MSc Thesis

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Lateral steering behaviour of cyclists on narrow bidirectional bicycle paths

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Preface

This thesis is the final chapter of my master Transport & Planning at the TU Delft. The conducted research is about the influence of bicycle path width on steering behaviour of cyclists. In relation to safety, this is a very relevant study, since the number of accidents with insufficient path width as a potential cause is increasing.

I would like to thank my thesis committee for their support throughout the process of writing this thesis. In particular my daily supervisors, Paul and Winnie, thanks for the all the useful meetings during this process. Your feedback always gave me new insights on the topic and helped me to keep making progress. In addition, I would like to thank Edwin and Peter for their support during the experiment and their help in the preparation phase of the experiment by preparing all equipment that was needed. All the colleagues at SWOV, thank you for involving me in the company even in these strange times, when everybody works at home. Finally, I would like to thank my family and friends for their support and encouragement throughout the process.

Eline Theuwissen
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Summary

In the Netherlands, the bicycle is a popular means of transport. One of the benefits of cycling is improved health due to more physical activity. However, cycling also causes a health burden due to the many cycling accidents in the Netherlands. The share of cyclists in the total number of Dutch traffic fatalities is 34% and 63% of the persons with serious injuries due to traffic incidents were cyclists. Causes of bicycle accidents can be divided into cycling accidents with and without a motor vehicle involved. The number of cycling accidents with motor vehicle involved remained fairly constant between 2009 and 2018, while the number of cycling accidents without motor vehicle slightly increased. Especially the number of single bicycle accidents, where no collision with another road user is involved, has increased. In 2000 only 10% of all bicycle accidents were single bicycle accidents, while in 2018 this increased to 35%. Single bicycle accidents can be accidents where an obstacle is hit, a cyclist rides off the road or a cyclist falls without hitting an obstacle. One of the potential causes for single bicycle accidents is narrow bicycle paths. This is a cause that could be prevented. This research focussed on the influence of the bicycle path width of narrow bidirectional bicycle paths on steering behaviour, which can support a discussion on the required minimum width for bicycle paths in the guidelines.

The impact of bicycle path width on steering behaviour is studied, because steering behaviour determines the course of a cyclist and its position on the infrastructure. The course of a cyclists influences the risk on single bicycle accidents, because the closer one cycles to the path edge, the higher the risk of riding off the path. Steering movements are needed to keep the bicycle balanced. In this research a straight piece of infrastructure is considered, therefore the course of the cyclists is in this case reduced to the lateral position of the cyclist on the path and the steering movements are reduced to the required movements for balance control and passing or overtaking manoeuvres. These variables can be measured in an experiment. Next to bicycle path width, many factors influence steering behaviour. These influencing factors consist of other infrastructural factors, such as road surface, line markings and path edge design, but also weather, visibility and characteristics of the cyclist, such as gender, cycling experience and age, might affect steering behaviour. In order to isolate the effect of path width as much as possible an experiment was setup.

An experiment was conducted using bicycle path widths of 1 meter, 1.5 meter and 2 meter. The CROW guidelines prescribe 1.5 meter as minimum width for solitary bidirectional bicycle paths and 2 meter as minimum width for non-solitary bidirectional bicycle paths. In reality some paths are even smaller, therefore the width of 1 meter is added as well. On the 1.5-meter wide path and the 2-meter wide path a setup with an oncoming cyclist was created as well as a setup without an oncoming cyclist. It is expected that passing an oncoming cyclist leads to smaller distances to the path edge, which leads to higher risks to ride off the path. For the 1-meter wide path a setup with an oncoming cyclist was not included, because this path width is narrower than the guidelines prescribe. In the experiment the oncoming cyclist is simulated by a parked bicycle. Due to the coronavirus pandemic, interactions with other people could not be arranged. The measurements were done on a bicycle path on the TU Delft campus, which is originally 3 meter wide. On the bicycle path a temporary path edge has been created with a movable white band on the cyclists' left hand side. The path edge on the right hand side remains the original path edge. Because the path width can be changed during the experiment, all measurement can be done on the same path. Five scenarios are used in the experiment, being the 1-meter wide path, the 1.5-meter wide path with and without parked bicycle and the 2-meter wide path with and without parked bicycle. Each scenario is repeated three times to reduce the influence of variances in personal behaviour on the results. The participants cycled on an instrumented bicycle that measured speed and location with GPS, steering angle with a sensor on the steering wheel, lateral position with a lidar and filmed the lateral position of the front wheel as a back-up. For the

measurements with the lidar, a temporary barrier was placed in the verge on a fixed distance of 1 meter from the path edge. The lidar measured the distance of the rear wheel to this barrier. A group of 24 students participated in the experiment. The participants were all experienced cyclists, which means they are familiar to bicycle traffic situations in the Netherlands.

The results of the experiment show that cyclists cycle significantly closer to the path edge on narrower bicycle paths (55.6 centimeter on a 2 meter wide path and 37 centimeter on a 1 meter wide path), while there are no differences in average steering angle. An oncoming cyclist, which is in the experiment represented by a parked bicycle, forces cyclists to cycle even closer to the path edge, which makes the minimum distance to the path edge smaller. The minimum distance to the path edge becomes 15.1 centimeter on a 1.5-meter wide path. This smaller distance to the path edge increases the risk of riding off the path, which makes the narrower paths less safe. Speed was measured as well, because cycling speed influences steering angle data. The differences in speed on the path widths were significant. However, the cyclists entered the measurement track with low speeds and were still accelerating, which influences the average speed. Therefore, no conclusion can be drawn on the relation between speed and bicycle path width. No differences were seen in the lateral position measurements for the lower and higher speeds.

A questionnaire was used to examine the perception of the different path widths. The perceived safety of cyclists decreased on narrower bicycle paths for both the scenario with and without oncoming cyclist. In a scenario without oncoming cyclist, the 1.5-meter wide path and the 2-meter wide path were considered to be safe. The opinion on the 1-meter wide path was neutral. In a scenario with oncoming cyclists, only a 2 meter wide path is considered to be safe. The opinion on the 1.5-meter wide path with oncoming cyclist is neutral and the 1-meter wide path with oncoming cyclist is considered unsafe. This is the perception of the participants, which is not directly linked to actual unsafety. Another conclusion that could be drawn from the questionnaire results is that cyclists are very aware of their lateral position. In the questionnaire after finishing the results participants correctly indicated their lateral position.

The main research question was "*What is the influence of the width of bidirectional bicycle paths on cyclists' steering behaviour?"*. It can be concluded that lateral position is related to the width of bidirectional bicycle paths, while steering angle rotation is not related to the width of bicycle paths. The distance kept to the path edge decreases when the bicycle path width decreases. The results of the experiment are transferable to real-life traffic conditions, but do not include the variety in infrastructural conditions, cyclist ages and bicycle types. These varieties in real-life traffic conditions might increase the required bicycle path width.

In the discussion, the knowledge gained from the study, can be used to discuss the current guideline of a minimum width of 1.5 meter for solitary bidirectional bicycle paths. The study clearly shows that a 2-meter wide path is safer than a 1.5-meter wide path. The participants of the experiment cycled closer to the path edge and kept smaller minimum distances to the path edge when passing an oncoming cyclist on a 1.5-meter wide path compared to a 2-meter wide path. The perceived safety is also higher on a 2-meter wide path than a 1.5-meter wide path.

It is recommended to improve the accuracy of the speed measurements in future research by using a cycling computer that measures speed and distance using the circumference of the wheel. This will give more accurate measurements compared to the GPS used in this experiment and it does not have to find connection with a satellite before it starts working. If possible, the power supplies of the instrumented bicycle can be attached to the luggage carrier on the back wheel instead of putting them in a crate that is attached to the steering wheel. When attached to the rear wheel, the influence on the steering behaviour will be smaller.

Future research can focus on the steering behaviour of cyclists on narrow bicycle paths in real-life traffic conditions to define the sizes of the effects of different age groups, bicycle types and infrastructure conditions. More accurate steering angle data could be collected, to find out whether the frequency of the steering angle is influenced by path width. Another option for future research is investigating the distance used by cyclists to anticipate on an oncoming cyclist and how this relates to bicycle path widths. New research may also elaborate the concept of 'peak hour bicycle traffic intensity' used in guidelines as recreational solitary bicycle paths experience peak intensities at different moments in time than bicycle paths in urban areas used for commuting. An important question with regard to bicycle path width and safety is the amount of encounters a peak results in.

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Introduction

In the Netherlands, the bicycle is a popular means of transport. Travelling by bicycle has personal and societal benefits. From a personal perspective the bicycle is a good choice, because the health benefits of cycling are substantially larger than the risks of cycling relative to car driving (de Hartog et al., 2010). From a societal perspective, the benefits can be even larger. Society also benefits from the increased health of individuals when people cycle more. When people take the bicycle for a trip they usually ride by car, this will not only have health benefits, but also cause a reduction in air pollution emissions and eventually it might also cause a decrease in traffic accidents (de Hartog et al., 2010).

Even though the health benefits outweigh the risks of cycling, the health burden due to bicycle crashes is substantial. In the Netherlands, the number of traffic fatalities among motorists halved between 1999 and 2019 (from 587 to 237 fatalities), while the number of traffic fatalities among cyclists barely decreased (from 227 to 203 fatalities) (CBS, 2020a). In 2017 more cyclists (206) were killed in traffic accidents than motorists (201) (CBS, 2020a). Of all traffic fatalities 34% involves cyclists (CBS, 2020b). In injury statistics, the share of cyclist accidents of the total number of accidents is even higher. Of all serious road injuries, which are injuries that needed treatment at the emergency department of the hospital, 63% were cyclists (Weijermars et al., 2019).

A distinction can be made between different types of accidents, that is, cycling accidents with and without a motor vehicle involved. Cycling accidents without a motor vehicle involved are bicycle-bicycle accidents or single bicycle accidents. Single bicycle accidents are accidents where an obstacle is hit, a cyclist rides off the path or a cyclist falls without hitting an obstacle or another road user. In the last 10 years, the number of cycling accidents with a motor vehicle involved remained fairly constant. However, the number of cycling accidents without involvement of a motor vehicle increased (Weijermars et al., 2019). In a study predicts how road safety will develop in the future, it is expected that in the next ten years the share of fatal bicycle accidents will only become larger and within the fatal bicycle accidents the share of bicycle accidents without motor vehicle involvement will increase (Weijermars et al., 2018).

The traffic injury and fatality statistics indicate the vulnerability of cyclists and the relevance of improving cycling safety. The design of the infrastructure can have a significant role in reducing the number of cycling accidents and the severity of the injuries. This research will focus on the influence of path width. Some research on this topic has been done already. For instance, Hoogendoorn (2017) and Van Weelderen (2020) found that the width of bicycle paths can be one of the causes in bicycle accidents without motor vehicles. These studies show the importance of width for safety but do not provide sufficient details to identify specific widths and other safety measures such as markings to improve cycling safety. Guidelines for the width of bicycle paths such as in the CROW (2017) Design Manual for Bicycle Traffic are primarily based on studies on cyclists' steering behaviour conducted around 1980 (Godthelp & Wouters, 1980). The number of studies on cyclists' steering behaviour on bicycle paths has increased during the past decade. However, most of them, like the study of de Waard & Westerhuis (2014) have been based on wider bicycle paths than the guidelines prescribe as a minimum, while safety may be compromised to a greater degree on narrower paths. In relation to safety, it is very relevant to study the steering behaviour of cyclists on narrow bicycle paths.

1.1 Problem statement

Research on the impact of bicycle path widths is mostly done on wider bicycle paths. These studies concluded that the wider the bicycle path, the safer it is, but did not indicate a lower threshold. The increase in bicycle accidents without motor vehicle involvement makes safety studies on the impact of the infrastructure on accident risk very relevant.

1.2 Research questions

The objective of this research is to increase knowledge about how steering behaviour of cyclists is influenced by the bicycle path width on narrow bidirectional bicycle paths in order to be able to assess the guidelines for design criteria regarding minimum width. If the width of bicycle paths influences the risk of single bicycle accidents, future accidents can be prevented by increasing bicycle path width leading to high societal benefits.

The research question is formulated as follows:
What is the influence of the width of bidirectional bicycle paths on cyclists' steering behaviour?

A number of sub questions have been formulated to support the main question, broaden knowledge of steering behaviour and to help prepare and design the experiment.

- Which variables of steering behaviour are most often considered in determining the required lateral space on a bicycle path?
- Which factors influence steering behaviour?
- How are the steering behaviour variables related to the width of bicycle paths?
- What is the relation between cycling speed and the width of bicycle paths?
- How does passing an oncoming cyclist influence the relation between steering behaviour and bicycle path width?
- How do cyclists experience the different path widths?
- How does the steering behaviour of cyclists on narrow bicycle paths affect safety?

In Figure 1.1 the relation of the sub questions to each other and the main question are visualised. Most sub questions are part of the steps towards formulating an answer to the research question. Two sub questions broaden the understanding of steering behaviour on narrow bicycle paths which improves interpretation of the results (these relations are shown with a grey arrow in Figure 1.1). The last sub question on how steering behaviour affects safety is partly answered by the literature study, which is combined with the results of this study to interpret the results of this study.

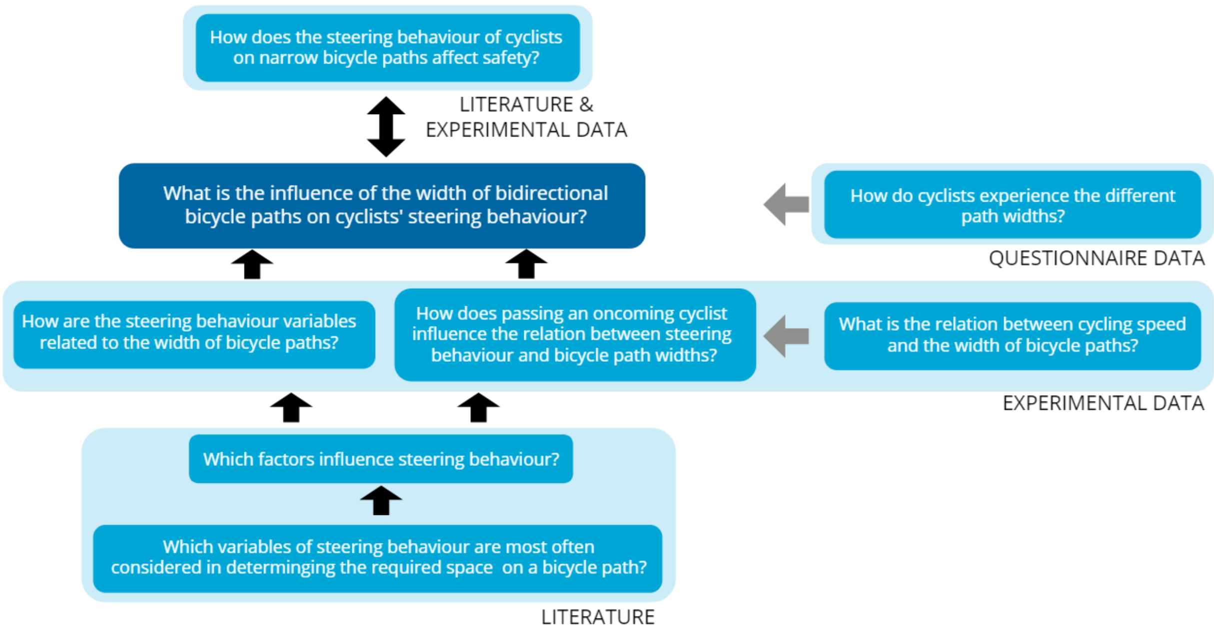

Figure 1.1 Conceptual model of the relation of the sub questions to the research question

1.3 Research approach

In order to answer these research questions an empirical research approach is used, because there is no data available of steering behaviour on narrow bicycle paths. The research approach therefore consists of three main parts which are literature research, data collection and data analysis.

The literature study will be used to get an overview on existing research and guidelines to support the research question and create hypotheses. Literature study will also be used to learn more about steering behaviour of cyclists and the influencing factors of cyclists' steering behaviour, which is necessary to design a good experiment. With data collection new information will be conducted on cyclists' steering behaviour on narrow bicycle paths. An experiment design is created where all influencing factors found in literature are kept constant, while the path width varies. With data analysis the steering behaviour data on the different path widths is compared and the differences are tested for significance.

1.4 Research scope

This research will focus on narrow solitary bidirectional bicycle paths. There are different factors that influence the lateral position of cyclists on a bicycle path. In this research the focus will be on the impact of the width on steering behaviour of cyclists. The steering behaviour variables that are studied in this research are lateral position and steering angle. Differences in other variables like steering behaviour between age groups and bicycle types are not included in the study.

1.5 Structure of the report

In the second chapter, a literature review is conducted to provide more information on single bicycle accidents, safety on narrow bicycle paths, steering behaviour, factors that influence steering behaviour and the guidelines for bicycle path width. In the third chapter, the methodology of the research and the design of the experiment are described. The fourth chapter explains how the results of this experiment are analysed and filtered. In the fifth chapter, the results of the experiment on steering behaviour are presented. The sixth chapter presents the results of the questionnaires on perceived safety and behaviour. Lastly, the seventh chapter discusses the results and presents the main findings on how path width influences steering behaviour of cyclists.

2

Literature review

In this literature review single bicycle accidents and the guidelines for bicycle path width are more elaborately discussed. The existing literature about safety on narrow bicycle paths is discussed, which is part of the answer to one of the sub questions. The most often considered steering behaviour variable in determining the required path width, are discussed as well as all factors that might influence these steering behaviour variables, which answers two sub questions. The chapter finishes with some hypotheses for the results of this research.

2.1 Single bicycle accidents

Single bicycle accidents are accidents where a cyclist has an accident without colliding with another traffic participant. Other traffic participants may play a role in single bicycle accidents, but they do not collide. For example passing, avoiding or overtaking other cyclists can cause an accident without the two cyclists colliding. Figure 2.1 shows the distribution per mode of all traffic fatalities in the Netherlands in 2018 and Figure 2.2 shows this distribution for all serious road injuries in the Netherlands in 2018. From these figures can be concluded that of all traffic fatalities 34% are cyclists and of all serious road injuries 64% are cyclists (Weijermars et al., 2019). The share of cyclists in both fatalities and serious injuries is very high. Figure 2.2 also shows that 80% of all serious injuries among cyclists are due to crashes without motor vehicles, most often single-bicycle crashes.

