans often cannot. For example, a depth sensor can determine how far a car is behind you and whether that is dangerous at the current speed. In addition, sensors can observe several objects at the same time and communicate with each other in order to recognize hazards.

Currently odometers are used to measure the speed and distance traveled on a bicycle. Odometers are one of the few sensors that can be found on a bike. This is not enough for reducing the number of bicycle injuries. Since the number of accidents on bicycles is still increasing [61]. This new era grants more possibilities to solve this issue.
Currently research has only been conducted on private projects and accident causes, not on finding the critical accident causes and improvements for existing bicycle safety methods.

This paper is to gain knowledge about the causes of bicycle accidents and to do research on existing safety techniques used on bikes today. In addition, current systems used in automobiles were investigated. Based on literature research, the critical and interesting problems for cycling safety were identified and were provided with available solutions based on qualitative analysis. Thereafter, improvements for existing systems and potentially more sensors that could improve safety were discussed. In the results section the simulation in Sumo is discussed, to substantiate the answers found by means of literature research.

The structure of this paper is provided in sections. Section 2 will show related work in bicycle safety systems. Section 3 will explain the methodology and approaches to answer each research question. Section 4 gives an overview of the results obtained by the research. In section 5 the studies and results found are discussed. Finally, at section 6 a conclusion is shown and future work is discussed .

1.1 Problem Statement

Despite the fact that research has been done into improving safety for cyclists in general. There is a lack of research on bicycle safety systems and techniques that could improve cycling safety. This thesis should provide more insight into what causes bike safety issues, the systems that are currently available, and potentially more sensors that could improve the safety. Existing investigations into bicycle accidents alone are not enough to tackle the major cycling safety issues. There is a need for research into potential solutions to predict and prevent accidents in the first place.

In order to understand what kind of sensors and systems are needed, we first need to know what causes bicycle accidents. In addition, we must examine existing systems on the bicycle to see if there are flaws in current methods. This will lead to the research questions stated in section 1.2 *Research Questions*.

1.2 Research Questions

The goals mentioned in the introduction and the problem statement will lead to the following research questions (RQ) the basis of our research:

- **RQ1:** What causes cycling safety issues?
- **RQ2:** What are the available sensors and methods used in bikes and automobiles that improve road safety ?
- **RQ3**: How can existing sensors and methods be adapted by bikes?

This research provides a great insight into the application of the methods and techniques used for cycling safety on the road. By gaining knowledge of different research methods and applying the systems of cars to bicycles, the reader should gain new insights into the optimal use of sensors. Detailed description of the research questions can be found in Section 3. *Methodologies and Approach*.

2. RELATED RESEARCH

Relatively little research has been done into road safety for bike riders in particular. This research is unique because it is a combination of three research questions that require literature research. Related research is discussed per section. The general approach of the literature surveys is described in section 3. *Methodology and Approach*.

3. METHODOLOGY AND APPROACH

In this section, the steps taken are discussed to answer the research questions. In addition, it describes how research is done. First the causes for cycling safety issues will be determined. Secondly, research on existing safety techniques used on bikes will be used. In addition, we look at what sensors are available and how they can add value to the goal of providing research on eventually improving road safety. Thirdly, we perform research on how we can improve the existing methods and possibly adapt some techniques from automobiles. Lastly, we will evaluate the new and improved versions which we base on previously conducted literature reviews supported by a simulation in Sumo.

3.1 Databases and Search Strategies

This literature research was performed from 5 May 2021 until 30 may 2021. In order to gather related literature to this research question domain IEEE, Google Scholar, UTLibrary and Scopus were used to search for papers. The following keywords were composed to identify relevant papers: concept 1: TITLE-ABS-KEY (bicycle* AND accident* AND causes*), concept 2: TITLE-ABS-KEY (bicycle* AND accident* AND causes* AND characteristics) and concept 3: TITLE-ABS-KEY (cycling* OR bicycle* AND accident*). The option "Peer reviewed" was set to true and the publication date was set to 2000-2021. TITLE-ABS-KEY means the keywords are searched in the title, abstract and keywords of the relevant paper.

A selection was made based on the papers found. The first step was to screen the title, abstract and keywords to identify the relevance. After screening, the literature found was compared with the In- and exclusion criteria. Thereafter, for the papers that met the criteria, full-texts were acquired to extract relevant information.

3.2 In- and Exclusion Criteria

Articles that were used for this research are all in English. The year 2000 was chosen, because the number of cyclists has increased rapidly in the past two decades. With an exception, because the year and time are not a concern for some sub-questions. More recent studies were used for investigating the available sensors and systems on bikes, since intelligent bicycle systems are still under development and research has only been done in the past few years.

During the search for relevant papers for the aforementioned research questions, it was tried to select papers with many peer-reviews. It is, however, to be noted that some authors are no expert on the fields of cycling safety, sensors and system applications. Therefore the validity can be applied up to a certain level.The results are stated in the upcoming section and is subdivided into the causes of bicycle accidents, available systems and adaptation of such systems to the bicycle.

3.3 Simulation

In this project, Simulation of Urban MObility (SUMO) was used to simulate bicycle and vehicle behaviour. SUMO is an open source traffic simulation designed to handle large networks. It is possible to build a network and environment using NetEdit.

However, OpenStreetMap was used to directly import map data. After installing the corresponding files the osmWebWizard python script was executed, which opened in a web browser. An intersection near the University of Twente was selected to simulate bicycle-car and bicycle-bicycle accidents, which can be seen in Figure 2. Additional code was written in the configuration file, which was necessary to collect data and set up a Bluetooth connection. Python was used as the main programming language to change and adjust code. The results of various literature researches and simulations are described in section 4. *Results*.

4 RESULTS

4.1 Causes Bicycle Accidents

The search queries and filters used on the database resulted in 318 results in the Scopus database, 97 useful results on Google Scholar and a total of 185 articles on IEEE and the University of Twente library. After removing duplicates, a total of 393 unique studies remained. The abstract of these papers were screened and papers that deviated were removed, which resulted in 52 papers in total for the first research question. The papers that remained were downloaded and read completely to eliminate more irrelevant papers. There were also inaccessible articles, a license was required to read them. These papers were therefore deleted for this selection. A total of 40 usable papers remained, which were reviewed.

An overview of the remaining studies are described in Table 1 in the Appendix. Articles in this table are sorted on the year of publication. The table includes the subject, method(s), discussion and conclusion of the articles. The causes of bicycle accidents are divided into five separate parts, which is determined based on found literature, government recommendations and policy guidelines. After performing research the following five main causes of bicycle accidents were encountered.

