Bicycle Handling Qualities

finding objective measures for subjective handling qualities

MSc Thesis
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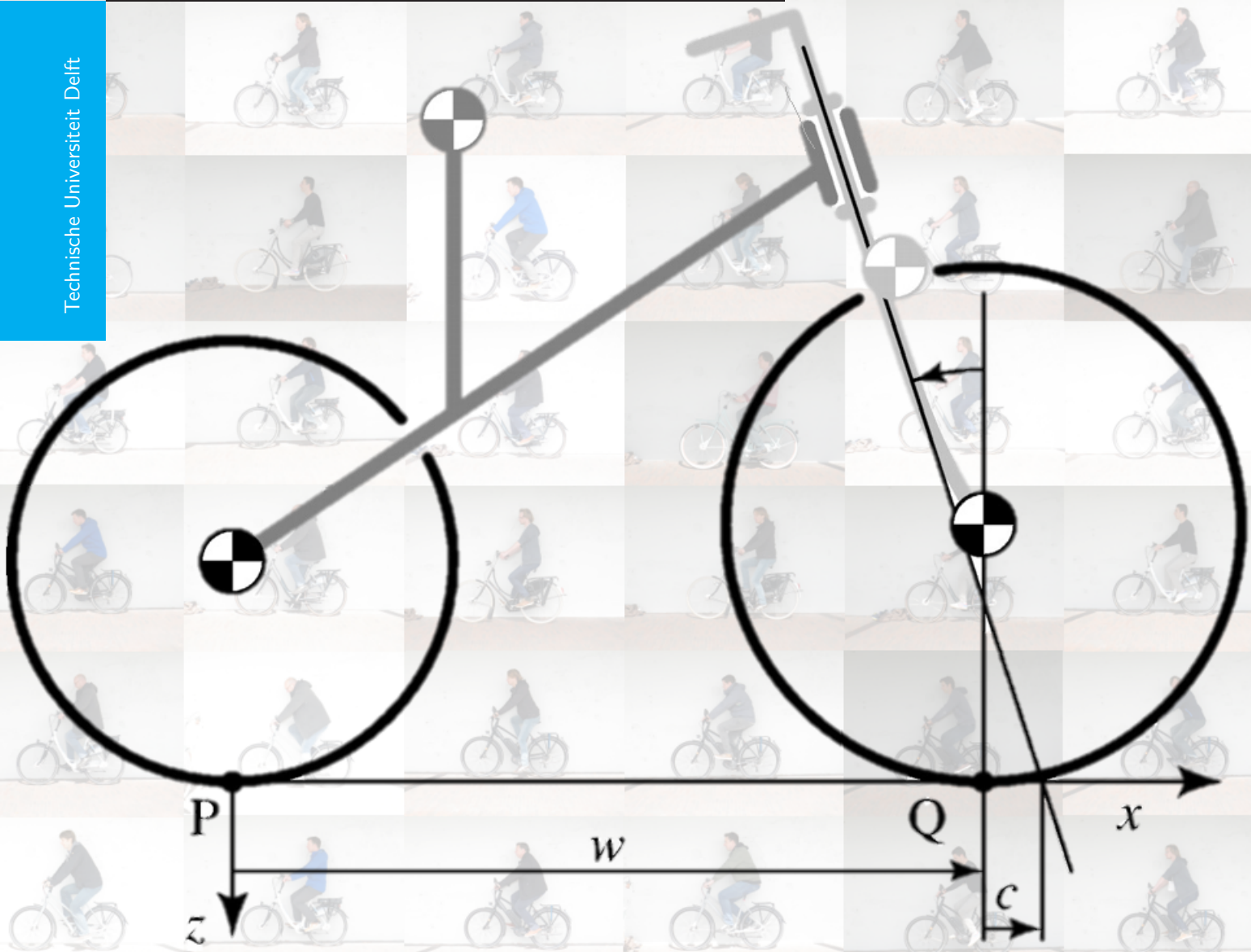

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Challenge the future

BICYCLE HANDLING QUALITIES

FINDING OBJECTIVE MEASURES FOR SUBJECTIVE HANDLING QUALITIES

by

C. Sluiter

to obtain the degree

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in Mechanical Engineering - Biomechanical Design; Sports Engineering

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ABSTRACT

The 'feeling' of a bicycle while riding can be described by handling qualities. This feeling is subjective and differs for every individual. In the design process of a bicycle for a specific target group with specific demands, bicycle handling qualities could be helpful. A literature study prior to this research pointed out that currently there is no consensus on definitions for handling qualities and how to measure them. At the Royal Dutch Gazelle bicycles are developed since 1892 and a lot of knowledge is present among their employees. This knowledge is undocumented and ideas about their handling qualities is evolutionary based. This study subtracts the information about the handling qualities from the employees and searches for objective measures to link to the subjective handling qualities. Within an experiment, 10 participants tested and rated 10 bicycles on 10 different handling qualities. From this data, a handling quality profile for each bicycle is set up. In addition, all bicycles are modelled according to a passive rider-bicycle model with the use of a combination of measurements and Solid Works. These models are evaluated in an open loop system for their eigenvalues and steer stiffness. These objective modelled measures are correlated to the results of the handling quality rating from the cycling experiment. These correlations show that five subjective handling qualities can be correlated with two types of objective measures. The correlations are not strong, but they do provide guidelines to work with in the design process of a new bicycle. To show the possibilities of the combination of the objective measures and subjective handling qualities, the results are applied to one of the tested bicycles. Model parameters of the bicycle are changed, resulting in changed objective measures. The correlations between the objective measures and handling qualities are then used to predict new bicycle handling qualities of the bicycle with changed parameters. New handling quality profiles can be constructed by applying the correlations between objective measures and subjective handling qualities and using the 10 tested bicycles as references.

Keywords: bicycle; handling qualities; subjective; objective measures; correlations

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1

INTRODUCTION

The best way to describe bicycle handling qualities, is in terms of the ease of control of the bicycle. How does the bicycle 'feel' while riding? How does the bicycle respond to steering actions? Where 'feeling' is a subjective measure, response on a steer input can be modelled and therefore can be an objective measure. By enhancing the handling qualities of a bicycle, the safety of the bicycle can be increased. In the Netherlands the bicycle is one of the main vehicles in traffic. In 2009, 185 cyclists died in traffic and 10810 where severely injured[1]. These accidents included often just one vehicle, non-motorized. The amount of accidents with severely injured cyclists increase every year, and there is no decrease in deadly accidents since 2004. Bicycles with electrical support are more likely to be involved in an accident than normal bicycles[2]. By improving bicycle handling qualities, an attempt is made to increase the safety of bicycle riding. The downside of bicycle handling qualities is the lack of consensus on these qualities. In a previous literature study, there was found that although several studies researched bicycle handling qualities, no consensus is found on how to define and study them[3]. All studies used different definitions and different test methods, so they could not be compared. Also handling qualities in other single-track vehicles were not in consensus on definition and test method either. It became clear that the definitions were merely universal words, to which multiple descriptions could be assigned on what that words imply. For example: 'stability' is named a handling quality, were it is described as 'staying upright' or 'riding in a straight line'. Or 'maneuvering' with definitions as 'going into a corner' or 'avoiding an obstacle'. Therefore, the qualities are still vague terms, were no consensus is found on how to define, test and improve them.