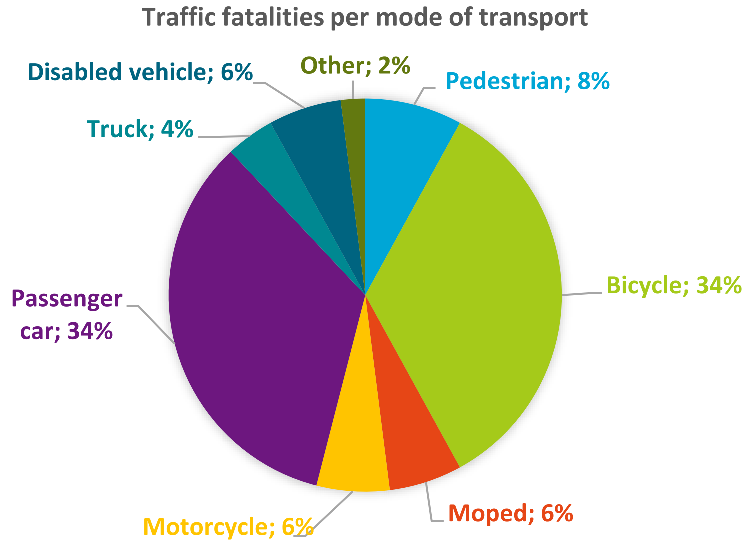

Figure 2.1: Traffic fatalities per mode of transport (source: Weijermars et al., 2019)

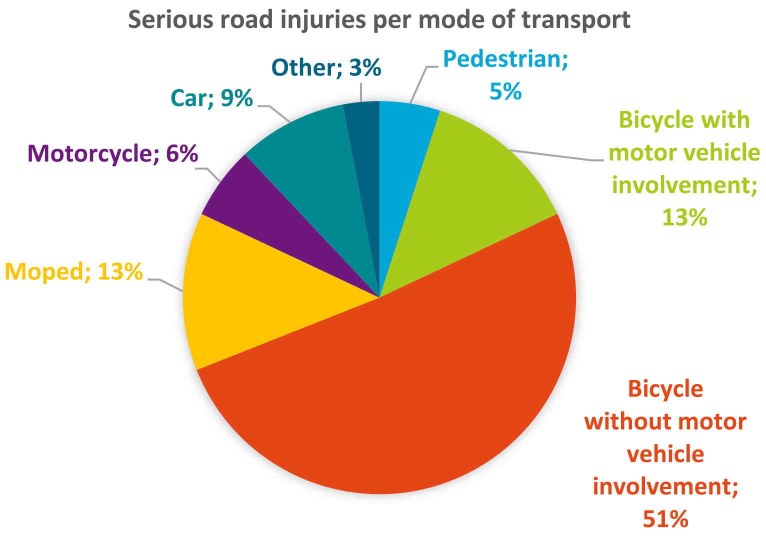

Figure 2.2: Serious road injuries per mode of transport (source: Weijermars et al., 2019)

In Figure 2.3 the development of traffic fatality causes for cycling fatalities is given. The share of single bicycle accidents, accidents with 'no collision' as fatality cause, increased largely over the years (CBS, 2020b). In Figure 2.3 this share of single bicycle crashes is coloured blue. A high number of single bicycle crashes is found in other countries with a high level of cycling as well (Schepers et al., 2015).

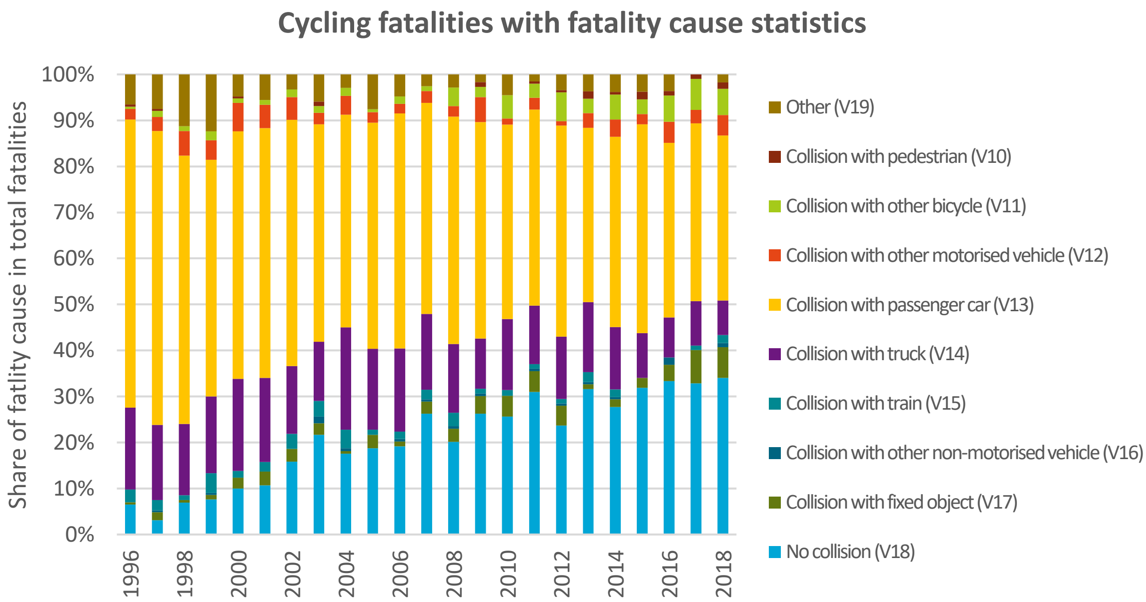

Figure 2.3: Development of the causes of traffic fatalities among cyclists (source: CBS, 2020)

Older cyclists turn out to have a higher risk of an injurious single-bicycle accident (Schepers & den Brinker, 2011). It also seems that this age group is the reason that the total number of traffic fatalities among cyclists has not decreased in the last 20 years in the Netherlands. The share of fatalities in the age group of people younger than 60 years did slightly decrease, but in the older age categories, especially in the category of 80+ fatalities have increased largely (Schepers et al., 2020). This pattern is seen in the numbers of serious injuries as well. Almost two-third of all seriously injured traffic participants in the Netherlands were cyclists in 2018 and half of them were in the age category 60+ (Schepers et al., 2020). The risk per kilometer has not increased, but the number of cycling kilometers by elderly increased: in the period 2005-2017 by 12% (Harms & Kansen, 2018). All these numbers partly explain the increase in single bicycle accidents. However, the increase of older cyclists is not a controllable variable. So, for prevention of these type of accidents an in-depth research on the causes of single bicycle crashes would be needed.

There is a variety of causes that lead to single bicycle accidents. Causes can be balance problems, mechanical failure, distraction, the use of alcohol or riding off-path. The causes influence each other. For example, riding off the path could be the result of one of the other potential causes. Verge accidents, accidents where cyclists ride off the path and end up in the verge, were the reason for this study. About 7% of all single bicycle accidents are verge accidents (Schepers, 2008).

2.2 Safety of narrow bicycle paths

Safety is often assessed with accident studies and these studies sometimes indicate the potential causes of the accidents. This gives an indication of unsafe situations, however it is often not possible to directly link accidents to a specific cause.

One of the causes of single bicycle accidents, riding off the path, is associated with conditions of the side of the pavement and the verge, limited width of the bicycle path and obstacles close to the edge of the road (Schepers, 2008). This is in line with the findings of a project about forgiving bicycle paths of which the results were translated into five principles for designing forgiving bicycle paths (den Brinker & Schepers, 2018). The first design principle is sufficient width of the bicycle path. The study on forgiving bicycle paths showed that insufficient width of bicycle paths can be unsafe. The other design principles are visual guidance, extra attention to edge marking by making them feel or sound different, forgiving edges and verges and minimized obstacles close to the verge (den Brinker & Schepers, 2018)

Limited bicycle path width is also indicated as a possible accident cause in an in-depth study of bicycle crashes with older cyclists by Davidse et al. (2014). This study indicated limited width as a potential accident cause in accidents where a cyclists gets off course and ends up in the verge, where a cyclist is surprised by an obstacle on the path and where the cyclist underestimates the complexity of the situation (for example in a road work situation or a difficult turn) (Davidse et al., 2014).

Based on these studies it can be concluded that limited width of bicycle paths can create unsafe situations and can cause accidents. But there are no studies that quantify when a bicycle path is too narrow or not from a safety perspective. Acquiring more knowledge about steering behaviour of cyclists on narrow bicycle paths can provide more insight into the behavioural changes on narrow bicycle paths that might lead to unsafe situations.

2.3 Steering behaviour

Steering behaviour determines the course of a cyclist and its position on the infrastructure. The course of a cyclist is relevant in this study, because it determines the distance to the path edge. When small distances are kept to the path edge, the chances of riding off the path are higher. Steer movements are also needed to keep the bicycle balanced. These steering movements of cyclists are the reason that cyclists cannot cycle a perfectly straight line, which is why these steer movements are also relevant in this study. The sizes of the deviations from the course might also influence the risk of riding off the path. In this section these two aspects of steering behaviour, lateral position and balance control, are discussed.

2.3.1 Lateral position

The lateral position shows the distance that is kept to the edge of the bicycle path. The closer one rides to the edge of a bicycle path, the higher the chance to ride off the path due to a perturbation, which will in some cases lead to an accident. In a study on the safety of kerbstones by Janssen (2017) lateral position is measured in order to find a relation between lateral position and the type of kerbstone. Janssen did not find a relation between lateral position and type of kerbstone. However, the measured lateral distances can be used as a reference for this research. For a single bicycle the average distance to the kerb is 0.66 meter and for a double bicycle this is 0.44 meter (Janssen, 2017). The path width of the paths where these measurements are done, are not mentioned. In a study on visually impaired cyclists of Jelijs (2020) lateral position is also measured. The measurements of the control group can be used as an indication for the results of this study. The study of de Goede (2013) which focusses on conflicts on bicycle paths, also includes lateral position measurements. The lateral position results of both Jelijs (2020) and de Goede (2013) are plotted in Figure 2.4. The measurements are done for other purposes and on different types of bicycle paths, but it gives a first impression.

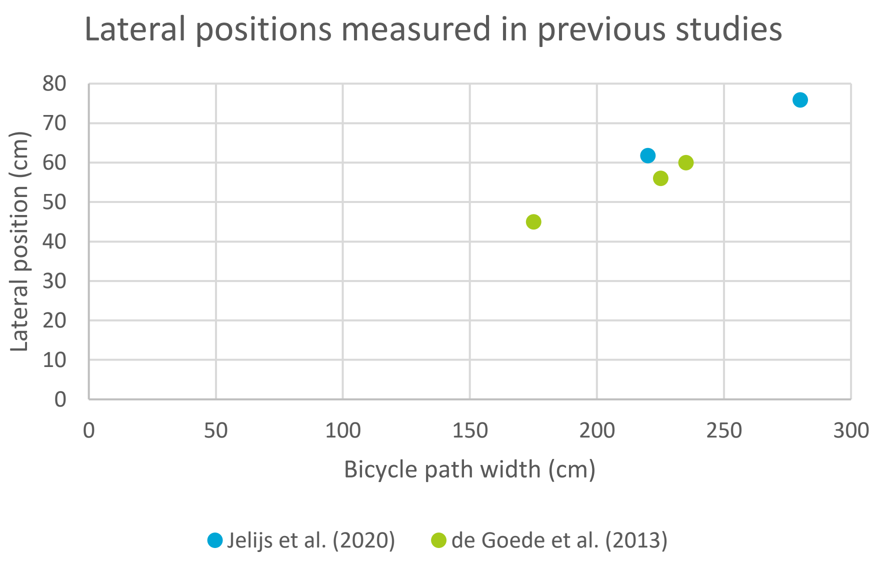

Figure 2.4: Lateral position measurements related to the path widths based on previous studies

2.3.2 Balance control

A bicycle is a two-wheeled vehicle and therefore it has no lateral stability when stationary. Research with a passive rider model shows that with steering and upper body rotations the lateral stability of the bicycle is fully controllable (Schwab et al., 2012). Of these two methods to ensure lateral stability steer torque control is much easier than upper body lean (Schwab et al., 2012). Based on an earlier study with an instrumented bicycle a steering angle between -3° and +3° can be assumed as a reference value for cycling on a straight piece of infrastructure (van den Ouden et al., 2011).

Cycling speed is also important in balance control of a bicycle. At speeds of 12 km/h or higher the bicycle becomes self-stabilizing (Schwab et al., 2012). Different phases are described for accelerating on a bicycle. The first phase is the mounting phase, which is finished at a speed of about 5 km/h (Dubbeldam et al., 2017). This phase is followed by the harmonic cycling phase, which ends at a speed of 10 km/h (Dubbeldam et al., 2017). In these phases of accelerating, balance control of the bicycle is more challenging, because the bicycle is not yet self-stabilizing.

As mentioned earlier older people are more likely to be injured in a bicycle accident, which is why there has been done a lot of studies on the differences in cycling behaviour between older and younger people. A comparison study on balance control showed that older people are more likely to use additional outward knee movement as a control mechanism than younger people (Bulsink et al., 2016).

These outward knee movements result in a larger chance of perturbations and a higher risk to ride off the path.

2.4 Influencing factors of steering behaviour

This section discusses factors that may influence cyclists' steering behaviour. Figure 2.5 is a conceptual model that shows the different influencing factors that will be discussed in this section.

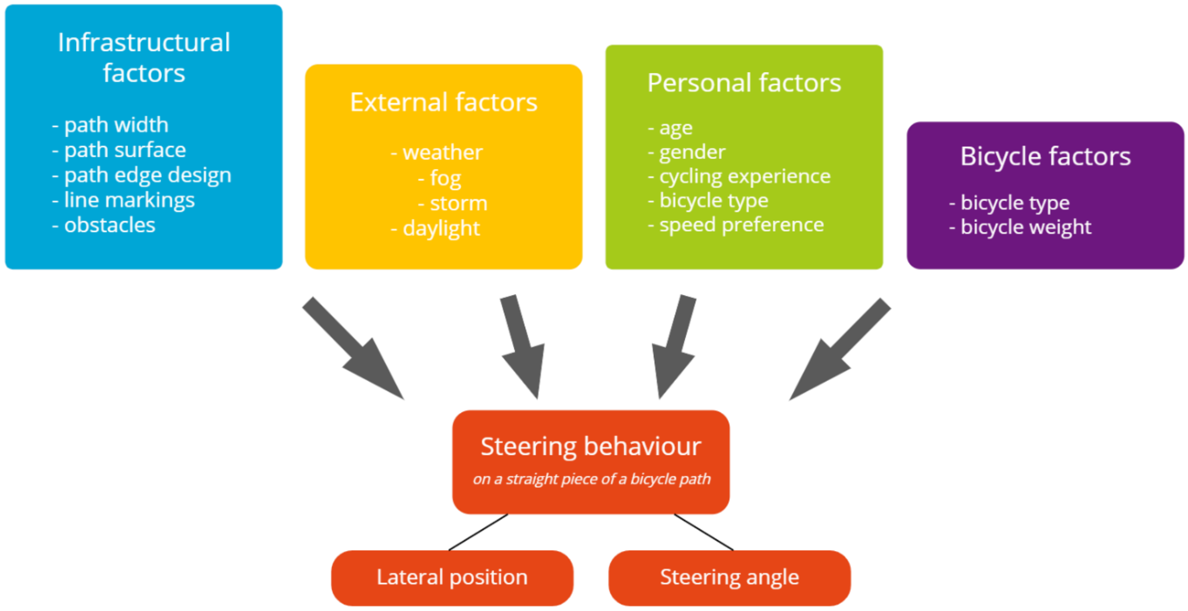

Figure 2.5: Conceptual model of the influencing factors of the steering behaviour variables

First of all the design of the bicycle infrastructure can influence the steering behaviour of cyclists. Many different elements of the infrastructure design can influence steering behaviour, such as road surface, line markings, path edge, obstacles and path width. However, the size of the influence differs. The research of Janssen (2017) showed that there is no relation between the type of kerbstone (vertical, diagonal or horizontal) and lateral position of cyclists on bicycle paths. Whether someone cycles alone or next to someone else, has more influence on the distance that is kept from the kerb (Janssen, 2017). The quality of the road surface mainly influences the ability of cyclists to maintain balance. When bumps, cracks and/or holes in the road surface and shoulder are large, these create a higher probability for cyclists to lose balance, which might cause a perturbation in the steering behaviour. Therefore, bumps, cracks and/or holes in the road surface can be marked as bottlenecks (van Weelderen, 2020). A higher share of these bottlenecks on path edges and the presence of obstacles near the road surface increase the risk of bicycle accidents (van Weelderen, 2020). The lateral position can be influenced by road marking. Adding white edge strips to a bicycle path causes cyclists to keep a larger distance from the path edge, which lowers the risk of single bicycle accidents (Westerhuis et al., 2020). Adding shoulder strips results in a smaller distance to the main path edge, but in a larger total distance to the path edge and is considered to have a positive effect on safety (Westerhuis et al., 2020). Visibility of the infrastructure is generally important, because bad visibility of the infrastructure has a role in a substantial number of single bicycle crashes (Fabriek et al., 2012). Visibility can be influenced by infrastructural, external and personal influencing factors. Examples of causes of bad visibility are blockages by obstacles or buildings, fog or absence of daylight and visual impairment of the cyclist.

There are several studies that conclude that bicycle path width influences safety (de Goede et al., 2013; Hoogendoorn, 2017; Janssen, 2017; van Weelderen, 2020; Westerhuis et al., 2020). TNO for example compared the lateral position on the bicycle paths within a city and concluded that people take the same lateral position proportionally to the width of the bicycle path, which means that on smaller paths cyclists cycle closer to the edge of the bicycle path and that may increase the risk of riding off the path or cycling against a kerbstone (de Goede et al., 2013). The guidelines for necessary widths of bicycle paths are mostly based on an early field study by Godthelp & Wouters (1980). Recently, Schwab & Meijaard (2017, 2018) developed different methods to derive the necessary width of a bicycle lane by means of simulation on a bicycle rider model and on the basis of multibody dynamics. With the multibody dynamics method they found a strong relation between speed and necessary width to recover from lateral perturbation (Schwab & Meijaard, 2018). At speeds under 4 m/s a significant width measured from the centre line of the bicycle is needed to recover from lateral perturbation and at speeds higher than 4 m/s the necessary width decreases largely, which is opposite of what happens with motorised vehicles (Schwab & Meijaard, 2018). So, bicycles at lower speeds require more width than bicycles at higher speeds. This makes it relevant to identify whether a bicycle path will be mainly used by faster or slower cyclists. Generally young children, elderly, inexperienced cyclists and probably also most recreational cyclists, except many sporty cyclists, will be the slower cyclists compared to students, commuters and race cyclists, on average faster cyclists. High speed differences between the users of infrastructure has a negative influence as well. The introduction of e-bikes can cause higher speed differences and increase the injury risk for themselves and other road users (Gitelman et al., 2020).