First, crashes caused by distraction of the cyclist self. Distraction while cycling is a complicated issue, since the biker is responsible and is difficult to prevent. Examples are riding hands free, using a mobile phone while cycling or riding side by side and hitting each other's handlebars. Several studies have reported that distractions have a major prevalence among bike users and the effect of distraction on traffic was significant [100].

The second cause that is defined based on previous studies is the bad state of infrastructure. Part of the main cause of 'single bicycle crashes'. Infrastructure plays an important role in single bicycle crashes without third parties involved. Examples are holes in the road, badly visible lanes, lubricity, rail tracks or the lack of space on the road.

A third cause involves a third party and one or both parties failed to notice each other [37-42]. Different studies have shown that third party accidents are one of the major issues in cycling safety. Examples are distracted car drivers, unsafe lane changes, turning without looking or driver fatigue. Research has been done into the causes of this distraction of motorists, but falls outside the scope of this research.

The fourth cause that is defined based on previous studies is technical failure. Examples are defective lights, defective brakes or defective steering. In 2014 statistics showed that only 2% of the accidents are caused by technical failures [44-54]. Previous causes mentioned before are of greater importance, since this issue induces few casualties.

The last cause of cycling accidents is traffic rule infringement [53]. This means that a person does not adhere to the traffic rules. For example, a cyclist who thinks he has priority to cross the road but that is not the case. Or a pedestrian who thinks he can walk to the other side in case of a red light and walks into a cyclist. Ignoring the slow down sign and fall of the bike.

It was found that the human factor was the main cause in 79% of the crashes, which is an average based on previous studies and datasets. These crashes occurred at places where a third party crossed the bicycle path (and failed to see the cyclist) or because there was a lack of attention of the cyclist [10-16,54].

A diagram with percentages describing bicycle accident causes is shown in Figure 1. Third party involvement accounted for 40%, where distraction of the cyclist was good for 30%. Technical failure is the least common cause of a bicycle accident at only 4%. Data used for this diagram is based on the articles found. Different percentages were compared and a roughly rounded average was taken.

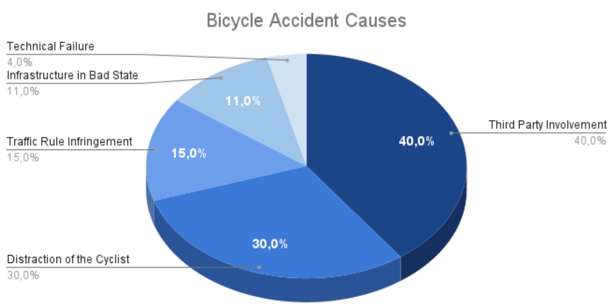

Figure 1. Diagram Causes Cycling Casualties

It is, however, to be noted that, only 21% of the bicycle crashes registered at insurance companies were registered in police databases and thus 79% of the actual crashes are excluded in official statistics used for policy makers. [54] Incorporating data from insurance companies in national statistics might lead to a better decision and policies on cycling.

Bicycle crashes involving a car accounted for 42% of the total reported accidents. [53,54] The motorist is therefore a serious danger for cyclists. Research was conducted into how the number of accidents can be reduced. Sensors can contribute to road safety for cyclists. Part of the next section describes the sensors that are already available and how automotive systems can contribute to the bicycle safety issue.

4.2 Available Sensors & Systems

The search queries and filters used on the database resulted in 98 results in the Scopus database, 42 useful results on Google Scholar and a total of 32 articles on IEEE and the University of Twente library. After removing duplicates, a total of 22 unique studies remained. The abstract of these papers were screened and papers that deviated were removed, which resulted in 9 papers in total for the second research question (section 1.2). The papers that remained were downloaded and read completely to eliminate more irrelevant papers.

Only systems and sensors that are applicable to bicycles were used in this research. For example oxygen sensors to measure the amount of fuel and air needed in a car is not discussed in detail. Webshops, studies, literature and manufactures websites were used to answer the second research question.

The use of sensors on bicycles is something new. Normal city bikes do not have special sensors, because there was no need. Since the advent of the electric bicycle, more research has been done into technologies that can increase bicycle safety, especially for electric bicycles. Figures from BOVAG [60], a Dutch trade association, show that 41.7% of the bicycles sold in 2019 were electrically motorized. These bicycles all have sensors to control the motor. These sensors can also be used to increase safety on the road. Subject 4.2.1 is about existing sensors on the bicycle that have already been applied.

4.2.1 Sensors on Bicycles

Sensors of an electric bicycle work on the basis of a pedaling force sensor, a motion sensor and/or rotation sensor. A pedal force sensor of an electric bicycle registers how hard you have to pedal. The registered signal is passed on to the computer. The computer compares the effort you have to make with your chosen driving program and on that basis the motor is controlled to give more or less energy.

In addition, there are electric bicycles that are equipped with a rotation sensor, also called speed sensor. Unlike a pedaling force sensor, which registers how hard you have to pedal, the rotation sensor registers your speed.

Rotation sensor. One of the sensors on an electric bicycle is the rotation sensor. A rotation sensor only checks whether the bottom bracket is rotating. The degree of support is independent of your own effort.

Torque sensor. A torque sensor also measures how much pressure is put on the pedals. The cycling computer not only determines the cadence, but also the pressure. This is necessary to determine the amount of torque assistance needed while cycling.

Speed sensor. All e-bike motors calculate the bicycle speed, because by law the assistance must stop at 25 km/h (45 km/h for speed pedelecs). A speed sensor (or acceleration sensor), in combination with the other sensors, can ensure that the support is tuned even more precisely.
A speed sensor can be used in combination with an odometer,

which measures current speed, distance traveled, average speed and other distance related information.

The sensors mentioned above are sensors that are already present on bicycles. Based on various bicycle manuals and information from manufacturers worldwide. The potential of car sensors in bicycle safety issues is discussed in the subsequent sections.

4.2.2 Sensors on Automobiles

Modern cars are becoming more and more advanced and automated. Technology is developing at a rapid pace and this also continuously leads to innovations in the car industry. Sensors ensure that the car receives all the necessary information and can function efficiently. An overview of the sensors discussed can be found in Table 2.

A comparison is made based on the information given in Table 2 and various studies. Previous work and projects have shown the following advantages and disadvantages.