1.1. PROBLEM DEFINITION

At the Royal Dutch Gazelle (Koninklijke Gazelle), bicycles are produced since 1892. With 275.000 a year, they are leading the bicycle market in the Netherlands. They produce city bicycles, but all types of bicycles have their own signature. These signatures are defined by geometry and consequently have different handling qualities, as mentioned by their engineers (Appendix A). A transport bicycle has a different appearance and a different feeling when controlling the bicycle, then for instance a sportive electric bicycle. At Gazelle these differences are known and evolutionary based, but unfortunately undocumented. This knowledge has evolved over the years by trial and error and is passed on from old to new employees. In an attempt to develop new bicycles with enhanced performance, they might design a bicycle that fulfils the requirements, but it can also occur that the bicycle's handling does not turn out how they intended. The bicycle has to be remodelled and geometry parameters changed to optimize the performance, all by trial and error. This is time consuming work, and sometimes it is not known why a bicycle is responding to the rider as it does. It would be very useful to have a set of objective measures of a bicycle that specifically defines a bicycle handling quality. That way, a bicycle can be given a specific handling quality, as specified by Gazelle, just by using the right parameter values. This would solve the problem of unwanted responses of the bicycle or unpredictable features. The handling qualities could be modelled on forehand.

1.2. OBJECTIVE

The aim of this master thesis is to find objective measures from a rider-bicycle model that correspond with subjectively defined handling qualities, as used at the Royal Dutch Gazelle. This means that there is a sub-

jective experience from the rider when riding the bicycle, defined as handling quality. This handling quality might be linked to an objective measure. This objective measure can be retrieved from a rider-bicycle model, when the right bicycle and rider parameters are put into that model. If a subjective handling quality from the actual system can be correlated to an objective measure from the model of that bicycle and rider, a prediction for the subjective handling quality can be made when parameters of the bicycle are changed in the model. The goal of this study is thus to find the correlation between the subjective handling quality and the objective modelled measure. To reach this goal, three sub questions are defined:

- What subjective handling qualities are used at the Royal Dutch Gazelle?
- What objective measures can be modelled and used as bicycle handling parameter?
- Is there a correlation between any objective measure and subjective handling quality?

1.3. APPROACH

To find an answer to the three defined sub questions and subsequently to the main question, first the handling qualities used by Gazelle have to be mapped. This will be done by interviewing the engineers and marketeers, who design and develop the bicycles. From that point on, a list of handling qualities with their definitions can be set up, to asses in a bicycle riding experiment.

In a cycling experiment, 10 different participants will ride on 10 different bicycles. These bicycles are selected by Gazelle as most interesting and with specific signatures. The bicycles used are presented further on in this report. The experiment includes a 3.5 km ride on varying road surfaces, with different traffic situations and two parts with a speed-assignment. During the ride, rider measurements like the position, speed, steering actions and bicycle movements will be recorded. After the ride, the participants have to fill in a questionnaire about the handling of the bicycle. These questions should correspond to the handling qualities retrieved from the earlier interviews. Each participant will ride each bicycle.

Meanwhile, the geometry of each bicycle is investigated and the parameters are put into JBike6[4]. This program is able to model the bicycles and evaluate the open loop eigenvalues of the bicycle-rider system. The program and the required parameters are based on the Benchmark Bicycle by Meijaard et al. (2007), presented in figure 1[5]. The parameters include mass and moment of inertia from the R (rear wheel), F (front wheel), B (rear frame, including the rider) and H (fork and handlebar), the w (wheelbase), c (trail) and λ (steer axis tilt) and the rider measurements from the cycling experiment.

Afterwards, the subjective scores from the participants on the bicycles will be compared to the objective measures that came from the bicycle-rider model. This should point out if there are correlations between the objective measures and subjective handling qualities and if these measures can predict the handling qualities. That way, the handling qualities are objectified and easier to incorporate in a bicycle design. Also, the studies from Hess et al. (2012) and Moore et al. (2016) will be used to compare the data of the experiment with an existing handling quality measure[6], [7]. Hess et al. (2012)[6] developed a handling quality metric (HQM) and that metric will be compared to the subjective rating of the 10 participants, to see if there is any correlation. If

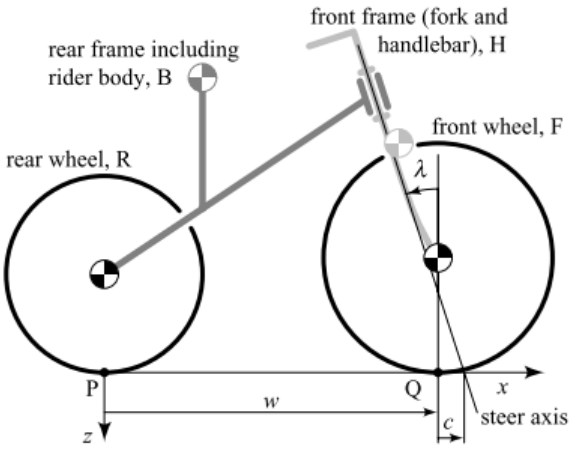

Figure 1: Benchmark Bicycle (Meijaard et al. 2007)[5].

so, then the HQM is capable of predicting the subjective findings on bicycle behaviour, and their model can be used to develop new bicycles. This will be further explained in the section about this analysis.

Finally, the obtained correlations will be applied to an already improved bicycle from Gazelle, a case study. The original bicycle is tested during the cycling experiment and modelled as rider-bicycle system. The improved bicycle is then modelled and the objective measures from the new bicycle will be compared with the original bicycle and based on the correlations between the objective measures and handling qualities, a prediction of the new handling qualities can be made. Is the bicycle improved, based on the model?

In short, employees of the Royal Dutch Gazelle are interviewed to find out how they define handling qualities, an experiment will be conducted to collect subjective rider data and real-life measures on bicycle control. The geometry of the bicycles and real-life measures will be investigated and used in the JBike6 program and an HQM is calculated for each bicycle. The objective measures and the HQM will be compared with the subjective rating in the search for correlations. In the end it will show if there are objective measures that can predict subjective bicycle ratings, or that the rating is dependent of the participant and not on bicycle parameters. These results are applied to an improved bicycle, to see if the model can predict improvements in the handling quality of a bicycle based on bicycle dynamics.