External factors that influence steering behaviour are weather, day of the week and time (Castells-Graells et al., 2020). Almost 10% of all bicycle kilometers are travelled in darkness and twilight (Schepers & den Brinker, 2011). The absence of daylight influences the visibility of the infrastructure, which influences steering behaviour. However, it seems that cyclists, especially more vulnerable cyclists, adapt to this by making less use of the bicycle. Older cyclists and cyclists with bad visual conditions avoid cycling in the dark, which makes the effect of darkness on safety less visible in injury statistics (Schepers & den Brinker, 2011). Some weather conditions influence steering behaviour. For example, fog influences visibility and storms might cause perturbations in the steering line of cyclists, especially when the wind blows cyclists sidewards. These weather conditions also influence the use of bicycles. This might be the cause that there are no consistent results on a relation between weather and safety (Schepers et al., 2020). To what extent the share of bicycle use in a city is influenced by weather depends on factors like the share of young inhabitants and the density of the bicycle network (Goldmann & Wessel, 2020).

Characteristics of the cyclist might influence steering behaviour as well. Gender, experience and age can influence steering behaviour of cyclists. In many countries, especially with low cycling densities, women cycle less than men (Shaw et al., 2020). A study in New Zealand showed that women generally travel less than men, men are more likely to cycle and women are more likely to walk or take public transport. Another reason that is addressed for this gender-gap in cycling is that women tend to have more fear of accidents than men (Ravensbergen et al., 2020). The fact that men are more fearless regarding accidents compared to women, might cause a difference in steering behaviour as well. There are no studies that show these differences in behaviour between men and women in the Netherlands. Experience influences steering behaviour, because inexperienced cyclists tend to ride at slower speeds and therefore require more width (Schwab & Meijaard, 2018). Next to the speed difference, experienced riders are also more familiar with different traffic situations which helps them in dealing with these situations. The main influence of age on steering behaviour is the reduced cognitive skills of elderly (Salthouse, 1996). Their speed of processing information and reacting to a situation is reduced, which results in steering behaviour that avoids risks and lower cycling speeds. Bicycle factors that might influence the steering behaviour are bicycle type and bicycle weight. Both can influence the steering movements needed to keep the bicycle balanced.

2.5 Guidelines for bicycle path width

The results of this study can be used to discuss the guidelines for designing bicycle paths and the minimum values these advise for bicycle path width. This section will explain more about these guidelines.

In 1993 the first guidelines for cycling infrastructure in the Netherlands were published by CROW. The growing use of cars was an important motivation to create these guidelines for cycling infrastructure (CROW, 1993). Cars and bicycles differ largely in mass and speed, which made the construction of new separate bicycle paths in more cases necessary for safety and comfort reasons. The guidelines are based on the normative dimensions of bicycles. The normative width of a bicycle used for the guidelines is 0.75 meters (CROW, 1993). In determining this normative width the space needed to keep the bicycle stable is also included. When two cyclists pass each other a distance of 1 meter between the wheels of both cyclists is needed (CROW, 1993). Based on the normative width of a bicycle and the distance between two passing cyclists, CROW concluded that 2 cyclists can ride next to each other on a path of 1.5 meters and cyclists can easily ride next to each other on a path of 2 meters (CROW, 1993).

The guidelines for bicycle path widths in the Netherlands are based on these conclusions about the required space for cyclists to pass each other combined with peak hour intensity. In Table 2.1 the guidelines for bicycle path widths according to CROW (1993) are shown. An important sidenote that is added to the smallest widths is that these narrow bicycle paths should have forgiving edges, so bicycles have a fallback option.

Table 2.1: Bicycle path width guidelines for diverse intensities according to CROW (1993)

One-way traffic		*Two-way traffic*	
Peak hour intensity (cyclists per hour)	**Bicycle path width (m)**	**Peak hour intensity (cyclists per hour)**	**Bicycle path width (m)**
< 10% mopeds			
0 - 150	1.50	0 - 50	1.50
150 - 750	2.50	50 - 150	2.50
> 750	3.50	> 150	3.50
> 10% mopeds			
0 - 75	2.00	0 - 50	2.00
75 - 375	3.00	50 - 150	3.00
> 375	4.00	> 100	4.00

In 2017 a new revised version of the CROW guidelines for cycling traffic was published in which the main part of the guidelines remained the same, however in 25 years it is evidently that some things change. If only because a lot has changed in traffic rules and regulations in those years

In 1993 the CROW made two distinctions in their guidelines, which is one-way and two-way traffic and more or less than 10% mopeds among the bicycle path users. In 2017 the first distinction between one-way and two-way traffic is formulated differently as solitary bicycle paths and bicycle lanes, because solitary bicycle paths are always two-way paths and one-way bicycle paths are always next to roads. Bicycle paths where mopeds are allowed are now called bicycle moped paths. The guidelines for solitary bicycle (moped) path widths are given in Table 2.2.

Table 2.2: Solitary bicycle path width guidelines for diverse intensities according to CROW (2017)

Peak hour intensity (cyclists per hour)	**Minimum width (m)**
Bicycle paths	
0 - 50	1.50
50 - 150	2.50
150 - 350	3.50
> 350	4.50
Bicycle moped paths	
0 - 50	2.00
50 - 100	3.00
100 - 300	4.00
> 300	5.00

What stands out is that these guidelines didn't change a lot. A category is added for both bicycle paths and bicycle moped paths, probably because crowded bicycle paths got more common than they were in 1993, but the minimum widths didn't change.

To which category of the guidelines a path belongs is determined with peak hour intensity. Peak hours in traffic are usually defined as the morning and evening peak caused by commuters. It is not specifically mentioned in the guidelines how to define peak hour. On recreational bicycle paths the peaks in intensity will be on different moments and less easy to predict, because it will depend on much more factors like the weather and holidays. Therefore, if the usual peak hour definition is used when applying these guidelines, the guidelines will not be suitable for recreational bicycle paths. Recreational bicycle paths will always belong to the smallest minimum width category if the usual peak hour definition is used.

2.6 Conclusion

The literature study starts with a review on single bicycle accident statistics and causes. The increasing share of single bicycle accidents supports the relevance of this study. Causes of single bicycle accidents can be balance problems, mechanical failure, distraction, the use of alcohol or riding off-path. Lateral position and steering angle movement turn out to be the most often considered steering behaviour variables that are related to the required lateral space of the cyclist when cycling straight lines. This answers the first sub question (*Which variables of steering behaviour are most often considered in determining the required space on a bicycle path?*). The factors that influence steering behaviour of cyclists are also derived from literature. There are infrastructural characteristics that influence steering behaviour, such as road surface, line markings, path edge, obstacles and path width. External factors like weather, day of the week, time of the day influence the results as well. Visibility and characteristics of the cyclists, such as gender, experience and age, also affect steering behaviour. This answers the second sub question (*Which factors influence steering behaviour?*) and is used as input for the experimental design.

2.7 Hypotheses

Several hypotheses are formulated that will be answered with the experiment results.

- Cyclists cycle closer to the path edge on narrower bicycle paths than on wider bicycle paths.
- Cyclists cycle faster on wider bicycle paths than on narrower bicycle paths.
- The average absolute steering angle rotation gets larger when the bicycle path width gets narrower.
- When passing another cyclist, cyclists cycle closer to the path edge (i.e. the minimum distance to the path edge is smaller) than without passing another cyclist.
- The perceived safety decreases when the bicycle path width gets narrower.
- Cyclists are aware of their own steering behaviour.

3

Methodology

In this chapter the choice of data collection method is explained first, followed by a description on the experimental design. The chapter finishes with an explanation of methods used to filter and analyse the data.

3.1 Data collection method

The literature study showed that lateral position and steering angle are the most important steering behaviour variables that determine the required width for one cyclist. Therefore, these are the variables that should be measured on different path widths. This section describes the different data collection methods that were considered and the reason why an experiment was preferred. Next to the choice of data collection method, the ethical approvement procedure is discussed.

3.1.1 Selection of a data collection method

Three different options to collect data have been considered, being a real-life experiment, an observation study and a controlled experiment. By comparing these option on internal and external validity and feasibility, a choice for one of the data collection methods is made.

Real-life experiment

One option was to let test subjects cycle a pre-mapped route on an instrumented bicycle. An advantage would be that the results resemble real-life conditions, i.e. that results have a good external validity. When cycling a real route that is not set-up for this experiment, the lateral position can be determined by filming the front wheel and the bicycle path. With this video data the lateral position can be determined, a method that is also used in the study of Westerhuis & De Waard (2014). It would be an option to let people cycle on their own bicycles and install a small camera with GPS on the steering wheel of their bicycle, but this would result in different positions of the camera in relation to the front wheel and the path and more time consuming data analysis. So, using the same bicycle for all participants is preferred. However, a disadvantage of this research is that bicycle paths do not only differ in terms of width but also in terms of road surface material and quality, objects in the verge, height difference between the verge and road surface etc. Such factors affecting cyclists' lateral position makes it more difficult to isolate the impact of width on lateral position, i.e. that results have a poor internal validity.

Observation study
An observation study can be done by adjusting camera's at a high position above specific bicycle paths and analyse the video material. With this research approach a dependency exists on the volume of cyclists on the bicycle paths. Similar to the real-life experiment this research approach has a good external validity because it is conducted at real bicycle paths. However, it has poor internal validity because bicycle paths may differ not only in terms of width but also in terms of other characteristics that might influence steering behaviour. The population on different bicycle paths might differ as well, which makes it hard to conclude whether difference in steering behaviour are caused by the difference in path width or by the differences in population.

Controlled experiment
The third option is a controlled setup, an experiment, where the relative differences in lateral position can be studied. In this option all other influencing factors such as path edge layout and height, proximity of obstacles and quality of the pavement can be kept constant, which creates a scenario where the relative difference in lateral position of cyclists on different path widths can be isolated. A disadvantage is that it is difficult to design realistic path edges which may compromise external validity. But it is the only method to isolate the influence of the width while all other factors are stable.

Table 3.1: Comparison of research designs

	Real-life experiment	Observation study	Controlled experiment
Internal validity	-	-	+
External validity	+	+/-	-
Feasibility	+	+	+

In Table 3.1 the three research designs are compared on internal validity, external validity and feasibility. Internal validity is the degree of confidence that a causal relationship found in the study is not influenced by other factors and external validity is the extent to which the results can be translated to other contexts. The controlled experiment is preferred, because this experiment has the best internal validity. Without this internal validity it is hard to answer the research question. Ideally the results from that experiment are compared with a small real-life experiment to make the link with a real-life surrounding, but this is outside the scope of this study. All options would be feasible. However, as an observation study requires observing high volumes of passing cyclists this option would have been less feasible as this experiment had to be conducted during the winter.

3.1.2 Ethical approvement

The experiment had to be approved by the ethical committees of both TU Delft and SWOV. Privacy rules made it very important to think about which information might be collected during the experiment and when it would become sensitive data. A data management plan for the experiment was created and approved by the Data Steward of the Faculty of Civil Engineering and Geosciences. An informed consent was created to inform participants about the data that would be collected during the experiment, how this data would be used and stored and how their privacy is guaranteed. For getting permission to use the location, another assessment of the safety of the experiment was done by the TU Delft Campus and Real Estate (CRE). When all sub parts were approved, the broader assessment of the experiment was done by both the HREC (Human Research Ethics Committee) of the TU Delft as well as the ECOS (Ethische Commissie Onderzoek SWOV) of SWOV Institute for Road Safety Research. Both ethical committees approved the research.

The coronavirus pandemic created some additional difficulties in organizing the experiment, because the possibilities for the experiment were bounded by the measures of the Dutch government to control the spread of coronavirus in the Netherlands. These measures changed a lot over time, which was a large uncertainty in the planning of the experiment. In the period when the experiment took place, December 2020, it was not possible to set up an experiment in which different participants are brought together at short distance, which could be used to create a passing manoeuvre. The maximum group size for meeting outside was four people. This made it possible to organize the experiment when only one participant at a time was on the experiment location. The bicycle was disinfected between each participant to prevent possible infection in case someone was infectious without symptoms.

3.2 Experiment

An experiment with a controlled setup is preferred as described in the previous section. In this section every aspect of the experiment is described in detail.

3.2.1 Data needs

To answer the research question of this study, data of steering behaviour variables on different path widths was needed. Other circumstances had to be constant, which made it possible to distinguish the effect of path width on steering behaviour. Data was needed on the steering behaviour variables that are described in section 2.3, lateral position and steering angle. Speed data was needed to answer the sub question about the relation of cycling speed and bicycle path width. A setup with an oncoming cyclist is needed to measure the influence of passing an oncoming cyclist on the steering behaviour variables. Questionnaire data is needed to answer the sub question on how participants experience the different path widths. This data is used to test the hypotheses that cyclists are aware of their own steering behaviour and that perceived safety decreases when the bicycle path gets narrower.

3.2.2 Experimental design

The experiment is setup to measure steering behaviour variables on different path widths. In order to extract the effect of the different path widths, it is important that all other circumstances are as much constant as possible. Section 2.4 of the literature review describes all influencing factors for steering behaviour, these factors need to be considered in the experimental design. All measurements are done on the same bicycle path to make sure all infrastructural influencing factors are the same. The measurements are done in two days, which causes least possible differences in external influencing factors, such as weather. All measurements are done in daylight conditions to ensure equal visibility conditions. Cyclist characteristics that might influence the steering behaviour are less influencing because it is possible to make a within subject comparison of results for different path width conditions.

The steering behaviour variables that will be measured are lateral position and steering angle. These variables are measured with an instrumented bicycle. Lateral position is determined by measuring the distance from the bicycle to a fixed barrier in the verge. This barrier is positioned 1 meter from the path edge to make sure it wouldn't become an extra obstacle in the verge.

Measurements are done on five different setups. The first three setups are the widths 1 meter, 1.5 meter and 2 meter as a bidirectional bicycle path without oncoming traffic. The widths 1.5 meter and 2 meter are based on the CROW guidelines. The guidelines state that two cyclists can pass each other on a 1.5 meter path and can easily pass each other on a 2 meter path. Even though the guidelines prescribe a minimum of 1.5 meters, a lot of Dutch bicycle paths are narrower. Therefore, the width of 1 meter is added to the experiment. The other two setups are setups with a parked bicycle to simulate an oncoming cyclist. Due to corona measures real passing manoeuvres could not be measured, because then the experiment would bring people together at a smaller distance than 1.5 meter. For the widths 1.5 meter and 2 meter a bicycle was parked as if it was an oncoming cyclist. On the path of 1 meter no oncoming cyclist will be simulated, because the guidelines state it is too narrow for two cyclists to safely pass. A parked bicycle is not a perfect simulation of an oncoming cyclists, but the behaviour with respect to the parked bicycle will give some indication of how people change or do not change their steering behaviour when negotiating an oncoming cyclist. The actual effect of an oncoming cyclist will probably be larger than what was measured with the simulation by a parked bicycle, because a parked bicycle is more predictable than a real cyclist.

3.2.3 Location

The location for the experiment is selected based on a few requirements and preferences. The requirements are related to the safety of the participants, the corona measures at the moment of the experiment and the data needs of the experiment.

For the safety of the participants it is important to have a path with a flat surface, no obstacles close to the path and a forgiving path edge. All these requirements should create an environment that reduces the risk of falling to a minimum. The forgiving path is especially important in this experiment, because on the narrow paths used in the experiment, the risk of riding off the path might be slightly higher. A forgiving edge will reduce the risk of falling when riding off the path and make it easier to ride back on the path.

Considering the corona pandemic, it is required to minimize the displacement of everybody involved in the experiment. A location nearby the TU Delft would be minimal displacement of the technicians and researchers involved and this would make it possible to ask fellow students to participate.

For the experiment different path widths are needed, this means that different paths are needed or one of the edges needs to be changed during the experiment. Finding a location with exactly these path widths close to each other is preferred but not realistic, therefore temporary path barriers will be needed. For that reason it is needed that the location can be blocked for other traffic during the experiment. Least possible hindrance for other traffic participants is preferred when the path is blocked, because this will make it easier to get permission to block the path.

After a search for locations that meet these requirements and preferences, the path between the faculties Aerospace Engineering and Applied Sciences on the TU Delft campus was selected. Figure 3.1 shows the location of the selected path. The path is newly constructed, the surface is very flat and there are no obstacles close to path edges.

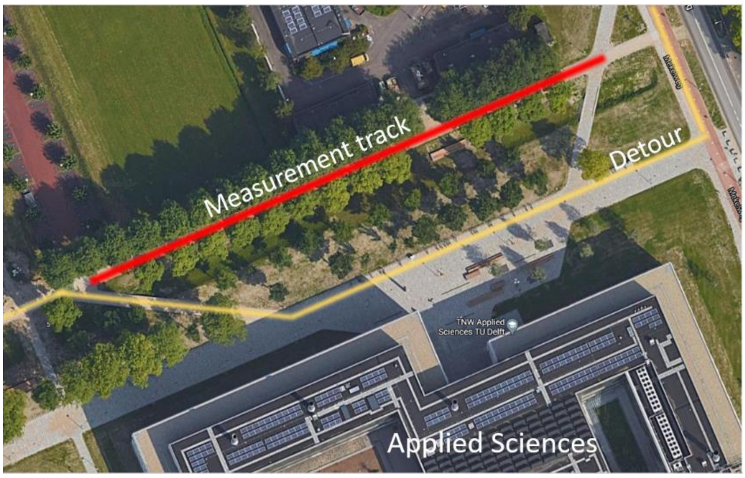

Figure 3.1: Selected path and detour option (source: google maps)

Next to the path that will be used for the experiment a parallel path exists that can be used as a detour for other traffic participants. Figure 3.1 shows the detour possibility from above.