Advantages. Radar sensors compared to visual sensors offer a lot more information, which also results in a higher resolution. Besides, radar sensors are not affected by the weather, which make radar sensors more reliable. Hence, radar sensors are used in Adaptive Cruise Control Systems (ACC), to detect objects and avoid collisions. Information from Light Detection and Ranging (LIDAR) in combination with radar sensors is used to produce an even better representation of the vehicle's surroundings.

Ultrasonic sensors are mostly used as parking assist. The frequency level of the sound produced by ultrasonic sensors is inaudible to humans and helps the driver park safely or completely by the car itself. Proximity sensors and ultrasonic sensors share the same purposes but operate differently as described in Table 2. Mounted on a bicycle, ultrasonic sensors can be used to determine distance between objects, people and other vehicles to avert accidents.

Pressure sensors are used in cars to detect pedal pressure, detect airbag deployments, ensure clean exhaust filters and check the pressure of liquids and gases. Pedal pressure could be useful for bicycle safety systems in terms of sending data to a bicycle computer system and controlling the electrical force on an ebike.

Hall-effect sensors have a long life span, are highly reliable, offer high speed operations and offers pre programmable outputs. This makes a hall-effect sensor the least sensitive to vibrations and temperature changes. Hall-effect sensors are a good alternative, since bicycles suffer more from vibrations than automobiles.

The temperature and rain sensor can be used for instance showing a warning message: "Risk of slipping" when the temperature is below 0 degrees.

Disadvantages. In addition to the many advantages of the discussed sensors, there exist some disadvantages as well**:** Radar sensors are relatively expensive and radar pulses are quite sensitive to interference, which is a problem with shortcut bicycle paths between buildings.

Lidar sensors, however, have limited usage in cloudy weather and nighttime. The operating altitude is 350-2000 meter and lidar sensors are expensive either.

Ultrasonic sensors cannot be used in spaces with high density objects, because the reflection is no longer correct. In addition, ultrasonic sensors can be influenced by the temperature, humidity and air pressure, since the speed of the transmitted wave depends on the medium used. The same holds for built-in electronics in Hall effect sensors, which are usually limited to applications in ambient temperatures.

Image sensors offer high power consumption due to active cooling and processing. Besides, the sensing range is affected by color and reflectivity of the target. Image sensors can be used for object detection, to determine the behavior of pedestrians, cyclists and other moving objects.

Table 2. List of Available Car Sensors

Type	Description
Radar Sensor	Measures distances, movements and speed. By reflecting a high-frequency signal on an object, the sensor calculates the distance to the object.
Lidar Sensor	LiDAR is a technology that determines the distance to an object or surface through the use of laser pulses. Lidar works on the same principle as radar.
Ultrasonic Sensor	Ultrasonic sensors are sensors that work with sound waves at high frequencies that are imperceptible to the human ear. With ultrasonic sensors, an ultrasonic wave is sent through the transmitter.
Pressure Sensor	A pressure sensor is a device for measuring the pressure of gases or liquids. Pressure is an expression of the force required to prevent a liquid from expanding, and is usually expressed in force per unit area.
Temperature Sensor	Measures the current temperature of the environment or of an object.
Hall effect Sensor	An electric current flows through a Hall sensor and is brought into a magnetic field perpendicular to it, which then produces an electric voltage. Used to detect objects in a magnetic field.
Proximity Sensor	A proximity sensor is a device that can measure the distance to a particular object. This is determined by the amount of light processed on the sensor.
Rain Sensor	The sensor emits infrared light and that light is reflected by the water droplets on the windshield.
Image Sensor	Image sensor is the general term for an electronic component that consists of several light-sensitive elements, with which images can be recorded electronically.
Magnet Sensor	Measures speed through magnetic charge every time two magnets come close to each other.

Summary. The sensors mentioned in table 2 are important to bicycle safety systems, since each sensor has unique properties and provides additional information to a potential system and rider. Considering the sensors and the conducted research, it is concluded that the many advantages of a few sensors outweigh the disadvantages. This research indicates the use of Hall effect sensors and Radar sensors as the most suitable for cycling conditions, when it comes to measuring distances between two or more objects.

In addition, sensors with other goals such as: pressure sensors, rain sensors and temperature sensors are a proper contribution to the intelligent bicycles as well.

Table 3. List of Automotive Systems & Solution to causes

Technology	Acronym	Description	Solution to (section 4.1)	Sensor (table 2)
Automatic Emergency Braking	AEC	Designed to detect panic or sudden braking and provide support to help prevent a collision.	- Third Party Involvement - Distraction of Cyclist	Radar, Lidar, Ultrasonic, Hall-effect, Proximity, Pressure, Magnet sensor
Collision Mitigation and Detection	CMD	Radar sensors are used to detect possible automobiles, pedestrians and other objects or slowing vehicles ahead and will warn you with audio and automatic braking.	- Third Party Involvement - Distraction of the Cyclist	Radar, Lidar, Ultrasonic, Hall-effect, Proximity, Magnet sensor
Adaptive Cruise Control	ACC	Measures the distance from the object ahead and controls acceleration and deceleration. Adaptive cruise control is especially useful for electric bicycles to control the power output with objects close to the bicycle.	- Third Party Involvement	Radar, Lidar, Ultrasonic, Hall effect, Proximity, Magnet sensor
Lane Departure Warning System	LDWS	Mechanism designed to warn a cyclist when the rider moves out of the road lanes. To prevent the cyclist accidently ending up on a motorway.	- Distraction of the Cyclist - Traffic Rule Infringement	Image sensor
Road Sign Recognition	RSR	Recognition of road signs captured by cameras and forward warnings to the cycle computer.	- Traffic Rule Infringement - Distraction of the Cyclist	Image sensor
Tyre-Pressure Monitoring	TPM	Electronic system designed to monitor air pressure in tires. Notification in case of a leak or flat tire.	- Technical Failure	Pressure sensor
Night Vision System	NVS	Thermo graphic cameras, infrared lights and heads up displays extend the visibility of the driver at night.	- Infrastructure in Bad State - Distraction of the Cyclist	Image, Temperature sensor
Driver Monitoring	DM	Monitor the cyclist's attentiveness using infrared sensors. Used for eye tracking and fatigue recognition.	- Traffic Rule Infringement - Distraction of the Cyclist	Temperature, Image sensor

It is, however, to be noted that this serves as an indication for this study. Mentioned sensors in table 2 can be subdivided in different types, which has not been stated in this paper. There is a chance the table is not complete and new developments are being introduced. The most common sensors are included in the table.