1.4. DOCUMENT STRUCTURE

This report will address each part of the complete project separately. First, in chapter 2, the collection of information on handling qualities by the Gazelle engineers will be presented. The most important information about these qualities and the translation into a single definition will be discussed. Subsequently, the composed questionnaire for subjective measurements on these handling qualities is presented. Then, chapter 3, will discuss the actual experiment with the 10 bicycles and 10 participants. The experimental set up and protocol will be discussed, together with the collection of the objective data. The results from the experiment are presented and a first small conclusion can be drawn on the handling qualities, based on the answers from the participants. In chapter 4 the geometry of the bicycles is assessed and how it is implemented in JBike6. The results from the analysis of JBike6 are shown. It also covers the modelling of the bicycle according to the study of Hess et al. (2012)[6] and the results of the HQM. Can these models predict the handling qualities of the bicycle, perceived by the participants in the experiment? The answer to that question will be discussed in chapter 5. All variables collected (JBike6-data and the HQM results) are compared to the subjective handling qualities, gathered in the experiment. In chapter 6, a conclusion is drawn from these results and this conclusion and the results are discussed. The final chapter will apply these results to a case study of an improved bicycle, where some parameters and thus the dynamics are changed. This bicycle with its new properties is put into JBike6, the results are compared with the original bicycle and a prediction of the handling qualities is made based on the results of this study.

2

BICYCLE HANDLING QUALITIES

The first part of this research was uncovering the handling qualities that are used by the Royal Dutch Gazelle. They made clear from the start that there is no list of handling qualities which they incorporate in their bicycles. There are only ideas of these qualities, developed by trial and error, and these are passed on through the years from one engineer to another. All these ideas are not well documented, but stored in the minds of the engineers. To find an objective measure for these handling qualities, first the actual handling qualities have to be documented. The goal of this research was to find a correlation between objective measures for subjectively defined handling qualities. From the handling qualities retrieved from the Gazelle employees, a questionnaire can be put together to asses these qualities for each bicycle. To assess the subjective part of the bicycle, test subjects have to give their opinion on the bicycles. The participants will all ride the bicycles in an experiment (this will be discussed later) and answer questions about the bicycle. These questions will cover the handling qualities as used by Gazelle. The construction of these questions will be treated after the interviews.

2.1. INTERVIEWING GAZELLE EMPLOYEES

At their factory in Dieren, the Netherlands, five engineers and two marketeers were interviewed about 9 bicycles. These bicycles were selected by Gazelle for the research. They included the Ami (not yet on the market at the time), the Balance, three Oranges (non-electric version, one with a front wheel electric support (HFP) and one electrically supported at the cranks(HMB)), a Cityzen and a Cityzen Speed (electrically supported up to 45 km/h), the Tour Populair and the Puur NL. After the interviews, one more bicycle was added, the Van Stael, but this bicycle was not discussed during the interviews. The bicycles are shown when they are discussed.

During the interviews, 5 questions needed to be answered about the bicycles.

1. What is the vision behind the bicycle?
2. How is this vision incorporated in the bicycle?
3. Which handling qualities are assigned to this bicycle?
4. Can you explain these handling qualities?
5. Which part of the bicycle gives rise to which handling quality?

An attempt was made to find an answer to each of the questions for each bicycle. But, because of the course of the conversations and due to time constrictions, not all questions were answered for each bicycle by each engineer. Altogether, each bicycle (except the Van Stael) is discussed and an overview is be created of the bicycles and their handling qualities.

Because the interviews were in Dutch and the specific words they use to describe the handling qualities, the qualities are also referred to in Dutch in the overview of the handling qualities at the end of this section. A translation is used in the description of the bicycles to make reading easier. After the overview a dictionary is provided with the Dutch terminology, translated to English with a sentence to describe handling qualities. The rest of the report, the handling qualities are referred to in English terminology.

2.1.1. BASIC STRUCTURE

At the Royal Dutch Gazelle, there are roughly two types of geometry used to define the handling of the bicycle. This defines the basic geometry of the bicycles and two classes of handling; 'lui' (lazy) and 'sportief' (sportive). According to the employees, the lazy geometry is characterized by a small angle between the seat tube and the horizontal and between the steering axis (head tube) and the horizontal. This angles ranges from 65°to 68°. The angles ensure that the rider sits straight up or even leans backwards a bit when cycling. Because of this posture of the ride, a steer with a large angle in the handle bars is required. Figure 2 shows a steer with a small angle and a large angle in the handlebars. Common for these type of bicycles, is that with the smaller angle for the head tube the fork offset is larger, which moves the front wheel further forward. The opposite geometry is used for the sportive type of bicycle. It holds a seat- and head tube with a large angle with respect to the horizontal, ranging from 68°to 71°(even larger for racing types). The angles are specifically designed to give the rider a more bend over posture. Because of this posture, a steer with a small angle for the handlebars can be used. The more sportive the bicycle, the more the rider is leaning forward with stretched arms. In addition, the fork offset is smaller for these type of bicycles, so the front wheel is closer to the rider. Figure 3 shows a sketch of the two geometry types.

Within these two geometry types defining the handling qualities lazy and sportive, lots of smaller adaptations can be made to fine tune the behaviour of the bicycles. The seat tube, head tube and fork offset can be changed to accommodate different target groups, with different preferences for bicycle type. These differences and the handling qualities that come with them, according to the Gazelle employees, are explained for each of the 9 discussed bicycles in the next section.

Figure 2: A. Steer with a large angle in the handlebars[8]. B. Steer with a small angle in the handlebars[9]

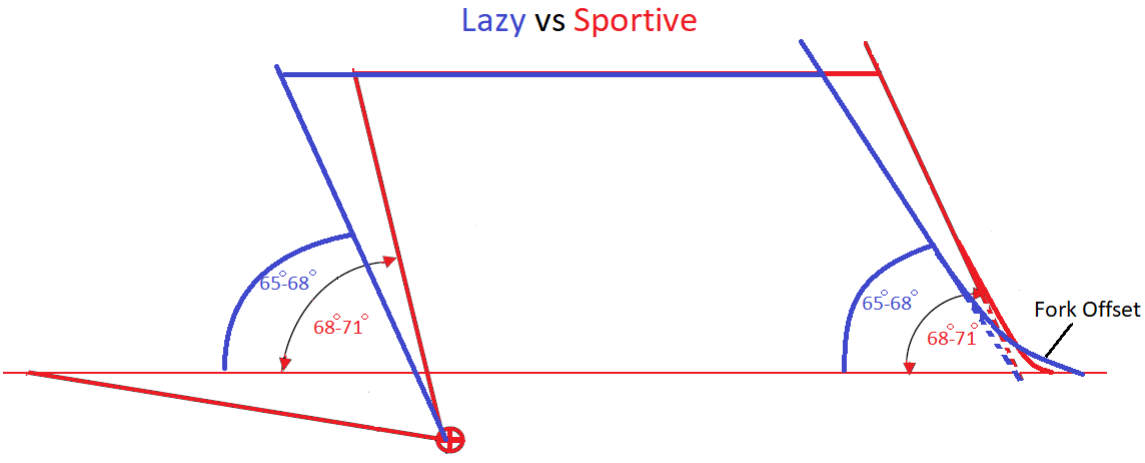

Figure 3: 'Lui' - lazy (blue) and 'sportief' - sportive (red). Lazy has small angles and a large fork offset, where sportive has large angles and a small fork offset.