Figure 3.2: The forgiving edge of the path (own picture)

The path edge of the selected location is forgiving. Figure 3.2 is a photo of the path edge, which shows that there is no height difference between the path and the verge. In between the path and the verge a concrete curb at the same level is present to make it even more easy to ride on and off the path. If it happens that one of the participants rides off the path, the participant can easily ride back on the path and it will be highly unlikely that this participant falls. These are optimal conditions, which is good because it ensures the safety of the participants. However, it might influence the lateral position of the cyclists. The risks of cycling off the path are lower, which might cause the participants to cycle closer to the path edge than they would when the path edge was less forgiving.

Figure 3.3: The path that is selected for the research (own picture)

The path is located on the terrain of TU Delft. After assessing the experiment idea and that safety was assured, TU Delft Campus and Real Estate (CRE) gave permission for the usage of the path for the experiment and for closing it off for other users.

3.2.4 Participants

The participants of the study were students of the TU Delft. Because older people are more susceptible to the corona virus, they could not be invited to participate. All students live nearby the experiment location, which is an advantage of this target group, because this means they do not have to travel a long distance to participate. In total 24 people could participate in the experiment. An attempt was made to find an equal number of male and female participants to be able to compare differences among gender. Regular use of a bicycle was required to make sure all participants master the skill of cycling. A very experienced group of cyclists was expected, because most students use a bicycle as their main mode of transport. The group of participants is a quite homogeneous group of participants. The group size of 24 doesn't allow for a comparison between many subsets of the data, because than the sample sizes for all sub sets will be too small for statistical relevant results. The homogeneous group will ensure significant results for this group of people. When discussing the results and the transferability of the results to other population groups, the age and experience of this group of participants will have to be considered as a positive influence on the results. The participants of this experiment have most likely cycled closer to the path edge and experienced the path widths differently than older or less experienced cyclists.

Participants were recruited among students of the mastertrack Transport & Planning, friends and roommates. Participants could sign up in an online form where their availability on the two experiment days was asked. When the required amount of participants (24) was met, a planning was made where all participants were assigned a timeslot that met their availability. The experiment took half an hour per participant and because the number of daylight hours is limited in December, 24 participants was the maximum amount of participants for two measurements days. The timeslots are shared with the participants together with some additional information and the informed consent. Due to the coronavirus, the moment of contact on the experiment location had to minimized. Therefore, participants were asked to read and sign the informed consent at home and send it per email or bring it to the experiment location.

3.2.5 Equipment

The required outputs of the equipment used in the experiment are described in section 3.2.1. In Figure 3.4 the required outputs of the experiment are shown in the blue boxes and the measurement equipment used the generate this output is shown in the red boxes.

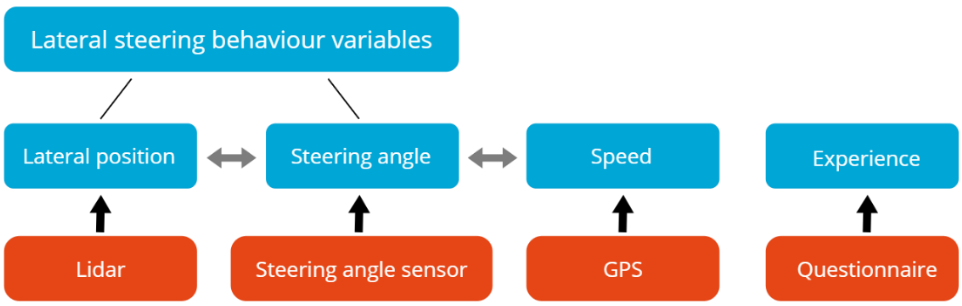

Figure 3.4 Conceptual model of the required data and the coresponding measurement equipment

An instrumented bicycle is used for the experiment. The bicycle contains a GPS in order to derive data about location and speed. Especially speed is an important variable, because speed influences the deviation in steering angle. The GPS generates on average 5 measurements per second. The steering angle is measured with a sensor on the handlebar of the bicycle. Cyclists use speed and small steering movements to stabilise their bicycle. The sensor on the handlebar of the bicycle measures these steering movements. This does not necessarily correspond to the deviations of the lateral position, because an equal deviation of lateral position can be caused by small steering movements or large but balanced (equal in right and left direction) steering movements. The steering angle sensor did not have a consistent number of measurements per second, but on average it registered 30 measurements per second. With a lidar sensor at the rear wheel, quite close to the ground, the distance to the closest obstacle is measured. The lidar sensor registered 100 measurements per second. On the experimental track this lidar measured the distance to the plastic barrier which is positioned 1 meter next to the path edge in the verge.


Figure 3.5: The instrumented bicycle used for the experiment (left hand side)


Figure 3.6: The instrumented bicycle used for the experiment (right hand side)

Figure 3.5 and Figure 3.6 show how the instrumented bicycle looks. The bicycle has a large crate on the front of the bicycle. A lot of things needed for the instruments on the bicycle are stored here, such as the battery. This makes it feel a bit heavier to steer than on a usual bicycle. All participants cycle a test round first, to make sure they get used to the bicycle before measurements start.

More equipment is needed to setup the measurement track on the selected location. The measurements were done on a length of 80 meters. The total path length is 130 meters and it was not possible to use the full length of the path, because some space was needed to let the participants accelerate and decelerate. That is why the length of the measurement track is set at 80 meters, this measurement track was placed in the middle of the path which left 25 meters at both ends to accelerate and decelerate. Orange cones were used to make sure participants use this acceleration and deceleration space. In Figure 3.7 the locations of all equipment to setup the measurement track is shown including the fences to block the path for other user and the detour route (in yellow) that was available for them.

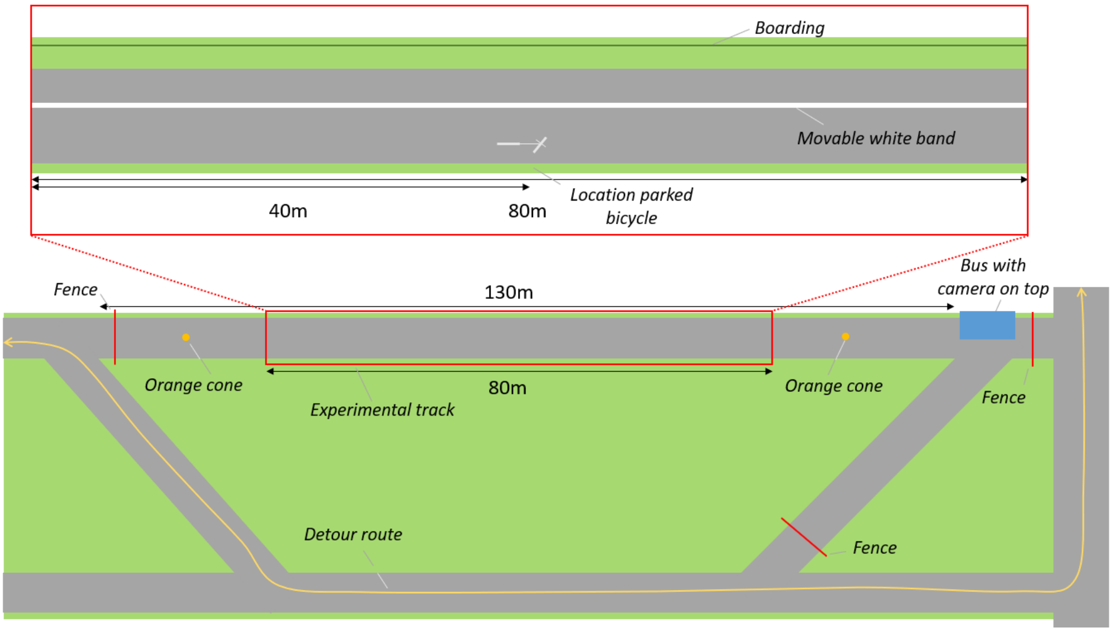

Figure 3.7: Schematic overview of experimental setup

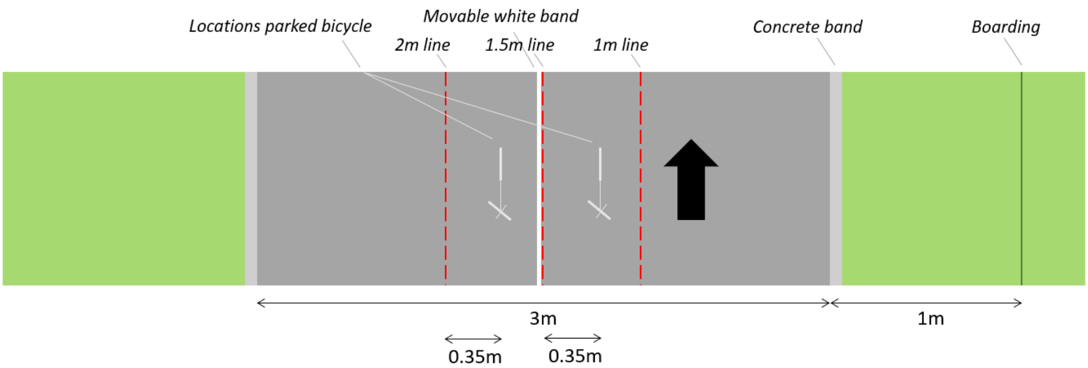

Figure 3.8: Cross section overview of experimental setup

In order to derive lateral position with the lidar sensor a reflection board at a fixed distance in the verge is needed. This temporary barrier was placed 1 meter from the bicycle path edge. The reflection board was a plastic barrier fixed in the verge with ground pins. The barrier has a wave pattern with a displacement of 1 cm in its surface, i.e. an amplitude of 0.5 cm. The total displacement is a little larger, because the barrier did not stand perfectly upright over all 80 meters due to limited ground pins, which is also visible in Figure 3.9. It is expected that the effect on the results is partly averaged out, because the wave pattern is balanced and the pieces that do not stand perfectly upright are also falling to both sides. The lidar recorded 100 measurements per second. With an average speed of 15 km/h it takes 19.2 seconds to cycle along 80 meters of boarding, which would result in 1920 measurements. In the results, the median value of these 1920 measurements will be used, which will not be largely influenced by the small displacements in the boarding.

Figure 3.9: Pictures of the plastic barrier used to measure the lateral position (own pictures)

The path width needs to be changed during the experiment. For the edge on their right hand side the original path edge is used. To simulate a path edge on the cyclists' left hand side a white band is used. Due to the colour the white band indicates a usual line markings on roads. Still it will look a little different compared to what the participants are used to see. However, a study on the influence of type of kerbstone shows that this hardly influenced the lateral position (Janssen, 2017). Based on this conclusion, it expected that the different looking line markings at the left hand side won't influence the result of the experiment. The surface is wider than the path, which could possibly lead to a different perception of the path width and cause slightly larger distances to the right hand path edge. However, no large differences are expected because the participants are instructed that only the path right from the movable edge could be used.

On the first measurement day the weather was good and the white band could be easily attached to the path with duct tape. On the second measurement day it was foggy, wet and there was more wind. Only duct tape was no longer enough to safely attach the white band to the path. Orange pylons were used to keep the band in place and at both ends of the band a stone was placed under the pylons.

Figure 3.10: Two methods used to attach the white band to the bicycle path (own pictures)

The different methods to attach the white band to the path did influence the visibility of the line marking. In Figure 3.11 overview pictures of the measurement track is given to show the different visibility situations. Because the left hand side border is expected to not influence the lateral position, it is assumed that these visibility changes won't influence the results either. Because on both days different people participated, it is not possible to check the influence with the results, because differences in the results of both days could have multiple causes.

Figure 3.11: Visibility on Tuesday (left picture) and Wednesday (right picture) (own pictures)

The last pieces of equipment are the parked bicycle and the overview camera. The parked bicycle is used to simulate an oncoming cyclist and is parked halfway the measurement track. For the lateral position of the parked bicycle the study of Janssen (2017) was used, who found that cyclists cycle on average 44 centimeters from the path edge in the situation of a double bicycle. The parked bicycle bends over a little, because the front wheel bends and the bicycle does not stand upright. The back wheel of the parked bicycle is parked 35 centimeters from the movable path edge to correct for this bending over. The overview camera was placed on a bus and filmed the experiment location. These videos were used to clarify what happened if the data showed some unexpected results.

Figure 3.12: Position overview camera

With a questionnaire data is collected on the participant's perception of the different bicycle path widths. Directly after finishing all repetitions on one of the path widths, the participants were asked whether they perceived the bicycle path width safe to cycle alone and to pass another cyclist. They were also asked to indicate how much effort it took to complete the cycling task. After finishing the complete experiment, participants were asked to fill in an online questionnaire. In this questionnaire they were asked about their cycling experience, what they thought about the experiment and to indicate their preferred lateral position on different path widths.

3.2.6 Course of the experiment

Before starting the experiment all participants were informed about the setup of the path, the different scenarios that will come by and that the order in which the parked bicycle will show up is random. The participants are informed about the questions that will be asked when the path width is changed. Although the circumstances are not completely the same as in real-life situations, the participants are asked to cycle like they would in a real-life situation and approach the parked bicycle as if it is a real oncoming cyclist. Participants signed an informed consent before starting with the experiment. In the informed consent the corona health check questions of the Dutch government were included. The bicycle was disinfected before every participant starts the experiment in order to minimize the chances of transferring covid-19 infections in case someone was unconsciously infectious. Then the sensors are all connected to the power supply and the participant can make a test round to experience how the bicycle feels. If needed the saddle height was adjusted to the participant and the experiment could start.

For the procedure of the experiment it is important to know how many repetitions per setup are required to collect enough data to find significant results. Data about lateral position and deviation in steering angle is collected. Both variables have a variation, which means that doing it twice wouldn't give the same results. Therefore, multiple runs should be done per setup in order to have more accurate measurements and results. In order to determine the number of repetitions that are needed per setup beforehand, the accuracy per number of repetitions is calculated for the variable speed. It was not possible to do this for the variables steering angle and/or lateral position and making an estimation for the variable speed was assumed to be the best alternative. The path is cycled 10 times and the duration per repetition is measured with a stopwatch. The path is 130 meters, so the speed could be calculated. In Table 3.2 the speed per repetition is shown.

Table 3.2: Duration of cycling the path 10 times with corresponding speeds

	time (s)	speed (m/s)
rep 1	29.95	4.34
rep 2	30.42	4.27
rep 3	29.18	4.46
rep 4	29.94	4.34
rep 5	28.34	4.59
rep 6	29.34	4.43
rep 7	30.33	4.29
rep 8	28.12	4.62
rep 9	29.71	4.38
rep 10	29.13	4.46
mean	29.45	4.42

The required sample size can be calculated with the following formula (Sullivan, 2006).

$$n \geq \frac{Z_{\alpha/2}^2}{d^2} \times \sigma^2$$

The Z-value for a 95% confidence interval is 1.96. The squared Z-value is 3.84. The variance can be calculated with the following formula.

$$variance\ (\sigma^2) = \frac{\sum_{i=1}^{n}(X_i - \bar{X})^2}{n-1}$$

For the desired accuracy various values that represent 1, 2, 3 and 5% of the mean speed are used to see how many repetitions of the experiment would be needed to get that accuracy level. The results are given in Table 3.3. Every setup in the experiment will be repeated 3 times, because this is a feasible number of replications considering the available time. The calculation for speed indicates that the results will have variations of 3% from the mean value. Assuming that the average lateral position will be 0.66 meter (see section 2.2.1), a deviation of 2 cm or more will be statistically relevant.

Table 3.3: Required number of repetitions per accuracy level

Accuracy	Repetitions (N)
1%	27.55074
2%	6.887686
3%	3.061194
5%	1.10203

All five setups are repeated three times, which means 15 runs per participant. The order in which the different setups come by are predetermined to minimize the influence of order effects on the results. Changing the path width costs time, therefore the amount of path width changes is minimized and all required repetitions per path width are finished consecutively. For the widths that have a setup with and without a parked bicycle. The order in which these scenarios come by is randomized as well. Except for the first round of a specific width, which is always without a parked bicycle. This will give the participant some time to adjust to the path width, because it is an artificial setup and the changes in path width are more sudden. At the end the first path width is repeated to be able to check whether there were learning effects and how large they were. This makes the total number of runs per participant 18. In Appendix A an overview of the executed order of events is shown for all 24 participants. Repetitions that are performed, but of which data was missing, are left out in the overview.

When changing the path width, the cyclists were asked a few questions on perceived safety. In these questions the 1-meter width with oncoming cyclist scenario is included even though it is not included in the experiment for safety reasons. When all runs are completed the participants were asked to fill in a questionnaire at home with questions about their cycling experience and their assumed steering behaviour.

3.3 Data analysis

The data collected in the experiment should be filtered and analysed to check the hypotheses and draw conclusions based on the results. For both filtering and analysing Python is used to automate this process as much as possible.

The data filtering consists of selecting the right start and end point of each repetition on the measurement track. The sensors were disconnected from the power supply after every participant. This made it easy to separate the data per participant afterwards. During the experiment of one participant the sensors are not paused, this means that the individual tracks need to be distinguished based on the data. Two methods are used to do this. The first criteria is to filter out all datapoints that have lidar measurements outside the expected area (i.e. on the bicycle path). The second criteria is to use the GPS angle data to distinguish the two different cycling directions. By identifying the gaps in time between two tracks, the start and end point of tracks can be identified. The globally selected tracks need some manual finetuning, because it is sensor data and all tracks look a little different, this process is hard to automate.

With the selected tracks a data analysis can be performed. To check the hypotheses, the average lateral position, its standard deviation and the point closest to the path edge are needed from the lateral position data. The average speed is needed to check a hypothesis as well as the average steering angle. The average lateral position will be determined by the median value, because some tracks have a few outliers, these outliers have a smaller influence on the median value compared to the mean value. To determine the point closest to the path edge the first percentile value will be used, this means that 99% of the values are higher and 1% is lower. This is used to make sure that one single outlier is not identified as the closest point to the path edge. The amount of outliers at this side of the graph is very low, most outliers are too high values and not too low values. Therefore, the first percentile value is suitable here.

All scenarios are repeated three times per participant, so with the mean value of these three tracks the value for that specific scenario is found per participant. A one-way repeated measures analysis of variance (ANOVA) is used to check whether the differences found in the results are significant. All scenarios are performed by the same group of participants. Therefore, this statistical test is used, because it allows for this type of within subject comparison.