Not mentioned apparatus that could be adapted to bicycles are for example an UV sensor, microphone, gyroscope or GPS receiver. The adaptation of the sensors and systems mentioned in this research will be discussed in section 4.3 *Adaptation Sensors & Systems*.

4.2.3 Safety Systems on Automobiles

Safety in cars has become very important in recent years. With the advent of electric cars, there are even more ways to increase safety on the road. Cars dispose of various systems today, these safety systems are divided into active and passive systems. However, only a selection of automobile safety systems are applicable to bicycles.

Active Safety Systems play a role in preventing crashes and accidents by providing assistance in controlling the automobile. Examples of Active Safety Systems are: Adaptive Cruise Control (ACC), Blind Spot Detection (BSD), Lane Departure Warning System (LDWS) and Night Vision Systems (NVS). Passive Safety Systems play a role in limiting the injuries that are caused by the driver. Seatbelts, airbags and pads are common passive safety systems. Passive safety only becomes important after an accident. In contrast to Active Safety which tries to prevent an accident.

Active safety systems are particularly interesting to this research, since passive safety does not prevent accidents and only reduces injuries. Only a collection of automobile systems are applicable to bicycles. After performing literature research, the following automotive safety systems were discussed in Table 3.

Table 3 states the system type, acronym, description and the five categories from section 4.1 *Causes Bicycle Accidents*. The stated systems are a potential solution to various causes. An overview is provided to reason about the function of the mentioned safety systems (table 3) for possible application to bicycles.

Cycling safety issues can be resolved using various automotive systems and prevent future accidents. Brake Assist detects sudden or 'panic' braking and provides support to avoid accidents. CMD and ACC use radar sensors (table 2) to monitor cars, pedestrians or other slowing vehicles ahead and behind.
In addition, LDWS and RSR provide more information concerning the environment, while TPM focuses solely on the technicalities. Night Vision Systems provides better visibility in dark and badly visible situations.
Lastly, driver monitoring (DM) keeps track of eye movement to detect and warn for fatigue riders. The technology is capable of warning the cyclist before an accident occurs by means of audio, vibrations or a notification on a cycling computer, such as Garmin. Table 3 shows potential solution systems that can tackle the causes of bicycle accidents. Existing automotive systems can help prevent accidents with especially third party involvement, which is with 40% (figure 1) the biggest cause of cycling casualty.

Merging the accident causes, potential sensors and the use of automotive systems leads to different methods that can increase road safety. In addition to the methods mentioned, proper wireless communication is required to guarantee safety even more. This is discussed in section 4.3.2 *Wireless Communication*. Where this statement is confirmed and substantiated by a simulation in Sumo.

It is, however, to be noted that table 3 serves as an indication for this study. There is a chance the table is not complete and new developments are being introduced. The most common systems are included in the table. Adaptation of sensors and systems from automobiles to the bicycle will be discussed in section 4.3 *Adaptation Sensors & Systems*.

4.3 Adaptation Sensors & Systems

Little to none research has been done into the application of existing systems of cars to bicycles. There are a number of individual projects that employ different types of sensors other than the existing sensors on cars. Examples of this are an UV sensor, microphone, heart rate monitor, gyroscope or GPS receiver. More about the use and results are explained in section 4.3.1 *Experiments & Research*.
Furthermore, the use of modern automotive systems and sensors are discussed in section 4.3.1. In this section, table 2 and table 3 were used to describe sensor and system usability.
In addition to the application of present automotive systems and sensors, wireless communication methods were investigated showing how obtained information from sensors can be sent.

The search queries and filters used on the database resulted in 98 results in the Scopus database, 25 useful results on Google Scholar and a total of 32 articles on IEEE and the University of Twente library. After removing duplicates, a total of 21 unique studies remained. The abstract of these papers were screened and papers that deviated were removed, which resulted in 7 papers in total for the third research question (section 1.2). The papers that remained were downloaded and read completely to eliminate more irrelevant papers.

4.3.1 Experiments & Research

There are a number of individual projects [1-3,8,12,17,25-28] that employ different types of sensors other than the existing sensors on cars. In 2013 Shinhye Joo [22] proposed a monitoring method that can be used for evaluating bicycle performance in terms of safety and mobility. A bicycle was equipped with global positioning systems (GPS) receiver, gyroscoop and an accelerometer. It has been found that the combination of a GPS and Inertial Measurement Unit (IMU) is a proper way to collect data.
However, Shinhye Joo mentioned additional research is necessary to find out the pros and cons.
A research conducted in 2020 by Misgeld, Berno J.E. [18], presenting a virtual torque sensor using GPS and Gyroscope sensor data. Concluded that those sensors could replace a torque sensor to save costs.
Fitch, Dillon T. [17] designed an experiment using heart rate sensors to measure stress levels between distinct road environments in California. It offers an intuitive representation of the effect of road environments on bicycle accidents.

Wu, Yun [57] presents a solution to the detection of traffic data using lasers also called range sensors. The laser system consists of a sensor head, control unit and man-machine interface. Results have shown this setup is suitable for bicycles and can be used to detect the distance between objects.

In 2020, a study conducted by Larson, Travis [28] about thermal sensors to detect and measure the behaviour of pedestrians. In general, thermal sensors achieved higher accuracy rates than optical sensors. Results from the sensors were compared by pedestrian, weather and lighting conditions. Thermal sensors turned out to be 90% accurate and optical sensors with only a 26% accuracy.

Almost all studies shared the same adaptation. The use of various sensors mounted on the bike, wirelessly transmitting data to an IMU all powered by batteries.

4.3.2 Wireless Communication

In order to make full use of applied sensors and systems on the bicycle, a proper way of communication is necessary. First, data transfer between sensors and systems, which is in most cases done wirelessly. Most common communication methods are Bluetooth and Wi-Fi communication. Secondly, communication between the bicycle and other vehicles is necessary, especially with automobiles.