2.1.2. HANDLING QUALITIES PER BICYCLE

This section will summarize the interviews with the Gazelle employees. Everything mentioned in this section is a summary of what the employees have said. During the interviews the Ami, Balance, Orange, Cityzen, Tour Populair and Puur NL are discussed. Also, the effects of placement of the electrical support motors are mentioned. Each bicycle will be discussed to give an idea on the thoughts about the bicycle, with respect to the handling qualities as well as to the vision behind the bicycle. One common remark; question 3 'Which handling qualities are assigned to this bicycle?' often could not be answered straight forward. The engineers explained that the handling qualities are not considered as an independent factor, but that they are incorporated in their ideas about the geometry. So, the answers are often about the ideas they have about the bicycle, not what they knowingly designed based on numbers. The unsummarized interviews about the bicycles are presented in Appendix A, translated to English. The following part is a summary of all those separate interviews for each bicycle.

2.1.2.1. BALANCE

The Balance bicycle is a bicycle specifically designed for people who are not able to cycle anymore, due to a decrease in movement control. Safety is the main property of the bicycle, the cyclist has to be able to touch the ground with their feet at all times and the bicycle has to be stable. The cyclist has to feel secure and feel safe to cycle again. This bicycle is approached from a different point of view than usual. Safety and security came first, not the 'perfect cycling experience'. The looks of the bicycle did not matter at all. The rear part of the bicycle, from seat tube to the rear wheel, was already designed by an external designer and the Gazelle engineers had to start from there, resulting in an odd geometry. An extreme seat tube angle of 50°, with adjusted seat post, makes sure the cyclist can reach the ground. This also ensures the cyclist has a safe feeling when mounting and dismounting. The front part of the bicycle has a head tube angle (steering axis angle) of 66°and a large fork offset. This causes the front wheel to be further in front and creates a larger wheelbase, which would increase the stability of riding in a straight line. There is no high oscillation of the front wheel (also known as shimmy) and it is not sensitive to perturbations. This makes the bicycle predictable and adds to the safe and secure feeling the cyclist should have. The frame has a high stiffness, so less torsion, what also adds to the stability and comfort. The bicycle is equipped with a telescopic fork, to transfer the force from the leg to the pedal as efficiently as possible, with the least amount of energy loss. Cyclists who will ride this bicycle often have decreased muscle power in their legs, so they benefit form a lesser amount of energy loss. On the other hand, the Balance bicycle does have a front wheel motor, what makes the steering more difficult.

Figure 4: Balance

Handling qualities that describe this bicycle are 'safe', 'stable', 'forgiving steering behaviour', 'comfortable', 'security', controllable', 'predictable', 'not direct', 'difficult in cornering', 'few delays from input to output'.

2.1.2.2. AMI

The Ami is a reaction on bicycles from other bicycle companies in the Netherlands. It is based on an Orange (the benchmark from the Royal Dutch Gazelle), but more focused on a target group of elderly cyclists. This bicycle has to give a secure and safe feeling, but is not as extreme as the Balance. The Ami has a wide and low entry for the bicycle, which reduces the time standing on one leg when mounting and dismounting the bicycle. The Ami also has smaller wheel diameters. This makes the bicycle easier to handle when walking with the bicycle, but also stabilizes the bicycle while riding it. Another feature that increases the stability of the bicycle is the location of the support motor, around the cranks instead of in the front wheel. This reduces the possibility of slip while riding over gravel and improves the steering behaviour over a motor in the

Figure 5: Ami

front wheel. The bicycle is based on a so called '70°geometry'. It has a head tube of 70°, but a smaller seat tube angle to address to the older target group. Therefore, it is a stable, straight-up-sitting bicycle. However, the steer is straight (a small angle for the handlebars), which causes the bicycle to behave a bit more sportive with direct steering behaviour.

Handling qualities that describe this bicycle are 'safe', 'secure', 'stable riding straight', 'good steering behaviour', 'comfortable', 'few delays from input to output' and 'direct'.

2.1.2.3. ORANGE

The Orange is the benchmark of the 'comfort bicycle'. The Orange is a modern, comfortable bicycle, which is designed for people between 35 and 60 years old. It is meant for everyday use and is branched as a sportive city bicycle. The bicycle is less lazy compared to the Balance. It is a typical ladies bicycle. A lot of elderly men ride the lady-version, from the moment they cannot lift their leg over the saddle. The Orange is the benchmark bicycle, it fulfils all needs of the consumer. It is important that the bicycle instantly feels nice: the saddle, the handlebars, shifting gears, everything has to feel right for the consumer instantly. The head tube angle is adjusted to create more space for the steer and the rider. It is a robust, stable bicycle, which is caused by the stiffness of the frame. The posture of the rider on this bicycle is straight up, which provides a better overview on the surroundings, without moving the neck up or down. Also in this bicycle the fork offset and angles are important for the stability and steering behaviour of the bicycle, as described in the previous bicycles. Because of the stability, cycling in a straight path is easy and can be executed with a low velocity. Steering into a corner will result in a fluent line, but correcting while cornering is more difficult. The bicycle has a relatively low entry, which is common in a comfort bicycle. Because of the robustness, low entry and complete finish with accessories, the bicycle is quite heavy. The finish touch of the Orange is the adaptivity; the frame always remains the same but the colours and different types of steering, forks, saddles and handlebars, make the bicycle fit and comfortable for different individuals. The bicycle comes in electrical versions and non-electrical versions. The electrical versions have the support motor in the front wheel, resulting in a decrease in steering behaviour, or in the cranks.

Handling qualities that describe this bicycle are 'safe', 'stable', 'sportive', 'comfortable', 'predictable', 'fluent in the corners' and 'direct steering behaviour'.

Figure 6: Orange, non-electric

Figure 7: Orange HFP, with a front wheel motor

Figure 8: Orange HMB, with a crank motor

2.1.2.4. CITYZEN

The Cityzen is a bicycle designed to bring people from A to B in a faster manner, especially with the electrical version (supported up to 45 km/h). The bicycle is more sportive and motivates for speed. Cycling at a lower velocity with this bicycle is more challenging. The frame is more straight up, because of the larger angles for the seat- and head tube. The posture of the rider is more bend over and together with a short and straight steer, it creates a sportive look and feeling. The position of the rider is also above the crank axis, instead of behind the crank axis as in the other bicycles. Moving the centre of mass forward makes the bicycle faster in the corners. The tires on the bicycle are smaller and more race like than in the others. The tires and the geometry cause vibrations in the frame by the road surface, making the bicycle less comfortable. The bicycle has a more direct steering behaviour, more nervous and is fast in the corners, because of the head tube angle and straight steer. The consumer associates the Cityzen with speed, because of the shape of the bicycle, but also because of colouring choices. The feeling of the bicycle is also influences by the looks of it, it biases the consumer.

Handling qualities that describe this bicycle are 'nervous', 'maneuverable', 'direct steering behaviour', 'less stable' and 'less comfortable'.