4

Data analysis

4.1 Participants

The group of 24 participants consists of 11 male and 13 female participants. All participants were between 19 and 27 years old. 21 participants have the Dutch nationality, 2 people an Indian nationality and one participant a Greek nationality. All participants were experienced cyclists and they all learned cycling at a very young age (2-6 years old) except for one participant who learned cycling at the age of 13, which is still quite young. 4 participants have not cycled for a significant period of time since they learned cycling. The length of this period varies between 1 and 4 years. 22 participants would describe their own cycling skills as good and the other 2 would describe their cycling skills as sufficient. How many people cycle per week on average varies a lot among the participants. Some cycle only 3 kilometers per week and others 300 kilometers. On average the participants cycle 64 kilometers per week. 19 participants cycle 5-7 days a week, 4 participants cycle 3-4 days a week and 1 participant cycled less than once a week.

In the questionnaire after the experiment was asked whether participants changed their behaviour consciously and if not, if participants think they cycled different than they normally would even though they didn't consciously change their behaviour. Three participants answered that they consciously changed their behaviour. Two of them were more conscious of the lines and whether they cycled in a straight line or not and one would ride faster on their own bicycle and keep more distance to a real oncoming traffic participant than to the parked bicycle. The other 21 participant didn't consciously change their cycling behaviour and didn't think they cycled different than they normally would. Still, some did mention in the last open comment box that the bicycle felt a little different compared to what they are used to due to the heavy crate in front of the bicycle. This might have led to some adjustment time, but that is exactly why at the end three more measurements are done on the path width where the participant started with. So, this learning effect can be analysed.

4.2 Data filtering

In the data filtering process the start and end point were selected for all repetitions on the measurement track. The start and end point of the repetitions were determined based on the lidar data, because the boarding in the verge was exactly the length of the measurement track, so the tracks were expected to be visible in the lidar data. The angle data of the GPS was used to support the filtering, because this data shows when the cyclists cycled back or forth on the measurement track. The raw data collected during the experiment was saved in two separate datafiles, one with GPS and lidar data and one with steering angle data. Both datasets had a different number of measurements per second and the number of measurements per second was not constant. Therefore, the synchronisation of the data is done in a later stage of the filter process. Both datasets saved the satellite time per datapoint, which makes it possible to select the same timeslots in the datasets with steering angle data once the start and end points were determined in the dataset with lidar and GPS data.

The data filtering is done with the dataset with GPS and lidar data and with the satellite times the same start and end points are selected in the steering angle data. The raw dataset with GPS and lidar data was already divided in pieces per participant, because the sensors were disconnected from the power supply after each participant. In Figure 4.1 the raw lidar data of one participant is visualised.

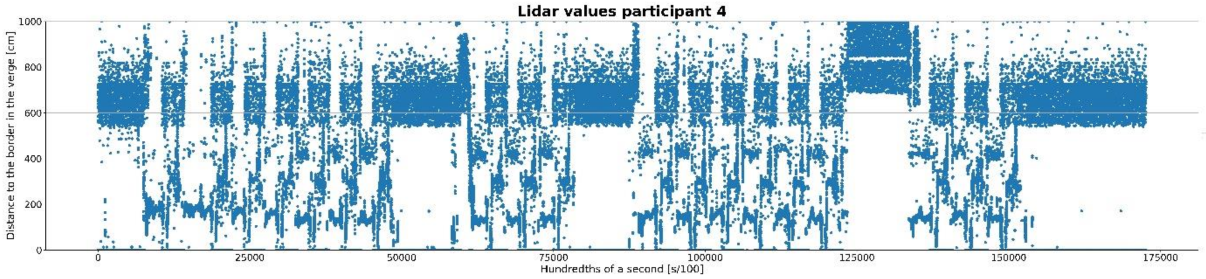

Figure 4.1: Raw lidar data of one participant

The first filtering criterion is excluding all lidar values that are not between 100 and 300 centimeter. The distance between the path edge and the boarding in the verge was 100 centimeter and the maximum path width is 200 centimeter, so all measurements on the track have to be values between 100 and 300 centimeter. Figure 4.2 shows the lidar data of one participant with this criterion applied.

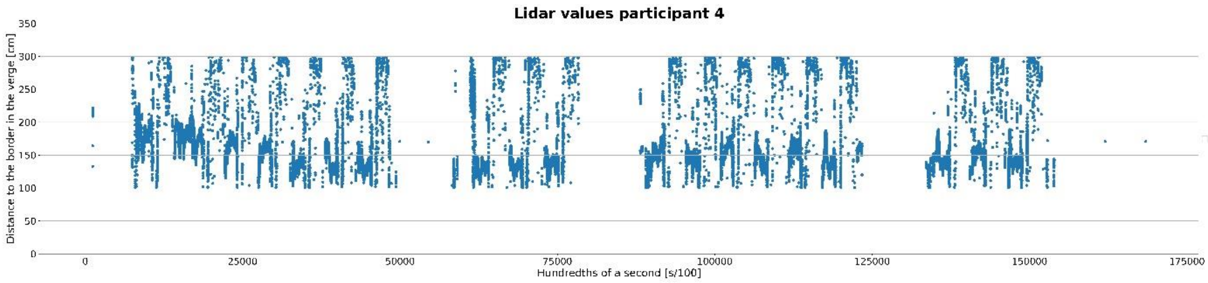

Figure 4.2: Filtered lidar data for values between 100 and 300 cm

Another filtering criterion is used to reduce the amount of noise in the data. The cycling angle that is recorded by the GPS is used for this criterion, because it clearly shows that the cyclists went back and forth on the same path (see Figure 4.3). The angle values higher than 240 correspond with the measurement direction. The values lower than 70 correspond with the return trip. Figure 4.4 shows the lidar data of one participant with both described criteria applied.

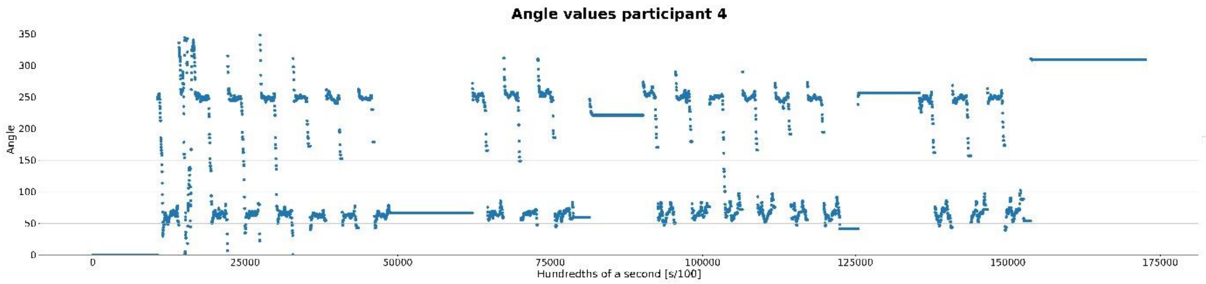

Figure 4.3: Angle data (GPS) of one participant

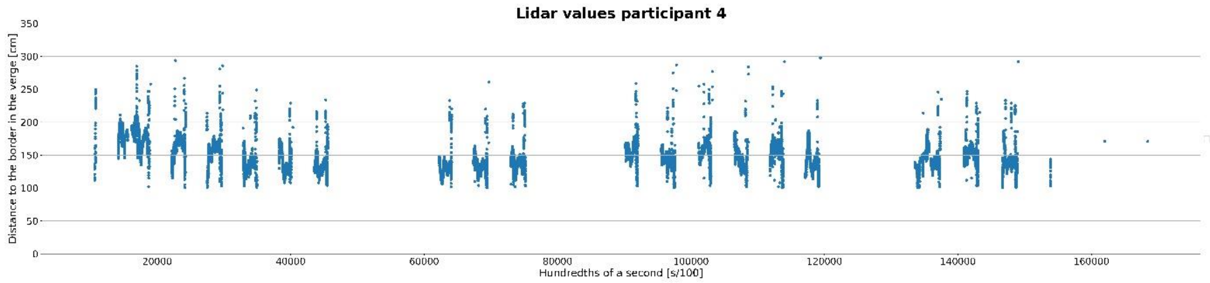

Figure 4.4: Filtered lidar data for values between 100 and 300 and angle values higher than 240

Based on this filtered dataset, the start and end points of the repetitions can be automatically selected by recognizing the gaps in time. Time gaps of 20 seconds or larger are used to identify when a new repetition starts. It takes approximately 20 seconds to complete the measurement track of 80 meters. Cycling back takes the same amount of time, but with the additions of cycling a bit further and turning around at both ends. Therefore, it can be assumed that the time gaps between the repetitions on the measurement track are slightly higher than 20 seconds.

Figure 4.5, Figure 4.6 and Figure 4.7 are examples of automatically selected tracks. In all tracks the start and end point selection can be improved, although the quality of the automated selection varies largely. Most automatically selected tracks are a good approximation of the actual track, like in Figure 4.5. In Figure 4.5 only the end point should be selected slightly earlier. In Figure 4.6 the track has some more noise and the end point selection is not accurate. For a few tracks the start or end point was quite far from the actual start or end point, like in Figure 4.7 where the first ¾ of the graph does not actually belong to the track. As described for these three examples, all tracks need a different adjustment to improve the selection of the start and end point, which might for example be explained by differences in human behaviour or sensor errors. Therefore, this latest improvement step is done manually.

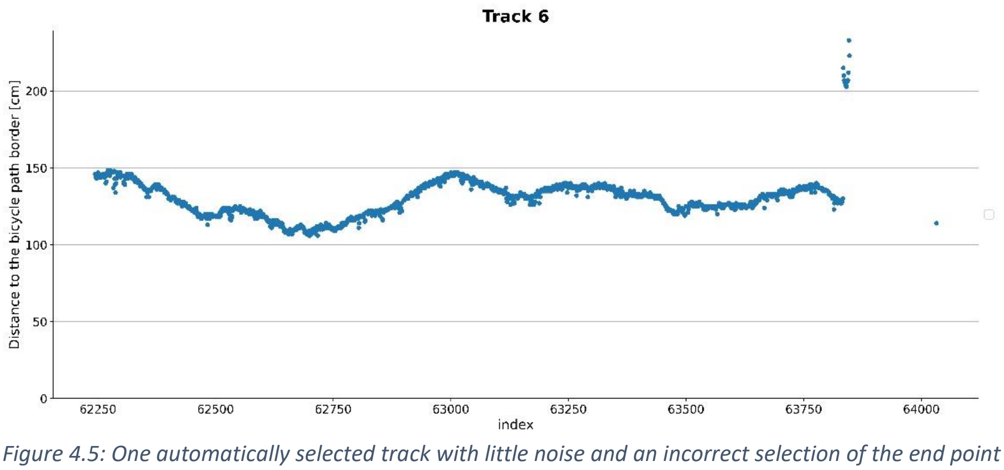

Figure 4.5: One automatically selected track with little noise and an incorrect selection of the end point

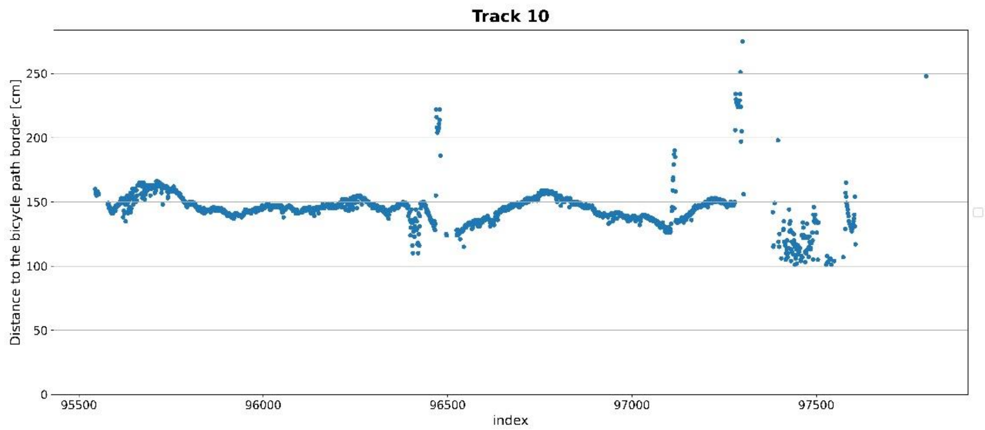

Figure 4.6: One automatically selected track with more noise and an incorrect selection of the end point

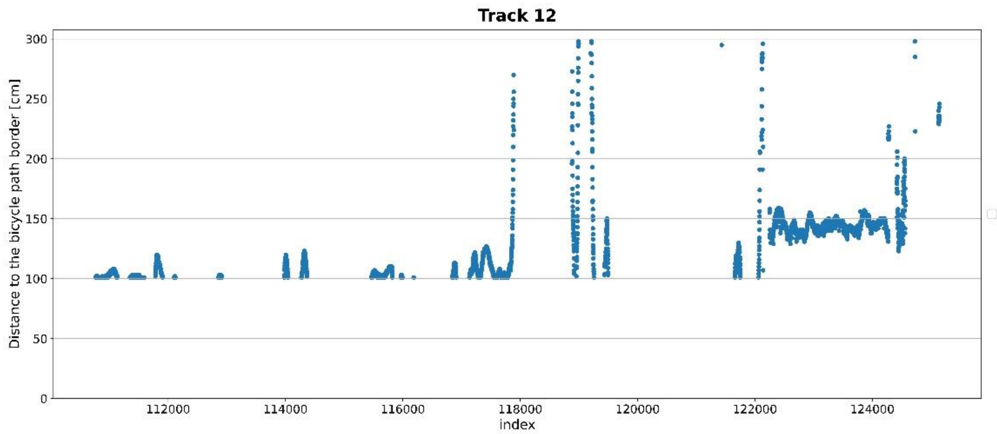

Figure 4.7: One automatically selected track with an incorrect selection of the start and end point

The tracks that could not be selected automatically, because GPS data was missing for these tracks were selected manually from the dataset with only a filter on lidar values between 100 and 300.

The track selection was checked with the speed data. Participants entered the measurement track while accelerating. These lower speeds at the start of the track might influence the results, therefore the start points of all tracks are changed. The lidar data doesn't show different patterns at lower or higher speeds, so the results of the lidar data won't be influenced by the track selection. The steering angle data does show differences for lower or higher speeds, so for the results of this data set, adjusting the selection of the start points is preferred. Based on literature a suitable boundary value is selected. In literature different phases of are described for accelerating on a bicycle. The first phase is the mounting phase, which is finished at a speed of about 5 km/h (Dubbeldam et al., 2017). This phase is followed by the harmonic cycling phase, which ends at a speed of 10 km/h (Dubbeldam et al., 2017). At speeds about 12 km/h the bicycle becomes self-stabilizing (Schwab et al., 2012). Not all participants reached a speed of 12 km/h, which made 12 km/h not a suitable boundary. The boundary value for the start points is set at the speed of 10 km/h, because all cyclists reached at least this speed as a constant speed and it is where Dubbeldam's phase of harmonic cycling ends.

4.3 Missing data

For two participants (1 and 22) the sensors stopped working halfway the experiment. For two other participants (13 and 14) the course of the experiment was a little different. On Wednesday morning the weather conditions were very wet compared to Tuesday, combined with a little extra wind this meant that a new method needed to be found to attach the white band of the movable path edge. This caused some time problems and a little improvisation was needed to collect data on all three different path widths of these two participants. Therefore, the predetermined sequence of setups is not fulfilled. The extra three rounds at the end of the experiment to check for learning effects were skipped due to lack of time.

Consequently, 4 out of 24 datasets are really different from what they should be. One dataset misses one track, because something went wrong when counting the number of repetitions that had been done, with the video material it was possible to determine which repetitions was skipped and therefore the data is still usable. The other 19 datasets are complete and followed the predetermined sequence of events. However, the GPS often needed some time to connect to the satellite, which causes some missing GPS data in the beginning of half of the datasets. The GPS data is needed to process and filter the other data. For example the angle data based on the GPS, is used for filtering the dataset and the speed data will be needed later on for converting time to distance along the track. For 13 participants the GPS data cannot be used to easily filter all the tracks out of the total files. Most of the time only the first 1-3 tracks miss the GPS data, so it is possible to use the GPS values for filtering the other tracks and select the first few tracks manually.

5

Steering behaviour on different path widths

The experiment was conducted, as described in section 3.2, to study the influence of bicycle path width on cyclists' lateral position and steering angle deviation. In this chapter the results of this experiment will be discussed. With the results of the experiment was tested whether cyclist cycle closer to the path edge on narrower bicycle paths and whether cyclists' steering angle rotation gets larger on narrower bicycle paths. This will lead to a conclusion on the influence of path width on steering behaviour variables. The influence of passing an oncoming cyclist on this behaviour on the different path widths will be discussed as well. The last variable of which the results are discussed in this chapter is cycling speed. The chapter will conclude with an analysis of the learning effect during the experiment.

5.1 Lateral position

Two hypotheses that had to be checked with the results of the experiment are related to the lateral position of cyclists. The lateral position measurements are done with a lidar sensor and filtered as described in section 4.2. Lateral position is measured from 0 at the right side of the path. The first hypothesis to check with the lateral position results is the hypothesis that cyclists cycle closer to the path edge on narrower bicycle paths than on wider bicycle paths. To compare the differences in lateral position between the different path widths, the lateral position results over time are aggregated to a median value for lateral position. The second hypothesis to check with the lateral position results is the hypothesis that when passing another cyclist, cyclists cycle closer to the path edge (i.e. the minimum distance to the path edge is smaller) than without passing another cyclist. To check this hypothesis, the minimum distance to the verge needs to be determined. Instead of the minimum value, the first percentile value (1% of the values is lower, 99% is higher) is used. The data still contains some small outliers and by using the first percentile value, the outcomes of the first percentile will fit best to the actual minimum. Most of the small outliers that are still in the data are values slightly higher than the actual lateral position, causing more outliers for the maximum value than for the minimum value. Therefore, the 95th percentile is used.

Figure 5.1 visualises the differences between minimum, median and maximum lateral position on the three path widths and the scenarios with the parked bicycle.