Table 4. Communication Technologies

Technology	Protocol	Range	Power cons
LPWAN	TCP/IP	<15km	Low
Cellular	3G/4G/5G	N/A	High
Zigbee	IEEE 802.15.4	<100m	Medium
Bluetooth	Point-to-point	<30m	Medium
Wi-Fi	IPv4/IPv6	<50m	High
RF(ID)	433~960 Mhz	<100m	Low

Low Power Wide Area Network (LPWAN) can only send small blocks of data at a low rate, and are better in cases that do not require much bandwidth. Cellular and Wi-Fi are not suitable for battery powered IoT applications in the bicycle case, but are suitable for cars. Zigbee provides higher data rates, but on the other hand a low power-efficiency. Zigbee is a perfect component for Wi-Fi systems. Bluetooth is short range, which is suitable for bicycles, since only data from vehicles nearby is useful for cyclists[42]. Radio Frequency (RF) has a proper range and relatively low power consumption, but a quite low accuracy with a high change on packet loss.

All communication technologies come with advantages and disadvantages. LPWAN and Bluetooth do have advantages for bicycles in particular. In this paper, only the communication between bicycles and other vehicles is discussed.There are different communications in terms of connected vehicles. Vehicle-to-everything (V2X) as shown in table 5, include vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-cloud (V2C) and vehicle-to-driver (V2D) communications. For this paper a V2V is discussed and used in the simulation described in 4.3.3 *Simulation with SUMO*.

Table 5. Communication Types V2X

	V2X			
Type	V2V	V2I	V2C	V2D
Definition	vehicle to vehicle	vehicle to infrastructure	vehicle to cloud	vehicle to driver

The bicycle is only suitable for simple computers, since the system should be fast, lightweight, cheap and powered by batteries. Hence, a V2V communication through Bluetooth is used in the simulation.

4.3.3 Simulation with SUMO

In this project, Simulation of Urban MObility (SUMO) was used to simulate bicycle and vehicle behaviour. SUMO is an open source traffic simulation designed to handle large networks. It is possible to build a network and environment using NetEdit.

However, OpenStreetMap was used to directly import map data. After installing the corresponding files the osmWebWizard python script was executed, which opened in a web browser. Figure 2 shows the intersection in front of the Spiegel building at the University of Twente. The simulation of bicycle-car and bicycle-bicycle accidents were accomplished, which can be seen in Figure 2. Additional code was written in the configuration file, which was necessary to collect data and set up a Bluetooth connection.

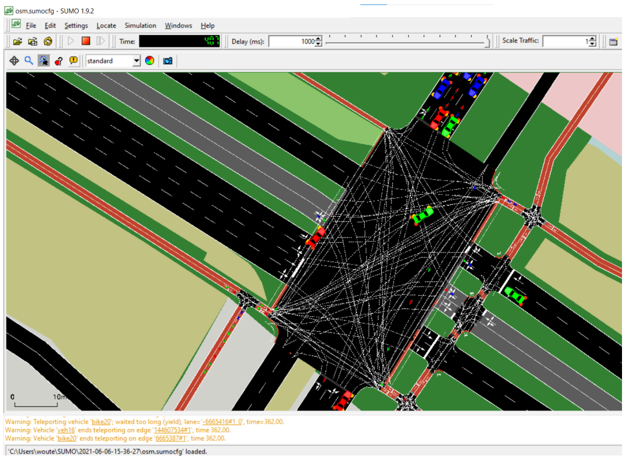

Figure 2. Simulation in Sumo GUI

This simulation solely focussed on automobiles and pedestrians. Those options were edited in the configuration file. Cyclists can be seen in figure 2 as small coloured dots.

In order to cause collisions in SUMO cars and bicycles needed some unexpected braking and weird behaviour. Parameters in the sumo vehicle files were added to accomplish unexpected braking and lane changing.

network: Parameter

Name	Value	Dynamic
loaded vehicles [#]	1318	
insertion-backlogged vehicles [#]	107	
departed vehicles [#]	1206	
running vehicles [#]	520	
arrived vehicles [#]	686	
discarded vehicles [#]	0	
collisions [#]	15	
teleports [#]	124	
halting [#]	476	
avg. speed [m/s]	0.31	

Figure 3. Collisions & Information

An overview of some collected information can be found in figure 3. A total of 15 collisions were observed in this simulation.

Finally, after implementing bluetooth senders and receivers, the simulation showed that the bluetooth connections prevented collisions between cars and bicycles (appendix). The amount of bicycle-car collisions decreased significantly.

5. DISCUSSION

This research is the first research that reviewed the bicycle accident causes, provided an overview of various sensors and systems and introduced potential adaptation of those sensors and systems supported by a simulation in Sumo. There were a total of 59 studies used for literature research.
Furthermore, factory manuals and webshops were consulted to provide additional conversance for this paper.

5.1 Limitations of this Research

The first significant limitation of this research is that, regrettably, relevant literature was not available to the author without subscription. The inaccessible papers could have been relevant to this paper and could have influenced the results.

Another limitation of this research is the amount of databases used for literature found. Only four databases were used and is limited in extensive research. This could have affected the results, since there is a possibility more results could have been found.

In addition, the number of sensors mentioned in this research could be more extended. For example, there are many different types of radar sensors that use different techniques. Subtypes are not discussed in this paper and could lead to an even more extended and complete research. Moreover, a more detailed description of current automotive systems could be added. The current tables contain enough information to draw a conclusion, but could have been more extensive.

The battery, and thus power capacity on a bicycle is very limited. This report could have investigated the power consumption of sensors and safety systems based on weight, computing power and processing.

Furthermore, a more extended literature survey about wireless communication systems could be included. Communication between vehicles ensures an important contribution to road safety. A detailed comparison between wireless communication systems based on previous studies could have been made.

5.2 Synthesis of Findings

Technology in this area moves at a rapid pace. Therefore, it is necessary to keep a close eye on current technologies.Topics investigated and researched are in some cases not complete. Incomplete means the possibility to dive deeper into several topics to draw an even better conclusion. The results found give a good indication but can be studied in more detail in future work. The third research question about adaptation of sensors and systems used, should have been structured differently. The simulation results could have been explained more extensively.

5.3 Simulation with Sumo

This research intended to investigate bicycle accident causes, potential sensors and safety systems and how those methods can be implemented on bicycles. Because of the short total time frame available for the project, only two weeks were available for the simulation in Sumo and the implementation of a wireless communication system. Since the inspected literature suggested using Bluetooth communication in Sumo, it was decided to leave out WiFi IPv4 and other communication methods. However, this research discussed better alternatives for a bluetooth connection, this could be added in future work.