Figure 9: Cityzen

Figure 10: Cityzen Speed, with a crank motor up to 45 km/h

2.1.2.5. TOUR POPULAIR

The Tour Populair is the original Gazelle bicycle, a classical model that has not been changed for the last 80 to 100 years. This bicycle is classified as extremely lazy. The rider leans back when sitting, resulting in an extreme upright back. Because of the classical model, a lot of torsion is possible in the frame and therefore the bicycle has larger absorption qualities. This makes the bicycle comfortable to ride on, it is more comfortable than the Orange. The large fork offset is part of the classic configuration and makes it easy to follow a straight path and is stable at low velocities. In Germany this bicycle is commonly known as the 'Holland Rad'. Over there it is accepted that the steer is colliding with body parts, due to the large angle of the handle bars, and that the posture is all the way backwards and that the bicycle feeling is not perfect. It is a typical classic bicycle, from which the current bicycles are evolved.

Handling qualities that describe this bicycle are 'lazy', 'stable', 'comfortable', 'not direct'.

Figure 11: Tour Populair

2.1.2.6. PUUR NL

The Puur NL is the modern version of the Tour Populair. Also in this bicycle, the handling qualities are inferior to the looks of the bicycle. The front rack is very important for the looks of the bicycle and addresses the demands of the consumer. This bicycle focuses on a younger target group. The frame is a little bit straighter than the Tour Populair (66.5°over 65°), but maintains the lazy geometry with an extreme straight up posture for the rider. The large fork offset and small angles are responsible for the lazy qualities: easy in a straight line but difficult in cornering. Because of the weight on the front wheel by the front rack, the steering behavior drastically decreases. When the front rack is loaded, it induces oscillation in the steering behavior and also steering in the corners is not optimal because of the rack. But, because this bicycle is designed and used by young adults, that does not matter. Young adults are flexible, can easily intervene and do not have a problem with riding with multiple persons next to each other and the possibility of collisions. Therefore, it is no problem that this bicycle has worse steering behaviour due to the front rack. Due to the rack, together with the robust structure of the bicycle, it feels and steers like a tank.

Figure 12: Puur NL

Handling qualities that describe this bicycle are 'lazy', 'stable', 'heavy steering behaviour' and 'indestructible'.

2.1.2.7. VAN STAEL

The Van Stael is not discussed during the interviews, but has been added to the list later. This bicycle is a race like bicycle, light weight with very large seat and head tube angles. It provides an even more forward position than the Cityzen. Because it is not further discussed, there are no handing qualities that describe the bicycle.

Figure 13: Van Stael

2.1.3. ADDITIONAL INFORMATION

During the interviews, more information came up than just the answers to the questions. Because this information is also valuable for defining handling qualities and translating them to valid questions, this extra information will be discussed briefly in this section.

The first thing noticed during the interviews, was that the handling qualities are often not considered on purpose in the design process. The effects of specific design choices, such as the head angles and fork offset, for the geometry are known and they do vary with them, but no to assign a specific handling quality on purpose. The knowledge is stored inside the heads of the engineers and not documented. Because of that, a lot of knowledge is lost, according to the engineers. Employees left and took the information they had with them, inside their minds. When this information is not passed through to the younger generation of engineers, knowledge about geometry disappears. The geometries that have been designed in previous years are mostly used in a copy-paste type manner, because the engineers do not know why some of the design choices have been made. They just know that it works. Original thoughts and possible improvements disappear.

Another interesting thought came from an engineer hires by Gazelle from another company. He has not worked on the designs of any of the bicycles and has only ridden on the Orange and the Cityzen. He has judged the bicycles by their looks. He is more focused on the stiffness of the frame and also thinks that multiple handling qualities are linked to this stiffness. The higher the stiffness, the less comfortable the bicycle,

due to less absorption from road roughness. A frame with lower stiffness (based on their looks) is therefore classified as comfortable. A frame with a high stiffness also has a more direct steering behaviour than a frame with a lower stiffness. A direct steering bicycle is predictable in its turn, there is no surprise element. The bicycle does what you ask without any delay. Because of the difference between bicycles for men and women, the top tube, a men's bicycle has a higher stiffness, and is therefore more direct and less comfortable. That can be altered by changing the stiffness of the frame in different directions. By decreasing the stiffness in vertical direction, there is more absorption from vibrations from the road, making a bicycle more comfortable. Increasing the stiffness in longitudinal direction increases torsion stiffness and adds more direct steering behaviour. According to this engineer, playing with the stiffness in different directions, an optimal set of handling qualities can be realized for a bicycle.

As one of the most interesting features in handling qualities, the engineers mention the posture of the rider on the bicycle. The posture of the rider alters, with an altering tuning of the bicycle. For example, with different forks or a different saddle position. A different posture has effect on the location of the centre of mass of the rider. It moves more down and forward when the rider has a posture that is leaning more to the front of the bicycle. This again has influence on the angle of initiating a corner that can be taken, according to the engineers. They say a different steer can add a whole different feeling and steering behaviour to the bicycle. One of them even dares to say that with the right assembly, a Tour Populair can be turned into an Orange and an Orange can be turned into a Cityzen. With a different fork, a shorter one, the frame tilts forward, increasing the angles of the tubes. And with a straighter steer, the rider takes a more forward leaning posture, making it all more sportive.
In conclusion, there are five important bicycle features that affect handling qualities of a bicycle, as told by the Gazelle employees: the seat tube angle, the head tube angle, the angle of the handlebars, the fork offset and the weight added to the front wheel. The added weight to the steering assembly can be caused by an electrical motor or a front rack. It increases the inertia of the assembly, making it more difficult to turn. The front wheel motor can cause problems, because most of the time older people ride these bicycles. The front basket is often not a problem, because it is designed and used by flexible younger cyclists who have better control.

The angles and fork offset can alter the distance between the wheels. Small angles and a large fork offset move the front wheel further away from the rear wheel, increasing the wheel base. This ensures a steady straight line, but difficulties in changing direction with the bicycle. Large angles and a small fork offset decrease the wheelbase, causing difficulties in riding straight, but easy cornering. The angles of the bicycle are also the main factor for the position of the rider. Often specific angles are matched with a specific type of handlebar. Large angled bicycles have often a steer with a small angle for the handlebars, because they both fit the sportive type of bicycle, while small angled bicycles have a steer with a large angled handlebar to create a lazy bicycle. Sportive bicycles invite for riding at high speeds, while a lazy bicycle invites for slow and relaxed riding. There is no clear distinction between the two, there is a grey area. For example, an Orange is a comfortable bicycle, but tends towards a sportive bicycle. The fine tuning of the bicycle can change a lot to the feeling, or handling qualities, of the bicycle. There was even said that a different steer has more effect on the handling of the bicycle than 1°change in the head tube angle. 5°would, on the other hand, be more noticeable. The reason for the thin line between sportive and lazy bicycles is the combination of angles and fine tuning with the assembly. But a real definition on handling qualities and thought through implementation is missing at the Royal Dutch Gazelle. It are mainly guesses and experiments.