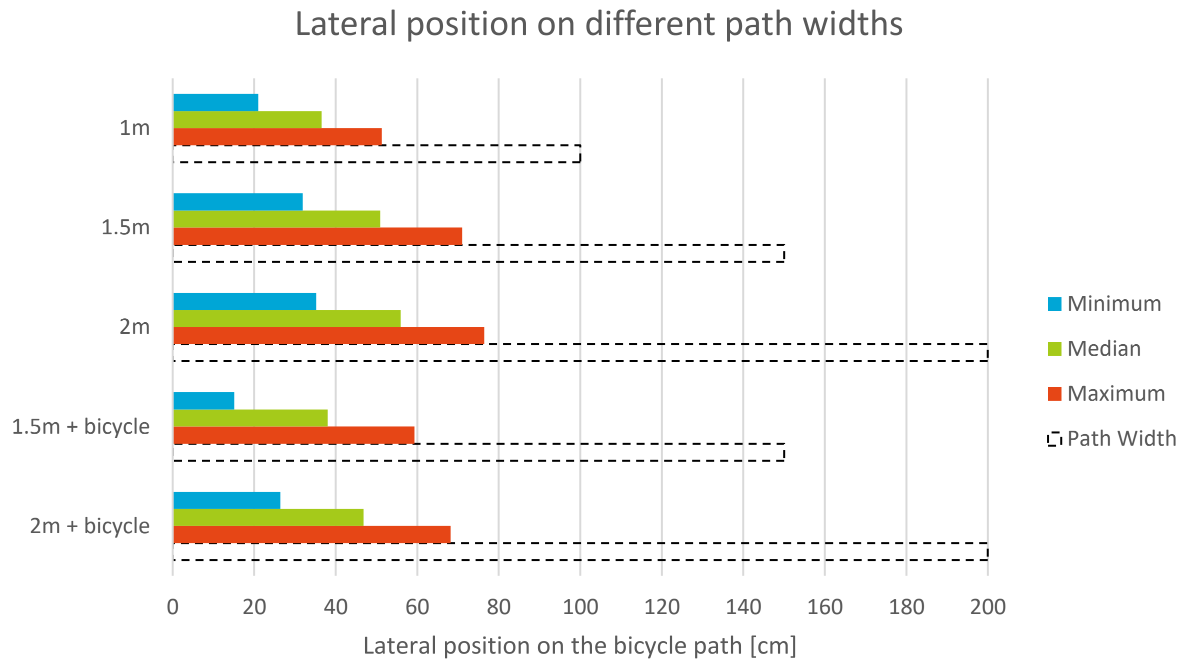

Figure 5.1: Lateral position for the different path widths with and without parked bicycle

Table 5.1 shows that the wider the bicycle path, the more distance cyclists keep to the path edge. The minimum, median and maximum show relatively similar differences between the different path widths. The difference in minimum, median and maximum lateral position is largest between the 1-meter wide path and the 1.5-meter wide path. The parked bicycle that simulated an oncoming cyclist reduced cyclists' lateral distance to the path edge. Cyclists did not only have a lower median distance to the path edge, the minimum distance kept to the path edge is also lower.

Table 5.1: Lateral position for the different path widths with and without simulated oncoming cyclist

	Median lateral position [cm]	*Standard Deviation of lateral position [cm]*	*Minimum distance to path edge [cm]**	*Maximum distance to path edge [cm]***
1 m	37.0	10.0	21.0	51.3
1.5 m	51.2	12.3	31.9	71.0
2 m	55.6	12.3	35.2	76.4
1.5 m + bicycle	38.2	14.8	15.1	59.3
2 m + bicycle	46.1	13.4	26.4	68.2

* For the minimum distance to the path edge the first percentile value is used
** For the maximum distance to the path edge the 95th percentile value is used

All these differences were tested on significance to draw conclusions from the results. The first hypothesis that is checked for statistical significance, is that cyclists cycle closer to the path edge on narrower bicycle paths. A one-way repeated measures ANOVA is conducted to see whether the median lateral distance is different for the different path widths. Mauchly's Test of Sphericity indicated that the assumption of sphericity has not been violated. The test results show that there is a significant effect of path width on lateral position ($F(2,130) = 65.346$, $p < 0.0005$). The next step is to identify for which scenarios the median lateral distance differs, which is done by a pairwise comparison of all five scenarios. As testing all pairs implies multiple tests, a Bonferroni correction was applied. Most of the pairs are significantly different from each other. Two pairs of scenarios do not have significantly different results. These pairs are the 1-meter wide path with the 1.5-meter wide path with oncoming cyclist and the 1.5-meter wide path and the 2-meter wide path with oncoming cyclist. This means that in the setups with a parked bicycle that simulated an oncoming cyclist, the distance people tend to keep from the path edge is similar to an empty path that is half a meter narrower.

The second hypothesis is whether the minimum distance to the path edge is smaller when passing an oncoming cyclist. A repeated measures ANOVA was performed to examine the differences in minimum lateral position for the 1.5-meter wide path with and without oncoming cyclist and the same was done for the 2-meter wide path with and without oncoming cyclist. The test results show that the difference in minimum lateral position between the 1.5-meter wide path with and without oncoming cyclist is significant ($F(1,67) = 111.834$, $p < 0.0005$). The difference in minimum lateral position is also significant for the 2-meter wide path with and without oncoming cyclist ($F(1,68) = 46.060$, $p < 0.0005$). It can be concluded that on narrow bicycle paths the minimum distance to the path edge is significantly lower when passing an oncoming cyclist. On 1.5-meter wide path the minimum distance to the path edge decreases with 17 centimeter and on a 2-meter wide path the minimum decreases with 9 centimeter.

5.2 Steering angle and speed

A hypothesis that can be checked with steering angle data, is whether the average steering angle gets larger when the bicycle path width gets narrower. And based on the speed data, the hypothesis that cyclists cycle faster on wider bicycle paths than on narrower bicycle paths, can be checked. These results of the steering angle are combined with results on average speed, because these relate to each other. As explained in section 2.2.2, the bicycle becomes self-stabilizing at speeds of 12 km/h or higher. At speeds lower than 12 km/h, balance control of the bicycle is more challenging, which might influence the deviation in steering angle.

Table 5.2: Steering angle and average speed on the different path widths and scenarios

	Average steering angle [degrees]	*Standard Deviation of steering angle [degrees]*	*Average speed [km/h]*
1 m	10.2	9.1	14.6
1.5 m	10.1	9.0	14.8
2 m	9.9	9.0	15.5
1.5 m + bicycle	10.3	9.2	15.4
2 m + bicycle	9.9	9.0	15.5

The measurement track used in the experiment was a straight track, which means the average steering angle is close to zero. To be able to compare the differences in size of steering movements, the averages of the absolute steering angle measurements, with negative values converted to positive values, are used. Table 5.2 shows the results of the average deviation from zero of the steering angle data per setup and the standard deviations. The differences are small and the standard deviation is high, which indicates that the differences are not statistically significant. The small differences in the average steering angle, show a slightly higher variation in steering angle and a slightly higher average deviation from zero on the 1-meter wide path and the 1.5-meter wide path with parked bicycle, which might indicate that these two scenarios are slightly more difficult to keep balanced on. A one-way repeated measures ANOVA was performed to test the differences on significance. Mauchly's Test of Sphericity indicated that the assumption of sphericity has not been violated. The test results show that there is not a significant effect of path width on steering angle ($F(2,118) = 0.037$, $p = 0.953$). The hypothesis that the average absolute steering angle gets larger when cyclists cycle on narrower paths, was rejected. A higher absolute steering angle was expected, because there is less space on narrow bicycle paths for deviations from your steering line, which was expected to cause more steering. A possible reason for the rejection of this hypothesis is that the increased steering did not result in a higher average absolute steering angle, but in a higher frequency of steering movements. Unfortunately the data is not accurate enough to determine the frequency of the steering movements.

The average speed for all scenarios is shown in Table 5.2 as well. The differences in speed between the setups are not large, but on the smaller paths the average speed was slightly lower than on the wider paths. These differences were tested on significance with the same one-way repeated measures ANOVA. Mauchly's Test of Sphericity indicated that the assumption of sphericity has not been violated. The test results show that there is a significant effect of path width on speed ($F(2,66) = 4.453$, $p = 0.015$). The hypothesis that cyclists cycle faster on wider bicycle paths was supported by the outcomes.

5.3 Multivariate regression analysis

A multivariate regression analysis is performed in order to find a relation between the different variables that were measured in the experiment and the lateral position of a cyclist. The set variables that were used are path width, average absolute steering angle, age, speed and gender. The R-square value of this multivariate regression is 0.532, which means that only 53% of the variability in lateral position can be explained by the entire set of independent variables. The sample size was not large enough for a significant result. This means that it is not possible to create a formula that predicts the lateral position based on path width, average absolute steering angle, age, speed and gender. However, the results give an indication of the relation between lateral position and these variables in this experiment.

Table 5.3: Results of multivariate regression analysis for lateral position

	Coefficient	*P-value*
Point of intersection	108.39	0.0001
Path Width [cm]	0.21	2.04×10^{-6}
Absolute average steering angle [deg]	- 0.52	0.0007
Age [years]	- 0.30	0.6981
Speed [km/h]	- 3.70	0.0026
Gender [0: male, 1: female]	- 9.46	0.0083

Table 5.3 shows the results of the multivariate regression analysis. The p-value of age is higher than 0.05, so age should be excluded. The age of the participants was very homogeneous, which is the most likely explanation for not finding a relation between age and lateral position with the results of this experiment. The other variables have p-values lower than 0.05 and can be included in the regression. The coefficient of path width shows that a wider path width results in a higher distance to the path edge, which corresponds to the results in earlier sections. A higher average absolute steering angle results in smaller distances to the path edge. This also corresponds to the findings in earlier sections, because the average absolute steering angle slightly increased on narrower bicycle paths (this differences were not significant) and the distance to the path edge is smaller on narrower bicycle paths. New insights from this multivariate regression are on speed and gender. Higher speeds seem to lower the distance to the path edge. An explanation might be that more experienced cyclists cycle faster and closer to the path edge, because they are less concerned about the risk of riding off the path. Female participants seem to have cycled closer to the path edge than male participants. An explanation for this difference in behaviour could be that women are generally more careful than men. However, that would mean that women focus more on the possibility of an oncoming cyclist that needs to be passed than on the risk of riding off the path, because the risk of riding off the path increases with smaller lateral distances. Another option is that it is coincidence and that the difference is related to the specific behaviour of the 11 men and 13 women that participated in the experiment.

5.4 Learning effect

The impact of a potential learning effect on the results was minimized by changing the order of events for each participant to balance out the order effects. However, for the interpretation of the results it is interesting to see whether there was a learning effect. Therefore, an additional analysis was performed.

In the Methodology section, it is explained that the bicycle used for the experiment had a large crate on the front of the bicycle. This increases the learning effect that might occur during the experiment. Learning effects might appear in this type of experiments, because participants get used to the experimental setup. To be able to test whether this learning effect existed or not, three repetitions were added at the end of the experiment for the same path width as where the participant started the experiment with. The results for the first three and last three repetitions were compared to determine whether a learning effect occurred or not. Table 5.4 shows the average results for the first three and last three repetitions per path width for both lateral position and steering angle measurements. An important side note to these results, is that in contrast to all other results discussed in this chapter, the results of the different path width cannot be compared with each other by a within subject comparison. For all three path widths the sample consists of different participants, which makes the sample sizes smaller and effects of individual participants cannot be excluded.

Table 5.4: Learning effect measurements for lateral position and steering angle

	Median lateral position [cm]		*Average steering angle deviation [degree]*	
	First three	*Last three*	*First three*	*Last three*
1 m	39.7	34.3	11.7	8.2
1.5 m	53.0	45.5	11.0	8.9
2 m	64.8	65.1	9.4	8.2

The differences between the first three and last three repetitions per path width are tested on significance. The learning effect in the lateral position data is significant for the 1-meter wide path and the 1.5-meter wide path (1m: $F(1,17) = 21.545$; $p < 0.0005$ & 1.5m: $F(1,20) = 7.886$; $p = 0.011$). For the 2-meter wide path, there is not a significant learning effect (2m: $F(1,20) = 0.018$, $p = 0.893$).

The same statistical tests are performed with the steering angle data. For all path widths the learning effect is significant in the steering angle data (1m: $F(1,15) = 28,084$; $p < 0.0005$ & 1.5m: $F(1,18) = 22,653$; $p < 0.0005$ & 2m: $F(1,19) = 9,636$; $p = 0.006$). The findings based the lateral position data indicate that there was no learning effect on the 2-meter wide path, while the findings based on the steering angle data indicate the opposite. It could be that the cyclists needed to get used to the bicycle on the 2-meter wide path and therefore had slightly higher steering angle deviations, but did not felt the urge to use this better control over the bicycle in the last three repetitions to cycle closer to the path edge.

There has been a learning effect in the experiment and the learning effect seems to get larger, when the bicycle path gets narrower. The differences in learning effect might be an indication on how challenging the other circumstances are apart from the new bicycle. In this case the path width is the only thing that changes in the circumstances, so it can be seen as an indication of smaller paths being more challenging. If the difference in steering angle on the 2-meter wide path is assumed to be the common part in the differences caused by the bicycle. The additional difference in steering behaviour (0.9 degree on the 1.5-meter wide path and 2.3 degree on the 1-meter wide path) is caused by the higher difficulty of the path width. However, the sample sizes for each path width were very small and the learning effect on each path width was analysed with results of different groups of participants. Therefore, the effects of behaviour of individual participants cannot be excluded.

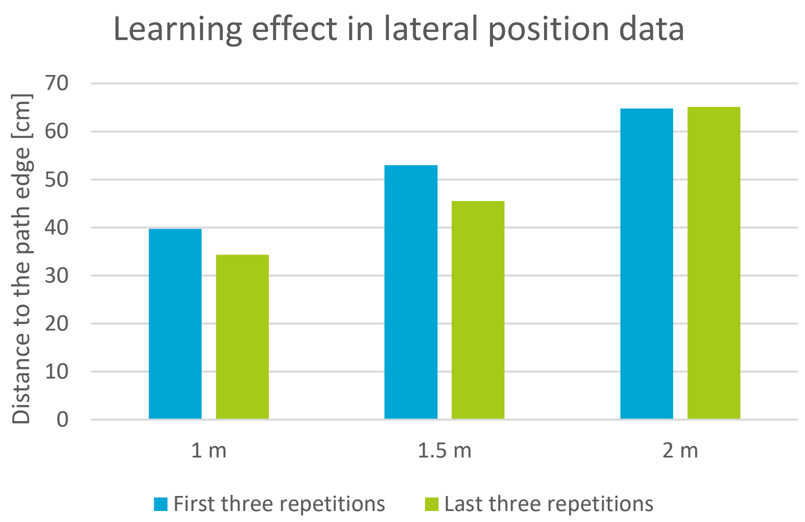

Figure 5.2: Learning effect in lateral position data for the three different path widths

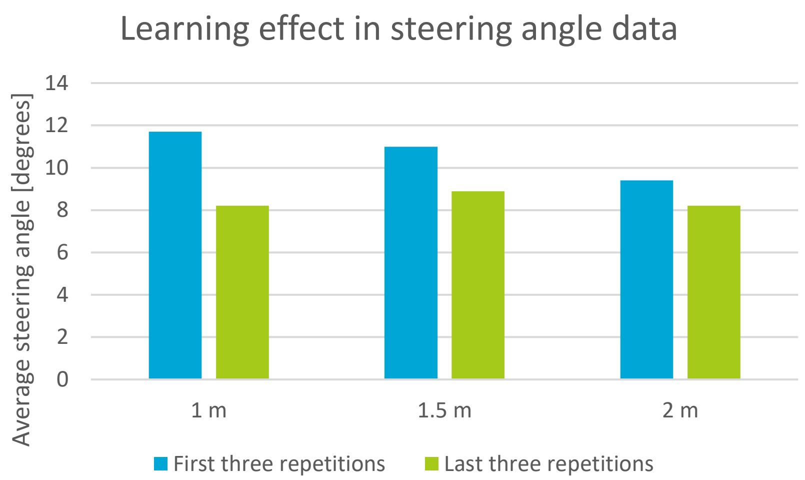

Figure 5.3: Learning effect in steering angle data for the three different path widths

5.4 Conclusion

From the experiment results presented in this chapter, different conclusions can be drawn. Cyclists cycle significantly closer to the path edge on narrower bicycle paths (55.6 centimeter on a 2 meter wide path and 37 centimeter on a 1 meter wide path) and there are no significant differences in average steering angle deviation for the different path width. This shows how the steering behaviour variables considered in this study relate to the width of bicycle paths. The outcomes of the speed measurements support the hypothesis that there is a relation between speed and bicycle path width. Participants entered the measurement track at very low speeds and were still accelerating, which influences the average speed. Therefore, no conclusion can be drawn on the relation between speed and bicycle path width. Passing an oncoming cyclist influences the relation between steering behaviour and bicycle path width. Participants cycle closer to the path edge when there is an oncoming cyclist on the bicycle path. The lateral position results for the scenarios with an oncoming cyclist are comparable to a scenario of a bicycle path that is half a meter narrower but without oncoming cyclist. Not only the average lateral position changes, the minimum distance to the path edge also becomes significantly smaller in scenarios with an oncoming cyclist on the path. The sample size was not large enough for a significant result with a multivariate regression analysis.

There has been a learning effect in the experiment and the learning effect seems to get larger, when the bicycle path gets narrower. The differences in learning effect might be an indication on how challenging the other circumstances, in this case the path width, are apart from the new bicycle. However, the sample sizes that were used to determine the learning effect for each path width were very small and consist of a different group of participants. Therefore, the effects of individual behaviour on the results for the learning effect on different path widths cannot be excluded. The learning effect does not influence the results, because order effects were already balanced out in the experiment order of events.

6

Perceived safety and behaviour

This chapter describes the experience of the participants. The perceived safety while cycling along the different path widths will be discussed as well as the relation between perceived lateral position and actual lateral position.

6.1 Perceived safety

In a questionnaire participants were asked to indicate whether the path width was sufficient to safely cycle alone and whether the path width was sufficient to safely pass an oncoming cyclist. A 5-level likert scale was used for the answer options of this question. The higher the score, the higher the level of perceived safety is. The most answered level of the likert scale on each question is shown in Table 6.1.