The simulation in SUMO is solely focused on one setup including an intersection. Various other setups and environments could be tested to ensure a greater accuracy for this experiment. Moreover, only cars and bicycles were added to the simulation. Future work could implement pedestrians and public transport as well. Furthermore, bluetooth was used as a wireless communication method for the SUMO simulation. Adding other communication technologies could improve the performance and ameliorate this research.

6. CONCLUSION

Three research questions were formulated to evaluate what the available options are to adapt current systems and sensors to the bicycle. The main bicycle accident causes, the investigation of available sensors and automotive systems provided a great insight into the application of the methods and techniques used for cycling safety on the road. By gaining knowledge of different research methods and applying the systems of cars to bicycles, the reader should gain new insights into the optimal use of sensors. The main cause 'Third Party Involvement' showed there is a need for sensors suitable for vehicle detection. According to studied literature, radar sensors and the hall-effect sensor are the most suitable sensors for bicycles. Adapting a V2V system in combination with automated systems and sensors on a bicycle would be a good contribution to cycling safety issues.

First, about the bicycle accident causes, third party involvement accounted for 40%, where distraction of the cyclist was good for 30%. Technical failure is the least common cause of a bicycle accident at only 4%. The greatest danger for cyclists is the automobile, therefore the focus of future safety systems should keep in mind the interoperability of systems with cars.

Secondly, the sensors mentioned in table 2 are important to bicycle safety systems, since each sensor has unique properties and provides additional information to a potential system and rider. Considering the sensors and the conducted research, it is concluded that the many advantages of a few sensors outweigh the disadvantages. This research indicates the use of Hall effect sensors and Radar sensors as the most suitable for cycling conditions, when it comes to measuring distances between two or more objects.
In addition, sensors with other goals such as: pressure sensors, rain sensors and temperature sensors are a proper contribution to the intelligent bicycles as well.

Thirdly, cycling safety issues can be resolved using various automotive systems. CMD and ACC use radar sensors (table 2) to monitor cars, pedestrians or other slowing vehicles ahead and behind. The automotive systems play an important role in ameliorating cycling safety. Table 3 shows potential solution systems that can tackle the causes of bicycle accidents. Merging the accident causes, potential sensors and the use of automotive systems leads to different methods that can increase road safety.

Fourthly, almost all studies about the adaptation of sensors to the bicycle shared the same implementation. Various sensors were mounted on the bike by clamps, wirelessly transmitting data to an IMU that are all powered by batteries.

Cellular and Wi-Fi are not suitable for battery powered IoT applications for bicycles. Bluetooth is short range, which is suitable for bicycles, since only data from vehicles nearby is useful for cyclists. Radio Frequency (RF) has a proper range and relatively low power consumption, but a quite low accuracy with a high change on packet loss.

The simulation in SUMO showed the use of bluetooth communication between cars in practice. It turned out that bluetooth connections within a range of 30 meters were suitable for warning a car or bicycle in time or even stopping the vehicle to prevent a collision.

Lastly, as mentioned in section 5. *Discussion* the number of sensors mentioned in this research could be more extended. Moreover, a more detailed description of current automotive systems could be added. The current tables contain enough information to draw a conclusion, but could have been more extensive. Furthermore, a more extended literature survey about wireless communication systems could be included in future work. The simulation could be extended as well with other communication technologies as well as simulating other road types and environments.

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APPENDIX

A. Causes Bicycle Accidents

Table 1. Research works discussing the causes and factors of cycling accidents

Work	Year	Country	Subject/Source	Method	Presented Discussion	Conclusion
Ballham, A., Absoud, E. M., Kotecha, M. B., & Bodiwala, G. G. (1985). https://doi.org/10.1016/0020-1383(85)90057-9	1985	GB	Survey Causes Bicycle accidents	Survey conducted, including 383 patients who have had a bicycle accident.	Study the human, environmental and mechanical factors leading to bicycle accidents and injuries.	The major morbidity occurs in accidents involving collisions between cars and bicycles. Mostly due to riders' errors.
Herslund, M., & Jørgensen, N. O. (2003). *Herslund_LBFTS_2003. 35*(May 2001), 885–891.	2003	Denmark	Survey & Interview Looked-but-failed-to-see errors	Interview 10 persons who had experienced a near accident.Analysed by TRK model.	Car-bicycle accidents at give-way points are sometimes due to not looking properly. Another purpose was to see if locations were irregular	Appears that drivers who have more experience are more likely to make junction errors. More data needed to clarify the conclusion.
Cho, G., Rodríguez, D. A., & Khattak, A. J. (2009). https://doi.org/10.1016/j.aap.2009.03.008	2009	US	Survey & NHTSA database	Literature research and identification interventions.	Crashes of cyclists have been studied with respect to the built environment. The goal is identifying interventions or to control potential confounding.	Result shows that the built environment plays a role in safety outcomes. Police-reported crash risk has an effect on association between built environment and perceived crash risk.
Kilbey, P., Wilson, D., Beg, O., Goodman, G., & Bhagat, A. (2011). *Reported Road Casualties Great Britain*. 1–261. www.statistics.gov.uk%0Awww.dft.gov.uk/pgr/statistics%0Awww.opsi.gov.uk/click-use/index.htm.%0AISBN%0Ahttp://www.dft.gov.uk	2011	GB	Reported Road Casualties	Paper about reported road casualties in Great Britain: 2011 Annual Report. Total of 203,950 casualties of all severities in road accidents reported to the police.	An overview and trends in reported road casualties. Contributory factors in accidents.Reviews the main trends in number of reported accidents in Great Britain 2011.	There is a clear increase in bicycle accidents. Both bicycle-car and individual bicycle accidents.
Otte, D., Jänsch, M., & Haasper, C. (2012). https://doi.org/10.1016/j.aap.2010.12.006	2012	Germany	Accident causation parameters	Comparison is made based on different data models about common injuries in road accidents.	Comparison is made of three groups of vulnerable road users. Also relevance of accident causes mainly responsible for injuries are pointed out.	Common causes are distraction or a missed observation of other road users due to a wrong strategy of observation.