2.1.4. HANDLING QUALITIES BY GAZELLE

The interviews were meant to figure out what ideas on handling qualities exist among the Gazelle employees. An overview is created, with some subcategories. The subcategories are based on the explanations in the interviews and an interpretation of that, to create a clear structure. The term 'indestructible' is left out, because this term was mentioned only once, for the Puur NL. This term was difficult to describe for the engineers and could be subdivided within other definitions.

The terms that came up during the interviews are divided in a group 'bicycle feeling' and 'bicycle behaviour'. The terms in bicycle feeling describe the feeling of the rider when riding the bicycle. These terms are difficult to measure in an experiment, because this is mainly subjective. The terms in the bicycle behaviour category should describe the dynamic properties of the bicycle, which can be measured or modelled. Of course, the moment the bicycles are rated by human participants on these handling qualities in an experiment, it is still subjective. But these terms might also be measured in terms of steer- and roll angles, speed and positioning on the road. This will be discussed later on, but have to be kept in mind when dividing the

handling quality terms of Gazelle in the two categories.

Dutch terminology	English terminology
Bicycle feeling	**Bicycle feeling**
'Lui'	Lazy
'Sportief'	Sportive
'Veilig'	Safe
'Zeker'	Secure
'Comfortabel'	Comfortable
'Ergonomisch'	Ergonomic
'Weggevoel'	Road surface
Bicycle behaviour	**Bicycle behaviour**
'Stabiel'	Stable
Capsize	Capsize
Weave	Weave
'Gemoedelijk'	Forgiving
'Beheersbaar'	Controllable
'Wendbaar'	Maneuverable
'Nerveus'	Nervous
'Direct'	Direct
'Voorspelbaar'	Predicatable

2.1.4.1. BICYCLE FEELING

In the summary of the bicycle feeling handling qualities, lazy and sportive are general terms, because all bicycles are based on a lazy or a sportive geometry. Safe and secure represent the feeling of the rider and not the qualities of the bicycle itself. Does the rider feel safe at all times, or are there moments that the rider is insecure? For instance, when riding down a curb, is there fear of falling? Secure describes the feeling that the bicycle is under control at all times, that the rider is secure of himself and the bicycle, that every situation is under control. Comfortable is divided in ergonomics (posture of the rider) and road surface. Is the condition of the road felt by the rider, or are any irregularities absorbed by the frame?

2.1.4.2. BICYCLE BEHAVIOUR

The bicycle behaviour describes the handling qualities that cover response of the bicycle to steering actions of the rider or external influences on the bicycle. Stable is a handling quality that addresses the roll angle of the bicycle. Does the bicycle remain upright, or does it tip over and results in a sway across the road? Stable is subdivided in capsize (falling over to one side at high speed) and weave (oscillation across the road at low speed). These two qualities are represented by the eigenvalues of the bicycle (weave and capsize mode), and can be discovered by an eigenvalue analysis of the bicycle when all properties are known. Because of that, and no solid description by the engineers on stability, it is decided to use these two parameters to describe stability.

The term forgiving ('gemoedelijk' in Dutch) is a hard quality to describe, in terms of translation from Dutch to English as well as in the description given by the Gazelle employees. However, all the employees have used this word to describe the handling of the bicycle, although they could not explain it very explicitly. It could describe the feeling of steering, or the feeling of the bicycle in general. Nonetheless, this term is added to the list of handling qualities, because it is a known term at Gazelle and this term could perhaps be filled in subjectively and with an own interpretation of the participants. The term controllable is used to describe the amount of control of the bicycle. Is the bicycle controllable in every maneuver, can the rider act at any time when something unpredictable happens? Maneuverable is the amount in which the direction of the bicycle can be changed. How easy does the bicycle go around the corner, how easy can the bicycle be maneuvered around an obstacle? Nervous describes the amount of correction that is required to keep the planned path. When riding a nervous bicycle, it will be more difficult to follow a straight line. The bicycle diverts easily from the planned line. Direct is about the response of the bicycle. Does the bicycle follow the given input directly, or is there a delay between the input and output? Predictable also acts around the directness of the bicycle.

Does the bicycle do what the rider wants it to do? If a steering action is executed, does the bicycle follow the intention of that action, or is there a delay? Is the corner wider or slower than intended? A rider knows how the bicycle reacts if the bicycle is predictable, and the output from the bicycle is in line with the given input by the rider.

2.1.4.3. DICTIONARY

Lui lazy ; Riding the lazy bicycle gives me a relaxed feeling.
Sportief sportive ; The sportive bicycle gives me a fast and active feeling.
Veilig safe ; I am not afraid of falling, I feel safe.
Zeker secure ; I am secure that I can handle the bicycle in any situation.
Comfortabel comfortable ; This bicycle feels comfortable. It gives me an ergonomic posture and I do not feel all the little bumps from the road.
Stabiel stable ; A stable bicycle easily keeps me on track.
Gemoedelijk forgiving ; The bicycle feels forgiving, in a sense of easy recovering from a disturbance.
Beheersbaar controllable ; The rider can control the bicycle at any time when something unpredictable happens.
Wendbaar maneuverable ; The bicycle can easily be maneuvered around an obstacle or into a corner.
Nerveus nervous ; Riding a nervous bicycle, it will be more difficult to follow a straight line, the bicycle quickly diverts.
Direct direct ; The bicycle follows the given input directly, is there almost no delay between the input and output.
Voorspelbaar predictable ; I can easily predict how the bicycle behaves under my control.

2.2. QUESTIONNAIRE

The handling qualities retrieved from the Gazelle employees are the handling qualities which they speak of when designing and developing a bicycle. Although this is not a set of predefined handling qualities, these are the terms they used when they communicate about the bicycles. Therefore, these handling qualities will be the qualities that are investigated in this study.

Because there is no consensus on handling qualities in the literature[3], no connection can be made between terminology from the bicycle literature and the handling qualities at Gazelle. However, the handling qualities from Gazelle can be translated to a questionnaire suitable for rating vehicles. A commonly accepted rating-scale for vehicles is the Cooper-Harper scale (figure 14)[10]. Within this scale, statements are made about the control of the bicycle. These statement are widely adopted for different types of vehicles, also for bicycle assessment[6]. The questions for the questionnaire will be partially based on the Cooper-Harper scale. Handling qualities from Gazelle are compared to the statements and checked for similarities. The Cooper-Harper scale makes use of terminology like 'pilot compensation', 'control' and 'performance versus workload', what can be seen as 'effort'. This will not be used in these terms directly, because the handling qualities show some differences with the statements of the Cooper-Harper scale and they have to be translated to Dutch for the actual questionnaire. However, variations of these terms will be used to describe the handling qualities from Gazelle.

Some other studies on vehicle rating have been reviewed and also these studies show similarities with the handling qualities and the Cooper-Harper scale[11]–[13]. These studies use words like 'effort', 'nervousness', 'steering response', 'cornering', 'smoothness', 'response of the vehicle', 'centering' and 'steering precision'. Also, these terms can be related to the questions about the handling qualities.