Table 6.1: Perceived safety results on a 5-level likert scale

	Without oncoming cyclist		*With oncoming cyclist*	
	Mode likert-scale score	*Percentage of participants that gave a score 4 or 5*	*Mode likert-scale score*	*Percentage of participants that gave a score 4 or 5*
1 m	4	63 %	2	0 %
1.5 m	5	100 %	3.5	42 %
2 m	5	100 %	5	96 %

In this case only scores 4 and 5 on the likert-scale indicate that the path is perceived safe by the participants. Therefore, this is used as a threshold value. Table 6.1 indicates the mode likert-scale score, which is the score that is most often chosen by the participants and the percentage of participants that gave a score 4 or 5 for the scenario.

When cycling on the path without oncoming cyclists, the 1.5-meter wide path and the 2-meter wide path are unanimously considered to be safe, all participants gave a score 4 or 5. The 1-meter wide path without oncoming cyclist was considered safe enough by almost two third of the participants. The other participants gave this path a score 2 or 3 and the average likert-scale score is below 4.

When oncoming cyclists are added to the scenario the differences in perceived safety are larger. The 1-meter wide path is considered unsafe by all participants. The opinion on the safety of the 1.5 meter path is divided, which results in a neutral overall safety perception. An overall neutral opinion, means that there are both people who consider it unsafe and those who consider it safe. The 2 meter path is considered safe to pass an oncoming cyclist by most participants. Only one response was neutral. Figure 6.1 shows the distribution of the answers for the situation with an oncoming cyclist.

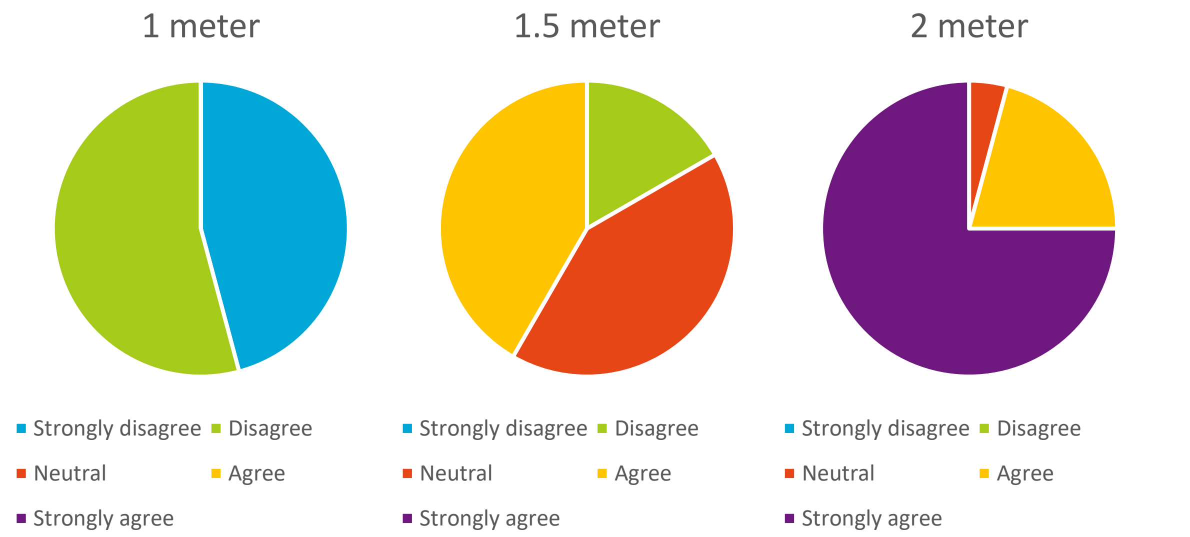

Figure 6.1: Answers on the question whether the bicycle path width is safe to pass another cyclist

6.2 Perceived lateral position

In the questionnaire that participants completed after the experiment, they were asked to indicate what their lateral position would be for different scenarios. The setups of the experiment are used as scenarios together with the 1-meter wide path with oncoming cyclist setup. In the questionnaire participants chose a box that indicates a range of 10 centimeter. In Table 6.2 the range that the participants chose on average is compared to the average actual lateral position. For the 1.5-meter wide path and the 2-meter wide path the actual and perceived lateral position correspond, these values are coloured green in the table. Overall, we can conclude that the participants were quite aware of their own steering behaviour in terms of lateral position as the actual lateral position during the experiment fell in the range indicated in the questionnaire for most scenarios. On the 1-meter wide path, people cycled closer to the path edge than they thought they did.

Table 6.2: Comparison of average actual lateral position and average perceived lateral position

	Actual lateral position [cm]	*Perceived lateral position range [cm]*
1 m	37.0	40-50
1.5 m	51.2	50-60
2 m	55.6	50-60
1 m + bicycle	-	10-20
1.5 m + bicycle	38.2	30-40
2 m + bicycle	46.1	40-50

6.3 Conclusion

The questionnaire results presented in this chapter were used to examine the perception of the different path widths and answer the sub question "*How do cyclists experience the different path widths?*". With no oncoming cyclists on the path 1.5-meter wide path and 2-meter wide path were both considered safe. The opinion on the 1-meter wide path without oncoming cyclist varied and was neutral on average. With an oncoming cyclist on the path, the 1-meter wide path was considered unsafe, the opinion on a 1.5-meter wide path was neutral and only the 2-meter wide path is considered safe by all participants except for one.

The participants of the study were very aware of their lateral position on the different bicycle path widths. From these results the conclusions can be drawn that cyclists are aware of their position on a bicycle path and bidirectional bicycle paths of 1-meter or 1.5-meter wide are not considered safe.

7

Discussion and conclusion

The number of single bicycle crashes has increased over the past decades. One of the causes of single bicycle accidents is riding off a bicycle path. Riding close to the path edge, increases the likelihood to ride off the path. This study focussed on the impact of bicycle path width on lateral steering behaviour of cyclists on narrow solitary bidirectional bicycle paths. An experiment was conducted to isolate the effect of path width and measure the influence of path width on cyclists' steering behaviour.

7.1 Discussion

This study aimed to address the gap in knowledge regarding steering behaviour of cyclists on narrow bidirectional bicycle paths to support policy makers and practitioners involved in updating design guidelines. The research specifically studied the impact of bicycle path width on the steering behaviour of cyclists. In this paragraph the findings of the research are discussed. First the outcomes of testing the hypotheses are discussed and interpreted. This is followed by a discussion on the transferability of the findings to real-life traffic conditions. The discussion will be concluded by comparing this research to previous studies and the guidelines for bicycle path width.

It was hypothesised that cyclists cycle closer to the path edge on narrower bicycle paths than on wider bicycle paths. A reduced distance to the path edge, increases the risk of cycling off the path, which increases the risk on verge accidents. Based on the results of the experiment, cyclists cycle at a closer distance to the path edge on narrower bicycle paths thereby confirming the hypothesis.

It was hypothesised that while passing another cyclist, cyclists cycle closer to the path edge (i.e. the minimum distance to the path edge is smaller) than without passing another cyclist. In addition to the comparison between the three different path widths, there were two scenarios where an oncoming cyclist was simulated to test this hypothesis. The results of the scenarios with a parked bicycle as simulation of an oncoming cyclist were similar to the outcomes of an empty path that is half a meter narrower. This is most likely an effect of simulating the oncoming cyclist with a parked bicycle. This bicycle's back wheel was parked 35 cm from the path edge and blocked a little more, because a parked bicycle does not stand upright, but bends over a little. When cyclists pass each other, they don't like to touch steering wheels, so they keep a little bit more distance to one another, which is called shy distance. It is possible that the distance blocked by the bicycle together with this shy distance is close to 50 cm, which might explain the similarities in the results of the paths with parked bicycle and the paths without parked bicycle that are half a meter narrower. In reality, the position of an oncoming cyclist is not as constant as it was in the experiment and the oncoming cyclist might take more space than the parked bicycle that was used in this experiment. Even this scenario with a completely predictable simulated oncoming cyclist yielded a very small minimum distances to the path edge. These results support the hypothesis that when passing another cyclist, the minimum distance to the path edge is smaller.

It was hypothesised that the average steering angle rotation is larger on narrower bicycle paths. The results do not support this hypothesis. The average steering angle rotation was not significantly different for the five setups. It was found that the steering angle rotation in the first few repetitions of the experiment was significantly larger than in the last few repetitions. The most likely explanation for this difference is the heavier steering wheel of the instrumented bicycle that participants had to get used to.

It was hypothesised that cyclists cycle faster on wider bicycle paths. This hypothesis was supported by the outcomes, but cannot be proven with the results of this experiment. There were a few limitations in the speed measurements (see section 7.3). Most important limitation is that participants were still accelerating when they entered the measurement tracks, which influences the average speed, even though all speeds below 10 km/h were excluded. In order to draw conclusions regarding the relation between speed and bicycle path width speed data is needed of a longer distance of cycling after reaching full speed. The effect that is seen in the outcomes might be behavioural adaptation to compensate for the more risky environment that the smaller distances to the path edge create by lowering speed.

In both the steering angle data as well as the lateral position data, a learning effect occurred. The learning effect was larger on the narrower paths, which might be an indication of the narrower paths already being more challenging. It is possible that the mental workload required to cycle on a narrow path was harder to combine with the mental workload of getting used to a new bicycle. This assumption is supported by the results on perceived safety. The wider paths were considered safer by the participants, especially for a bidirectional bicycle path.

7.1.1 Transferability of the findings to real-life traffic conditions

The experimental conditions were designed such that there were no factors that may cause cyclists to maintain a greater distance to the path edge than they would in real-life traffic conditions. It was easy and safe to ride off the path, ride over the verge and return to the path, while in real-life conditions the verge may be bumpy, slippery or there may be a kerb between the path and a side walk along it. Next to the forgiving path edge, there were no obstacles close the path edge and the oncoming cyclist was simulated by a parked bicycle, which is far more predictable than an actual oncoming cyclist. The selected experimental conditions represent the safest possible conditions based on current knowledge.

Also, the participants were all students who were young and very experienced cyclists. One of the trends in bicycle use is the growing number of older cyclists. Distance cycled by elderly increased by 12% in the period 2005-2017 (Harms & Kansen, 2018). Older cyclists are expected to have slightly different steering behaviour. Because elderly are more susceptible for the corona virus, we did not invite them to participate in the experiment.

Only one type of bicycle is used in this experiment, while the variety in bicycle types is growing in real-life traffic conditions. Next to the normal bicycle, mopeds, e-bikes, racing bicycles and cargo bicycles add to the differences in speed, width and weight of the bicycles on the cycling infrastructure. The larger variation in speed increases the number of overtaking manoeuvres, a larger variation in bicycle widths influences the required space on the infrastructure and the larger variation in bicycle weight influences the consequences of accidents.

The experiment is conducted in the Netherlands. The bicycle usage and cycling behaviour in the Netherlands differs from other countries, so it would be interesting to know whether the findings of this study would apply in other countries as well. Three participants of the experiment had a non-Dutch nationality, which is not enough to draw any conclusions. However, the impression is that experience is more important than nationality. The non-Dutch participants in this experiment lived and cycled for at least one year in the Netherlands and their results seem to be similar to the results of the Dutch participants.

The findings on the learning effect could be partly translated to real-life situations. The experimental setup was different from a real-life situation, which caused a large part of the learning effect. This indicates that familiarity with a situation helps. However, the size of the learning effect cannot be translated to real-life situations, because the difference of the less common situations in real life compared to a known situation will not be the same. Another thing that can be translated to real-life conditions is the finding that the learning effect seems to be larger on narrower bicycle paths.

To conclude this section, the results of the experiment are transferable to real-life conditions, but do not include all the variety in infrastructural conditions, cyclist ages and bicycle types. The greater variety in real-life traffic conditions is likely to increase the required bicycle path width. The fact that the learning effect seems to be larger on narrower bicycle paths supports a higher required bicycle path width as well, because when unfamiliar situations occur, this has a larger influence on cyclists' steering behaviour on narrower bicycle paths. The findings on the learning effect indicate in general that familiarity with situations is helpful.

7.1.2 Relating the findings to previous studies

In section 2.3.1 previous studies where lateral position was measured, have been discussed. In Figure 7.1 the results of the current study are compared to results of the previous studies. Only studies that indicated the width of the path on which these measurements are done, could be included. When comparing the lateral position results of the different studies, it is important to consider the differences in how these measurements were done. The lateral position results of the studies of Jelijs (2020) and de Goede (2013) were all measured on different bicycle paths with slightly different characteristics. The current experiment measured all three results on the same bicycle path. Still, Figure 7.1 gives an indication of the relation between bicycle path width and lateral position of cyclists.

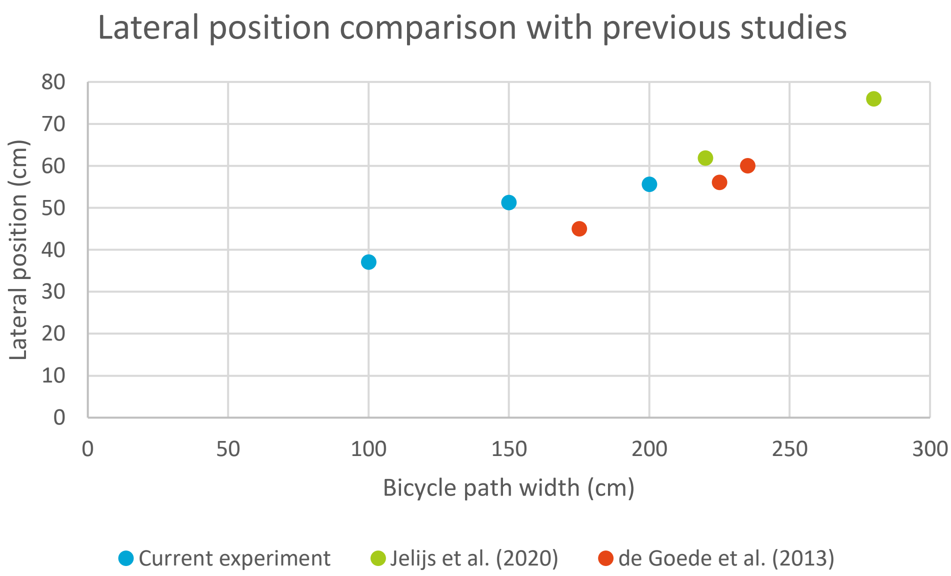

Figure 7.1: Lateral position results related to lateral position measurements of previous studies

7.1.3 Relating the findings to CROW guidelines

Given the differences in the lateral position, perceived safety, learning effect and the minimum lateral position during a passing manoeuvre the effectiveness of the guidelines in terms of road safety could be questioned. Current guidelines of the CROW prescribe a minimum width of 1.5 meter for solitary bidirectional bicycle paths and a minimum width of 2 meter for bidirectional bicycle paths alongside a road. The results of the experiment show that a 2-meter wide path is significantly safer than a 1.5-meter wide path owing to greater maintained distance to the verge on wider bicycle paths. Considering the increasing number of single bicycle accidents and the fact that cyclists may maintain less distance to the path edge in real-life conditions than in this experiment, it is recommended to raise the minimum width of solitary bidirectional bicycle paths to a minimum of 2 meter. Moreover, CROW advises to apply 1.5-meter wide bicycle paths only with a forgiving path edge and verge. However, in real-life traffic conditions this requirement is often not met and there are often other conditions that may compromise safety such as narrow curves, height differences in hilly terrain, uneven road surface and the like. These conditions are particularly present at solitary bicycle paths build for recreational cycling.

7.2 Conclusion

Based on the literature review, lateral position of the cyclists on a bicycle path and steering angle movement turn out to be the most often considered steering behaviour variables that are related to the required lateral space of the cyclist. Factors that influence the steering behaviour are also derived from literature. Infrastructural characteristics that influence steering behaviour are road surface, line markings, path edge, obstacles and path width. External factors like weather, day of the week, time of the day influence the steering behaviour as well. Visibility and characteristics of the cyclists, such as gender, experience and age, also affect steering behaviour.

From the experiments, the following conclusions can be drawn. Firstly, cyclists cycle significantly closer to the path edge on narrower bicycle paths. Secondly, there are no significant differences in average steering angle deviation for the different path widths. Thirdly, the outcomes of the speed measurements support the hypothesis that there is a relation between speed and bicycle path width. Participants entered the measurement track at very low speeds and were still accelerating, which influences the average speed. Therefore, no conclusion can be drawn on the relation between speed and bicycle path width. Fourthly, passing an oncoming cyclist influences the relation between steering behaviour and bicycle path width. Participants cycle closer to the path edge when there is an oncoming cyclist on the bicycle path. The lateral position results for the scenarios with an oncoming cyclist are comparable to a scenario of a bicycle path that is half a meter narrower but without oncoming cyclist. Not only the average lateral position changes, the minimum distance to the path edge also becomes significantly smaller in scenarios with an oncoming cyclist on the path.

A questionnaire was used to examine the perception of the different path widths. Without oncoming cyclists on the path, the 1.5-meter wide path and the 2-meter wide path are considered safe. The opinion on the 1-meter wide path is neutral. When there would be an oncoming cyclist on all path widths, the 1-meter wide path was considered unsafe, the opinion on a 1.5-meter wide path is neutral and only the 2-meter wide path is considered safe. The participants of the study were also very aware of their lateral position on the different bicycle path widths. It can be concluded that cyclists are aware of their position on a bicycle path and bidirectional bicycle paths of 1-meter or 1.5-meter wide are not considered to be safe.

The experimental results show that cyclists cycle significantly closer to the path edge on narrower bicycle paths and when passing an oncoming cyclist the minimum distance to the path edge is very small. Cycling closer to the path edge increases the risk of riding off the bicycle path, which affects safety. The results of the questionnaire supported this conclusion, because the 1-meter and 1.5-meter wide paths were not considered safe by the participants.

The main research question is "*What is the influence of the width of bidirectional bicycle paths on cyclists' steering behaviour?"*. Based on the results of the research it can be concluded that lateral position is related to the width of bidirectional bicycle paths, while steering angle rotation is not related to the width of bicycle paths. The distance kept to the path edge decreases when the bicycle path width decreases.

With the knowledge gained from the study, the current guideline of a minimum width of 1.5 meter for solitary bidirectional bicycle paths could be questioned. The study clearly shows that a 2-meter wide path is safer than a 1.5-meter wide path, but choosing a minimum width and level of safety remains a policy decision.