Juhra, C., Wieskötter, B., Chu, K., Trost, L., Weiss, U., Messerschmidt, M., Malczyk, A., Heckwolf, M., & Raschke, M. (2012). https://doi.org/10.1016/j.injury.2011.10.016	2012	Germa ny	Questionnair e & Data local police Bicycle accidents	Between 2009 and 2010, data on bicycle accidents were collected by the police of Münster. The use of questionnaires. Data was entered in central database	Bicycle accidents occur more frequently than actually reported to the police. This study discusses the causes of accidents and relevant information about injuries. Goal to evaluate actual number of bicycle accidents.	Around 70% of the participants did not report the accident to the police. Of those participants over 50% was hit by a car. Most of those accidents took place in the morning or evening hours.
Martínez-Ruiz, V., Lardelli-Claret, P., Jiménez-Mejías, E., Amezcua-Prieto, C., Jiménez-Moleón, J. J., & Luna Del Castillo, J. D. D. (2013). https://doi.org/10.1016/j.aap.2012.11.023	2013	Spain	Survey & Spanish register Risk factors causing road crashes	Performed separate analyses on various datasets. Logistic regression analysis used to relate factors that are responsible for collisions.	Suggestion that several bicycle related factors play a role in the risk of causing an accident on the road. Influence of factors change depending on type of crash	Cycling after alcohol consumption showed an increase in single bicycle accidents. Cycling for 1-3h without rest was related to single crashes.
Chaurand, N., & Delhomme, P. (2013). https://doi.org/10.1016/j.aap.2012.09.005	2013	France	Questionnair e Accident Analysis and Prevention	Two samples were used for the questionnaire. A version adapted to cyclists and the second version adapted to drivers. Consisting of 336 cyclists and 92 drivers.	Investigation about the perceived risk among cyclists and car drivers on city roads, when interacting with another vehicle and one executed a risky behaviour.	Results show that in general participants perceived more risk when the other vehicle was a car. Also cyclists perceived less risk than drivers.
Hollingworth, M. A., Harper, A. J. L., & Hamer, M. (2014).https://doi.org/10.1016/j.jth.2015.01.001	2014	GB	Survey Risk factors cycling accident	Study design and participants. Survey measures and statistical analysis.	Present results regarding cycling behaviour and cycling accidents	Increased rates of cycling accident-related injury were associated with demographic and behavioural factors.
Vanparijs, J., Int Panis, L., Meeusen, R., & De Geus, B. (2015). https://doi.org/10.1016/j.aap.2015.08.007	2015	Belgiu m	Literature survey Accident Analysis and Prevention	A literature search on bicycle safety. Retrospective and prospective measurements of exposure were used or this paper.	The strengths and weaknesses of prospective and retrospective study designs.	Well-maintained bicycle infrastructure improves bicycle safety. One of the major causes in cycling safety issues.
Stipancic, J., Zangenehpour, S., Miranda-Moreno, L., Saunier, N., & Granié, M. A. (2016). https://doi.org/10.1016/j.aap.2016.07.033	2016	Canad a	Measuremen t paper Accident Analysis and Prevention	Video data collection and processing using video tracking and classification methods. Research on causes of intersection accidents cyclists.	The impact of different factors on cyclist risk at urban intersections with cycle tracks.	Turns out the biggest cause of intersection are third party involvement with automobiles.

Ling, Z., Cherry, C. R., & Dhakal, N. (2017). https://doi.org/10.1016/j.jth.2017.01.004	2017	US	Measurement paper Accident Analysis	In this study, they relied on a video based observation of a single rail crossing. From that video, they extracted data of the entire traversing process of each bicycle across the railroad tracks in that area.	This study only collects data from one site so that means results are limited and could be more extended.	The purpose of this paper was to document the factors influencing single bicycle crashes on a skewed railroad grade crossing. This is a known problem but very little empirical analysis is done.
Useche, S. A., Alonso, F., Montoro, L., & Esteban, C. (2018). https://doi.org/10.7717/peerj.5616	2018	Spain	Empirical study Distraction of cyclists	In this study, participants completed an electronic questionnaire in Spanish. The full sample was composed of 1064 cyclists from 20 different countries from Latin America.	The results of this empirical study support the existence of a relation between individual factors and cycling habits, self-reported risky behaviors, and adverse traffic safety outcomes reported by cyclists.	Empirical studies have provided insightful recommendations for improvements and for new measures, such as the progressive inclusion of cyclist-related contents in the driver licensing system.
Kamaluddin, N. A., Andersen, C. S., Larsen, M. K., Meltofte, K. R., & Várhelyi, (2018). https://doi.org/10.1186/s12544-018-0301-0	2018	Sweden	Systematic literature review Self reporting crashes	A systematic literature search was performed in three databases, ScienceDirect, Scopus and Transport Research International Documentation (TRID), resulting in 134 reviewed studies.	Self-reported crash studies were found to be more common in Europe, NorthAmerica andAustralasia, but there are few studies in developing countries, so remains difficult to determine the actual number.	Increase efforts when it comes to using self-reporting to better assess the actual traffic safety situation and produce knowledge-based appropriate safety measures.
Shinar, D., Valero-Mora, P., van Strijp-Houtenbos, M., Haworth, N., Schramm, A., De Bruyne, G., Cavallo, V., Chliaoutakis, J., https://doi.org/10.1016/j.aap.2017.09.018	2018	Spain	International survey Self reporting crashes	Information on cycling habits, attitudes, and crashes was collected via an internet-based questionnaire in 30 countries represented by members of the European Union	The results showed that under- and biased reporting of bicycle crashes in police and medical records are pervasive world-wide phenomena.	There is an urgent need for greater harmonization among countries in crash definitions, especially for the inclusion of bicycle crashes. The most commonly reported crash type, “falling off the bike”, is also the least likely to be reported. Severity of the crash is clearly related to the likelihood of reporting the crash to the police or being admitted to a hospital.