Questions about the handling qualities are formed to prevent any bias from participants on the bicycle handling qualities. Since probably Gazelle engineers would also ride these bicycles as participants, they might rate the bicycle to what they think about the handling qualities and not what they feel. Also, for a non-Gazelle participant, a handling quality like 'nervous' might be difficult to interpret on its meaning. By translating the handling qualities to descriptive questions, the participants in the experiment will pay attention to how the bicycle responds to them, so they can answer that particular question. The questions are then again a measure for the handling quality, when evaluating them.

The first step into translating the handling qualities to questions, is writing down any description the Gazelle employees gave about that quality. After all, it is their terminology, and they explained what they meant with these qualities. These descriptions are compared to each other and adjusted or merged when there are similar descriptions. The highlights of the descriptions can be found in the previous section, where each bicycle was discussed about their handling qualities. The questionnaire will get a 5 point-Likert scale

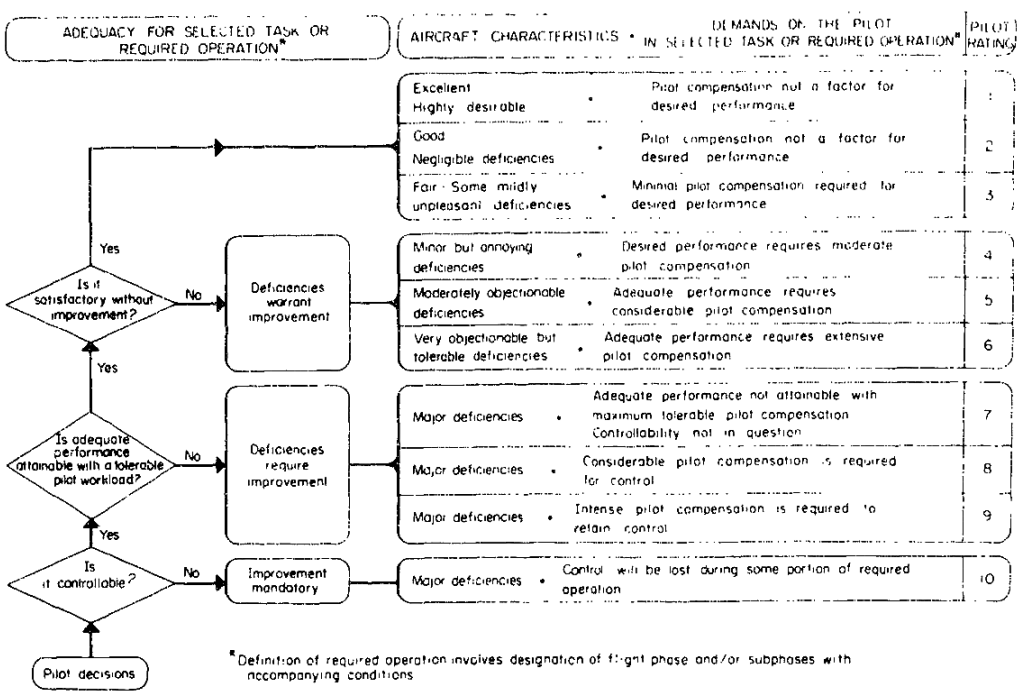

Figure 14: Cooper-Harper scale for pilot rating[10]

as rating method, as in many vehicle experiments. Therefore, the form in which the handling qualities are assessed will be short and clear statements, on which the participant can agree or disagree in 5 levels. In the formulation of the statements, the terminology of the Cooper-Harper scale and the other studies are taken into account. This resulted in the initial questionnaire. Both English as the original Dutch version can be found in Appendix B. The first column shows the corresponding handling quality, the second column shows the statement with the rating in the next columns. The last two columns show the corresponding terminology from the Cooper-Harper scale and the other reviewed studies[10]–[13].

The supervisors of the research project from the Royal Dutch Gazelle were informed on the results of the interviews and on the questionnaire. They agreed on the results of the interviews, but had some comments on the questionnaire. They thought it was too long, they would not want to fill in 26 questions 10 times themselves (one questionnaire for each bicycle). This would take too long and would be boring. So, the questionnaire had to be reduced. This has as downside that the handling qualities cannot be questioned as explicit as with the long version. Some statements have to be merged and some have to be removed completely. This gives a less clear picture of what the participants of the experiment think about the bicycles. So, the new questionnaire has to be as clear as possible, so the participants will know what is asked from them with less explicit statements about the handling qualities.

Because the list had to be reduced, handling qualities that are completely subjective and cannot be measured objectively are discarded. This was the case for 'comfortable'. One person might like a vibrating bicycle, another can find it very annoying. This is pure opinion and cannot be measured. The same accounts for 'ergonomics' in 'comfort'. This could be measured by an ergonomic therapist, but that has nothing to do with the handling quality of a bicycle. Therefore, 'comfortable' is discarded as handling quality for this research. Also 'predictable' has been removed. As already stated in the section about the interviews, predictable is liked to direct. Does the bicycle immediately follow the steering action, so does the bicycle what the rider wants it to do, or is the behaviour different. Because these two handling qualities are close together in definition and are also mentioned to be compliant with one another, it is decided to also remove 'predictable' from the list of handling qualities.

Removing those two handling qualities already took away 5 questions. The following step was to take a closer look to the questions and find similar statements that might be combined. Questions like 'I feel safe at all times riding the bicycle' and 'I am not afraid of falling' (statement 3 and 4 from figure 7), are very similar, point 3 already covers point 4. If you feel safe at all times, then you are not afraid of falling. Also statement 5 'I am self-secure...' is a similar statement as 'I can control the bicycle'. If a cyclist has the feeling that the bicycle

can be controlled at all times, the cyclists feels self-secure when cycling. Also, because these questions are from the category 'bicycle feeling', and are very difficult connect to an objective measure, these statements are considered less important for this research. They might be very important when the consumer value is investigated, but this project is about coupling objective measurement to subjectively defined handling qualities. And that is mostly about the bicycle behaviour. A consideration was made to also discard 'forgiving', because this quality was poorly defined and open for any interpretation. However, because every single employee of Gazelle mentioned this as handling quality, it is decided to keep this one in. Maybe they cannot explain what they mean, but if there is a strong correlation with an objective measure, this might provide the engineers of Gazelle a lot more insight. Because of curiosity, 'forgiving' remains a handling quality that will be looked into.

When closely looking to the other questions, it is concluded that the question for 'controllable' about intervening at all times (question 14) is similar to question 6, that covers the handling quality 'secure'. 'Secure' therefore is closely related to 'controllable', as is already stated above about self-security and controlling the bicycle.