7.3 Research limitations

To our best knowledge, this is the first experimental study on the relationship between cyclists' steering behaviour and path width. Experimental research on this issue is important because it allows for the establishment of causal relationship. However, it is important to be aware of limitations of the study. The setup of the experiment may not completely resemble real-life traffic conditions and may influence how the results should be interpreted.

First of all, the bicycle used in the experiment is slightly different from a normal bicycle. The measurement techniques that are added to the bicycle need a power supply, which is stored in a basket on the steering wheel. This makes the steering wheel heavier than that of a normal bicycle. This might have influenced the average steering angle. It is not possible to precisely indicate this effect on the results.

Part of the measurements were done with a GPS, the accuracy and consistency of the GPS are a limitation of the study. The accuracy of the measurements is not high and the time the GPS needed to connect to the satellite was inconsequent. This resulted in some missing data of the first repetitions for half of the participants and it complicated automating the data filtering process and the synchronisation of the two datasets.

Interpreting the speed results was not only complicated by the missing GPS data and the lower accuracy of speed from a GPS, it also turned out that most of the participants did not reach a constant speed before entering the measurement track. Therefore, all the pieces of the tracks where the speed was below 10 km/h are excluded. Excluding the speeds below 10 km/h ensures that the low speeds do not influence the other results, for example the steering angle results, and it improves the results for average speed. Still, there are differences in the time participants needed to accelerate and how long they have been on a constant speed. This needs to be considered when drawing conclusions based on the speed values and makes the results based on the speed data less reliable. Excluding all datapoints with speeds below 10 km/h did not cause an increase in measurement length differences between repetitions.

7.4 Practical recommendations

The conclusion of this study gives new insights in the steering behaviour of cyclists on narrow bicycle paths, but it also raises new questions on the topic. This section formulates possible improvements that could be used to strengthen the study design in future research.

The accuracy of the speed measurements could be improved by using a cycling computer that measures speed and distance using the circumference of the wheel. This would make it easier to acquire accurate speed and location results, where other results can be related to. It would also be better to create a longer track to accelerate, so participants finished accelerating when entering the measurement track. If it is possible on the instrumented bicycle, attaching the power supplies on the luggage carrier on the back wheel is a better choice. In this position it would influence the steering behaviour of the cyclist less and a smaller learning effect is expected.

The results of this study point out that the current guidelines on bicycle path width should be reconsidered. The study clearly shows that a 2-meter wide path is safer than a 1.5 meter path, so these results suggest to change the minimum path width of solitary bidirectional bicycle paths.

7.5 Future research

Future research can focus on real-life situations to define the sizes of the effects of different age groups, different bicycle types and different infrastructure. Another option is to collect more accurate steering angle data, to find out whether the frequency of the steering angle is influenced by path width. Both would contribute to an even better understanding of the steering behaviour of cyclists on narrow bicycle paths and make it possible to strengthen the conclusions.

Another option for future research on this topic might be to have a look at the distance used to anticipate on an oncoming cyclist and how this relates to bicycle path width. This could be done with the data collected in this study or with newly collected data. A potential method to analyse this anticipation distance is to use the first timestep before passing the oncoming cyclist where the participant cycles at his average lateral distance to the path edge. The distance between the location of the participant and the location of the oncoming cyclist on this specific timestep can then be used as the anticipation distance. It represents the distance to an oncoming cyclist when the participant starts leaving the normal steering line in reaction to this oncoming cyclist.

New research may also elaborate the concept of ‘peak hour bicycle traffic intensity’ used in guidelines as recreational solitary bicycle paths experience peak intensities at different moments in time than bicycle paths in urban areas used for commuting. An important question with regard to bicycle path width and safety is the amount of encounters a peak results in.

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Appendix A. Experiment order of events

The order of events during the experiment for each participant. Only events of which data is collected are given. White spaces are left when data is missing. In 4.3 Missing data is explained what the reasons are for the missing data.

1	2	3	4	5	6
1.5m	1.5m	1.5m	1.5m	1m	1m
1.5m+bicycle	1.5m	1.5m	1.5m	1m	1m
1.5m	1.5m	1.5m+bicycle	1.5m	1m	1m
1.5m	1.5m+bicycle	1.5m+bicycle	1.5m+bicycle	1.5m	2m
1.5m+bicycle	1.5m+bicycle	1.5m+bicycle	1.5m+bicycle	1.5m+bicycle	2m
1.5m+bicycle	1.5m+bicycle	1.5m	1.5m+bicycle	1.5m	2m
2m	1m	2m	1m	1.5m+bicycle	2m+bicycle
2m	1m	2m+bicycle	1m	1.5m	2m+bicycle
2m+bicycle	1m	2m	1m	1.5m+bicycle	2m+bicycle
	2m	2m+bicycle	2m	2m	1.5m
	2m	2m+bicycle	2m+bicycle	2m	1.5m+bicycle
	2m+bicycle	2m	2m	2m+bicycle	1.5m+bicycle
	2m+bicycle	1m	2m+bicycle	2m	1.5m
	2m	1m	2m	2m+bicycle	1.5m+bicycle
	2m+bicycle	1m	2m+bicycle	2m+bicycle	1.5m
	1.5m	1.5m	1.5m	1m	1m
	1.5m	1.5m	1.5m	1m	1m
	1.5m	1.5m	1.5m	1m	1m

7	8	9	10	11	12
1m	1m	2m	2m	2m	2m
1m	1m	2m+bicycle	2m+bicycle	2m	2m
1m	1m	2m+bicycle	2m+bicycle	2m+bicycle	2m+bicycle
1.5m	2m	2m+bicycle	2m	2m+bicycle	2m+bicycle
1.5m	2m+bicycle	2m	2m	2m+bicycle	2m
1.5m+bicycle	2m+bicycle	2m	2m+bicycle	2m	2m+bicycle
1.5m+bicycle	2m	1.5m	1m	1.5m	1m
1.5m	2m+bicycle	1.5m+bicycle	1m	1.5m+bicycle	1m
1.5m+bicycle	2m	1.5m+bicycle	1m	1.5m	1m
2m	1.5m	1.5m	1.5m	1.5m	1.5m
2m+bicycle	1.5m	1.5m	1.5m+bicycle	1.5m+bicycle	1.5m
2m	1.5m+bicycle	1.5m+bicycle	1.5m+bicycle	1.5m+bicycle	1.5m+bicycle
2m	1.5m	1m	1.5m+bicycle	1m	1.5m+bicycle
2m+bicycle	1.5m+bicycle	1m	1.5m	1m	1.5m+bicycle
2m+bicycle	1.5m+bicycle	1m	1.5m	1m	1.5m
1m	1m	2m	2m	2m	2m
1m	1m	2m	2m	2m	2m
1m	1m	2m	2m	2m	2m

13	14	15	16	17	18
1m		1m	1m	1.5m	1.5m
1m		1m	1m	1.5m+bicycle	1.5m+bicycle
1m		1m	1m	1.5m	1.5m+bicycle
1.5m	1.5m	2m	2m	1.5m+bicycle	1.5m
1.5m	1.5m	2m+bicycle	2m	1.5m	1.5m+bicycle
1.5m	1.5m	2m+bicycle	2m+bicycle	1.5m+bicycle	1.5m
1.5m+bicycle	1.5m+bicycle	2m	2m+bicycle	2m	1m
1.5m+bicycle	1.5m+bicycle	2m	2m	2m	1m
1.5m+bicycle	1.5m+bicycle	2m+bicycle	2m+bicycle	2m+bicycle	1m
2m	2m	1.5m	1.5m	2m+bicycle	2m
2m	2m	1.5m	1.5m+bicycle	2m+bicycle	2m
2m	2m	1.5m+bicycle	1.5m	2m	2m+bicycle
2m+bicycle	2m+bicycle	1.5m+bicycle	1.5m+bicycle	1m	2m+bicycle
2m+bicycle	2m+bicycle	1.5m	1.5m+bicycle	1m	2m
2m+bicycle	2m+bicycle	1m	1.5m	1m	2m+bicycle
	1m	1m	1m	1.5m	1.5m
	1m	1m	1m	1.5m	1.5m
	1m		1m	1.5m	1.5m

19	20	21	22	23	24
1.5m	1.5m	2m	2m	2m	2m
1.5m	1.5m	2m	2m	2m+bicycle	2m+bicycle
1.5m+bicycle	1.5m+bicycle	2m+bicycle	2m	2m	2m+bicycle
1.5m+bicycle	1.5m	2m	2m+bicycle	2m	2m
1.5m	1.5m+bicycle	2m+bicycle	2m+bicycle	2m+bicycle	2m+bicycle
1.5m+bicycle	1.5m+bicycle	2m+bicycle	2m+bicycle	2m+bicycle	2m
2m	1m	1.5m	1m	1.5m	1m
2m+bicycle	1m	1.5m+bicycle	1m	1.5m+bicycle	1m
2m	1m	1.5m+bicycle	1m	1.5m	1m
2m+bicycle	2m	1.5m		1.5m	1.5m
2m+bicycle	2m+bicycle	1.5m		1.5m+bicycle	1.5m
2m	2m	1.5m+bicycle		1.5m+bicycle	1.5m+bicycle
1m	2m+bicycle	1m		1m	1.5m+bicycle
1m	2m	1m		1m	1.5m+bicycle
1m	2m+bicycle	1m		1m	1.5m
1.5m	1.5m	2m		2m	2m
1.5m	1.5m	2m		2m	2m
1.5m	1.5m	2m		2m	2m

Appendix B. Questionnaires

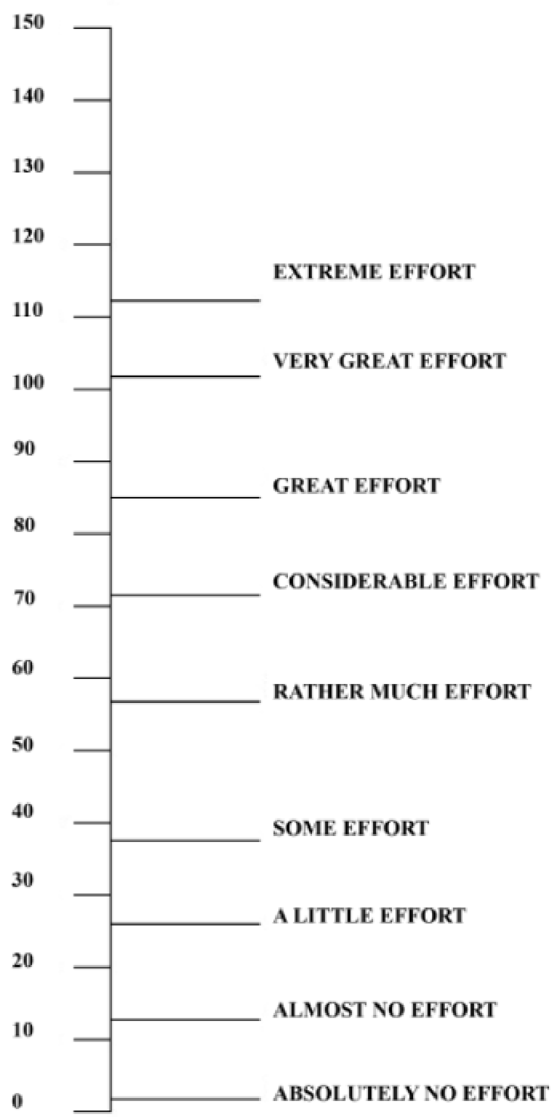
Questions asked on experiment location

After completing the repetitions required for a certain path width the participants are asked three questions while the path width is changed.

Width: 1 meter
1. The width was sufficient for me to cycle safely ◯ Strongly agree, ◯ Agree, ◯ Neutral, ◯ Disagree, ◯ Strongly disagree **2. The width was sufficient for me to safely pass or overtake other cyclists** ◯ Strongly agree, ◯ Agree, ◯ Neutral, ◯ Disagree, ◯ Strongly disagree **3. How much effort did it cost to fulfil the cycling task? ……………**
Width: 1.5 meter
1. The width was sufficient for me to cycle safely ◯ Strongly agree, ◯ Agree, ◯ Neutral, ◯ Disagree, ◯ Strongly disagree **2. The width was sufficient for me to safely pass or overtake other cyclists** ◯ Strongly agree, ◯ Agree, ◯ Neutral, ◯ Disagree, ◯ Strongly disagree **3. How much effort did it cost to fulfil the cycling task? ……………**
Width: 2 meter
1. The width was sufficient for me to cycle safely ◯ Strongly agree, ◯ Agree, ◯ Neutral, ◯ Disagree, ◯ Strongly disagree **2. The width was sufficient for me to safely pass or overtake other cyclists** ◯ Strongly agree, ◯ Agree, ◯ Neutral, ◯ Disagree, ◯ Strongly disagree **3. How much effort did it cost to fulfil the cycling task? ……………**

Effort scale

This effort scale is used to indicate the required effort of the cycling task.



Questionnaire after completing the experiment

This questionnaire is sent to the participants via email after completing the experiment.

Questionnaire – Cycling experiment

Thank you for participating in the study on cyclists' steering behaviour in relation to bicycle path width. The last part of the experiment is filling in this questionnaire about your cycling skills and experiences during the experiment.

The first section contains socio-demographic questions.
The second section is about your cycling skills and experience.
The third section asks questions about how you think you cycled during the experiment.
The fourth section contains questions about how the experiment set-up did or didn't influence your cycling behaviour.

Name: …

Age: …

Gender
○ Male
○ Female
○ Other: …

Cycling skills and experience

In this section questions are asked regarding your cycling skills and experience.

How old were you when you learned cycling?
…

Since then, what is the longest consecutive period of not cycling?
…

How often do you cycle per week on average?
○ < 1 day
○ 1-2 days
○ 3-4 days
○ 5-7 days

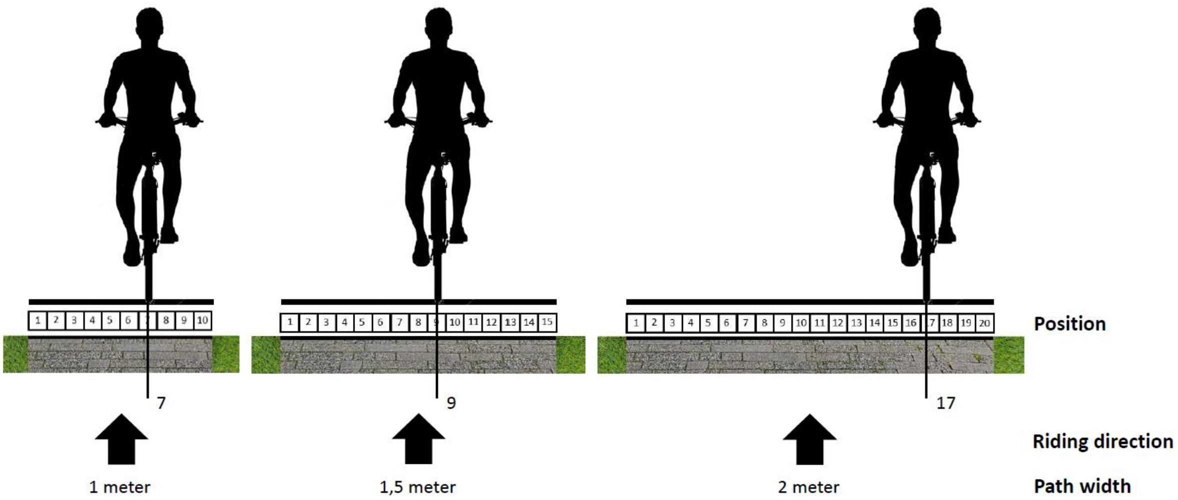
What is the average distance you cycle per week? (in km)
…

How would you describe your own cycling skills?
○ Good
○ Sufficient
○ Insufficient
○ Bad

Where would you cycle?

In this section you are asked to indicate your preferred place to cycle for different conditions. First a picture shows examples of cyclists on the different path widths. In the questions we ask you to indicate your preferred place to cycle on a grid of 10 centimeters which is shown on all path widths. For each width this question is asked for the situation with no other traffic participants around and for the situation when you approach an oncoming cyclist.

Examples of path widths and cyclists' position
If the three cyclist positions in this example would reflect your preference, please answer position 7 for the 1 meter path, 9 for the 1,5 meter path and 17 for the 2 meter path.



Bicycle path of 1 meter (10 is your right hand side, 1 is your left hand side)

Where would you cycle on a 1 meter wide bicycle path when no other traffic participants are around?

	1	2	3	4	5	6	7	8	9	10
Click one box	o	o	o	o	o	o	o	o	o	o

Where would you cycle on a 1 meter wide bicycle path when you approach an oncoming cyclist?

	1	2	3	4	5	6	7	8	9	10
Click one box	o	o	o	o	o	o	o	o	o	o

Bicycle path of 1.5 meter (15 is your right hand side, 1 is your left hand side)

Where would you cycle on a 1.5 meter wide bicycle path when no other traffic participants are around?

	1	2	3	4	5	6	7	8	9	10
Click one box	○	○	○	○	○	○	○	○	○	○
	11	12	13	14	15					
	○	○	○	○	○					

Where would you cycle on a 1.5 meter wide bicycle path when you approach an oncoming cyclist?

	1	2	3	4	5	6	7	8	9	10
Click one box	○	○	○	○	○	○	○	○	○	○
	11	12	13	14	15					
	○	○	○	○	○					

Bicycle path of 2 meter (20 is your right hand side, 1 is your left hand side)

Where would you cycle on a 2 meter wide bicycle path when no other traffic participants are around?

	1	2	3	4	5	6	7	8	9	10
Click one box	○	○	○	○	○	○	○	○	○	○
	11	12	13	14	15	16	17	18	19	20
	○	○	○	○	○	○	○	○	○	○

Where would you cycle on a 2 meter wide bicycle path when you approach an oncoming cyclist?

	1	2	3	4	5	6	7	8	9	10
Click one box	○	○	○	○	○	○	○	○	○	○
	11	12	13	14	15	16	17	18	19	20
	○	○	○	○	○	○	○	○	○	○

Experiment

In this section a few questions are asked to find out how the experiment set up affected your normal behaviour.

Did you change your cycling behaviour consciously?

○ Yes
○ No

Have you cycled differently than you normally would?

○ Yes
○ No

If one or both of these questions are answered with 'Yes':

> **How would you describe the difference?**
>
> …
>
> **What do you think was the reason you cycled differently?**
>
> …

Is there something else you would like to notify us about?

…