B. SUMO Simulation

Figure 3. OSMWebWizard

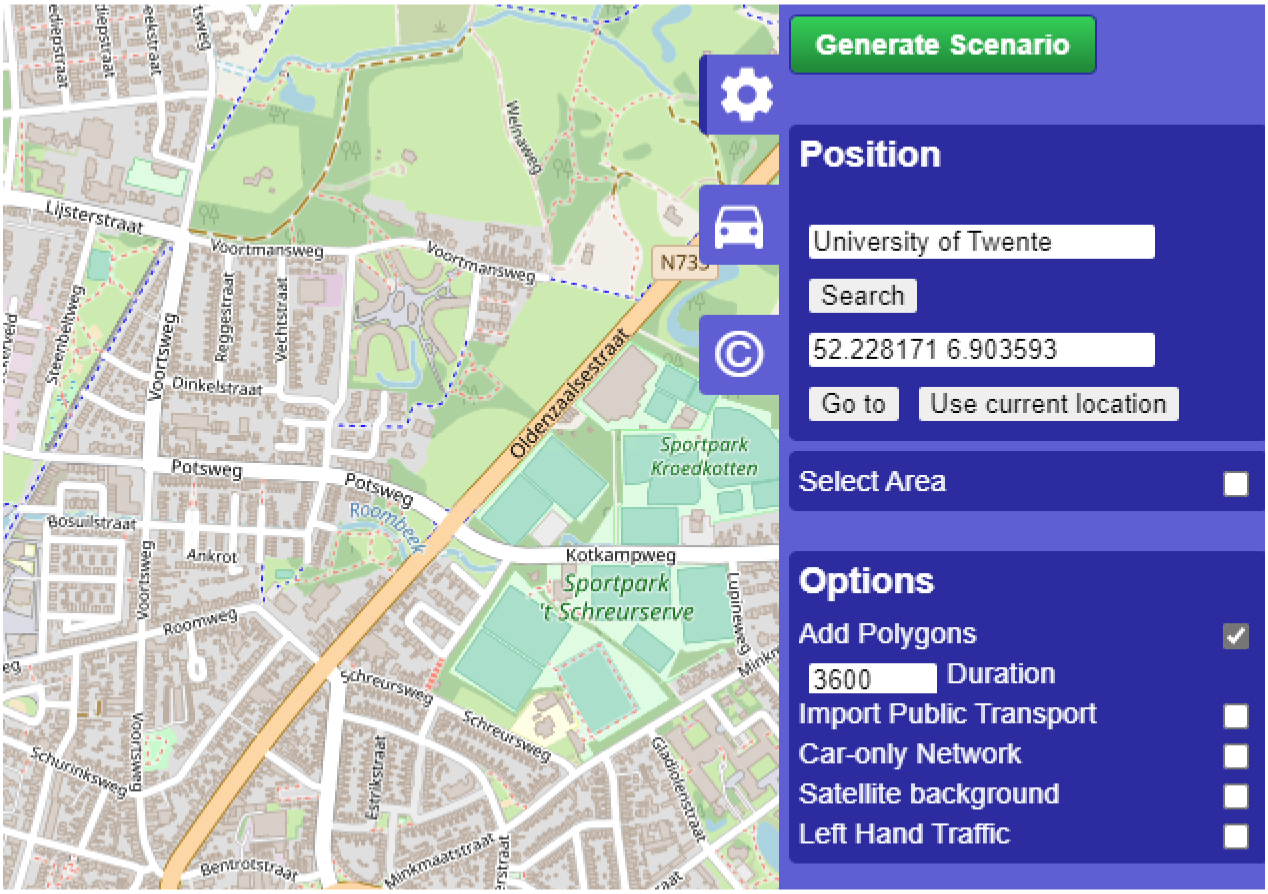

Figure 4. Log File while Running Simulation

```
Warning: Teleporting vehicle 'veh1173'; waited too long (yield), lane='318945059#0_2', time=3355.00.
Warning: Vehicle 'veh1173' ends teleporting on edge '144607528', time 3355.00.
Warning: Vehicle 'bike1109' ends teleporting on edge '-4415388#2', time 3356.00.
Warning: Teleporting vehicle 'veh1059'; waited too long (yield), lane='6665430#1_1', time=3358.00.
Warning: Teleporting vehicle 'veh1080'; waited too long (yield), lane='6665430#1_2', time=3358.00.
Warning: Teleporting vehicle 'bike1177'; waited too long (yield), lane='-6665435_0', time=3358.00.
Warning: Vehicle 'veh1059' ends teleporting on edge '144607534#1', time 3358.00.
Warning: Vehicle 'veh1080' ends teleporting on edge '144607534#1', time 3358.00.
Warning: Vehicle 'bike1177' ends teleporting on edge '256111937#0', time 3364.00.
Warning: Teleporting vehicle 'bike1282'; waited too long (yield), lane='144988075#0_0', time=3486.00.
Warning: Vehicle 'bike1282' ends teleporting on edge '6665387#1', time 3486.00.
Warning: Teleporting vehicle 'bike1213'; waited too long (yield), lane='410073271#0_0', time=3518.00.
Warning: Vehicle 'bike1213' ends teleporting on edge '6665387#1', time 3518.00.
Warning: Teleporting vehicle 'bike1367'; waited too long (yield), lane='6665430#1_0', time=3639.00.
Warning: Vehicle 'bike1367' ends teleporting on edge '-410073271#1', time 3639.00.
Warning: Teleporting vehicle 'veh1166'; waited too long (yield), lane='6665430#1_2', time=3663.00.
Warning: Vehicle 'veh1166' ends teleporting on edge '144607534#1', time 3663.00.
Warning: Teleporting vehicle 'bike1166'; waited too long (yield), lane='6665430#1_1', time=3664.00.
Warning: Vehicle 'bike1166' ends teleporting on edge '144607534#1', time 3664.00.
Warning: Teleporting vehicle 'bike1435'; waited too long (yield), lane='4415388#1_0', time=3756.00.
Warning: Vehicle 'bike1435' ends teleporting on edge '144607534#1', time 3756.00.
Warning: Teleporting vehicle 'bike1459'; waited too long (yield), lane='-410073271#1_0', time=3814.00.
Warning: Teleporting vehicle 'bike1367'; junction collision with vehicle 'bike1359', lane=':1568606399_1_0', gap=-1.00, time=3819.00 stage=move.
Warning: Vehicle 'bike1367' ends teleporting on edge '143331018', time 3819.00.
Warning: Vehicle 'bike1459' ends teleporting on edge '144607534#1', time 3819.00.
Warning: Teleporting vehicle 'bike1480'; junction collision with vehicle 'bike1359', lane=':1568606399_1_0', gap=-1.00, time=3832.00 stage=move.
Warning: Vehicle 'bike1480' ends teleporting on edge '143331018', time 3832.00.
'C:\Users\woute\SUMO\2021-06-06-15-36-27\osm.sumocfg' loaded.
```

Figure 5. Communication Setup

```
<communication>
    <device.btreceiver.all-recognitions value="true"/>
    <device.btsender/>
    <device.btreceiver/>
    <device.btreceiver.probability value="0.75"/>
    <device.btsender.probability value="0.75"/>
    <device.btreceiver.range value="10"/>
</communication>
```

Probability value is the percentage of cars and bicycles serving as Bluetooth sender and receiver.
A range of 10 meters was set to prevent bicycles detecting automobiles on harmless separated roads.