Because these qualities are almost the same, it is decided to remove 'secure' from the handling qualities and let question 6 account for only 'controllable'. A bicycle that is uncontrollable is unlikely to provide a secure feeling to the cyclists. Also the question about mounting and dismounting combined. There would probably not be much of a difference, since it is about stopping and starting when riding slowly. Control in the corners (question 17) is considered to be covered by the statements about 'maneuverable' in the corners and around obstacles (questions 18 and 19). So, also this question is removed from the questionnaire. Questions 22 and 23 as well are similar to 18 and 19. These can be linked to each other. The expectation is that when one question has a good score, the other would have that as well. Although this adds to the reliability of the questionnaire, it had to be shorted. So, these questions are taken out. After decreasing the amount of questions and combining some handling qualities in one statement, the list is shuffled and organized. The first part of the questionnaire contains questions about the feeling of the participant when riding the bicycle, from the 'bicycle feeling' category. Secondly, questions about the bicycle behaviour come forward. This part is divided in two subcategories, riding in a straight line and riding while steering. This division is made to give the participants guidance when they should pay attention to what or what situation to recall when filling in the questionnaire. After all corrections to the questionnaire, this is how the final version looked at the time of the experiment (figure 15). This is the version translated to English. The Dutch version can be found in Appendix B. Again, the first column shows the corresponding handling quality, the second column shows the questions followed by the rating. The last two columns show the corresponding terminology from the Cooper-Harper scale and the other reviews studies[10]–[13]. The questionnaire used in the experiment would only contain the columns with the statements and ratings.

While adjusting and reducing the list of questions, some of the handling qualities are removed and will not be assessed in this research report; 'comfortable', 'secure' and 'predictable' are taken out. The final handling qualities that will be looked into during this research project are the following:

Dutch terminology	English terminology
Bicycle feeling	**Bicycle feeling**
'Lui'	Lazy
'Sportief'	Sportive
'Veilig'	Safe
Bicycle behaviour	**Bicycle behaviour**
'Stabiel'	Stable
Capsize	Capsize
Weave	Weave
'Gemoedelijk'	Forgiving
'Beheersbaar'	Controllable
'Wendbaar'	Maneuverable
'Nerveus'	Nervous
'Direct'	Direct

Handling Qualities	Feeling of the bicycle	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	*Cooper-Harper terminolofy*	*Other used terminology*
		-2	-1	0	+1	+2		
Lazy	1. The bicycle gives me a relaxed feeling							
Sportive	2. The bicycle gives me a sportive feeling							
Safe	3. I feel safe at all times riding the bicycle							
Secure / Controllable	4. I can control this bicycle at any time						*controlability*	
Forgiving	5. The bicycle is forgiving							
	Riding a straight line	**Strongly disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly agree**	*Cooper-Harper terminolofy*	*Other used terminology*
		-2	-1	0	+1	+2		
Stable (Weave)	6. I have the feeling of tipping over when I ride **slowly**						*controlability*	centering
Stabe (Capsize)	7. I have the feeling the bicycle starts swaying across the road at **high** speeds						*controlability*	centering
Stable / Nervous	8. The bicycle easily holds a straight line						*rider compensation*	centering
Nervous	9. I have to make steering corrections to follow a straight line						*rider compensation*	nervousness / steering precision / centering
Controllable	10. The bicycle is under control when mounting and dismounting						*controlability*	
	While steering	**Strongly disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly agree**	*Cooper-Harper terminolofy*	*Other used terminology*
		-2	-1	0	+1	+2		
Manoeuvrable	11. The bicycle easily steers around an obstacle						*effort*	effort / smoothness / steering precision
Manoeuvrable	12. The bicycle easily steers into a corner							effort / smoothness / cornering
Manoeuvrable	13. I do not have to put in effort to turn the steer						*effort*	effort / smoothness
Direct / Manoeuvrable	14. I does not take much effort to change the heading of the bicycle						*effort*	effort

Figure 15: Final version of the questionnaire. Translated from Dutch to English

2.3. DISCUSSION

During the interviews with the Gazelle employees it became clear very quick that there just was no general set of handling qualities. Also the descriptions that were given by the employees differed per handling quality, some handling qualities were used more often for a bicycle and some bicycles were described with different qualities each time. From all the descriptions the employees gave, a general description for each handling quality had to be formed. This might have led to some distorted descriptions. The first list of handling qualities was longer than the final list. The first list held as many separate handling qualities as possible, to make it as correct as possible. However, the list of questions that came with the handling qualities was found to long and it had to be shortened. With this shortening, some handling qualities are discarded as 'not actual handling qualities', but some were incorporated in other qualities because of the similar description the employees gave. Due to the removal of some handling qualities and clustering of them, the list became shorter, but the handling qualities were not as distinct as before. Because questionnaire could not be too long, also the questions about the handling qualities had to cover most of the descriptions in 1 or 2 questions. If it was possible to construct more questions about one handling quality, than the handling qualities could be questioned more in depth. The way it is done now, some qualities might not be interpreted the same by everyone. It let room for real opinion, instead of rating actual events. This cannot be excluded completely, but it could have been decreased. Although the questions were discussed on forehand with the participants and from reactions of the participant it is known that they really tested the bicycle, there is still a great chance that the

questions are not answered the same way by every participant. This might lead to unexpected outcomes in the results. The experiment will point that out.

2.4. SUMMARY

In the first part of this research project on bicycle handling qualities at the Royal Dutch Gazelle, the handling qualities itself had to be discovered. None of these handling qualities were documented, so they had to be retrieved from the minds of the Gazelle engineers and marketeers. During interviews with 7 employees in total, 9 selected bicycles were discussed about the vision behind the bicycles and the handling qualities that the bicycles should have. From all these handling qualities that came forward, a list of handling qualities is created that will be assessed during this research project. The list of handling qualities had to be translated to a questionnaire, that could be used during an experiment were participants have to rate the handling qualities of the bicycles. With use of the descriptions that the Gazelle employees gave with the terms for the handling qualities, a list of questions is set up that can be rated on a 5-point Likert-scale. After discussing this questionnaire with the supervisors from Gazelle and adjusting the questionnaire, a list of 14 questions is put together. The questions represent the handling qualities on which the bicycles will be rated during the experiment. While adjusting and reducing the list of statements, some of the handling qualities are removed and will not be assessed in this research report; 'comfortable' and 'predictable' are taken out. The other handling qualities will be assessed during the experiment and compared to objective measures; 'lazy', 'sportive', 'safe', 'stable' (weave and capsize), 'forgiving', 'controllable', 'maneuverable', 'nervous' and 'direct'.

3

Cycling Experiment: Subjective Measures and Rider Measurements

In the previous part is explained how the handling qualities for this study are determined and how they are converted to a questionnaire which will be used in a cycling experiment. This part will cover the cycling experiment, the protocol and the collected data. The cycling experiment focuses on the collection of the subjective data and how the participants have cycled. The actual objective measures that will be modelled are discussed in chapter 4 and the comparison with the subjective data to check for any correlations will be presented in chapter 5.

The experiment was executed to collect data on how cyclists ride a bicycle and how they experienced riding the bicycle. The bicycles used in the experiment are the bicycles that were selected by Gazelle: Ami, Balance, Orange, Orange HFP, Orange HMB, Cityzen, Cityzen Speed, Tour Populair, Puur NL and Van Stael. These bicycles are discussed in chapter 2. First, the experiment is described, with all the pre-experiment activities and the protocol. After that the results will be presented from the questionnaire and the objective data

3.1. Preparation

The goal for the experiment was to collect subjective rider experience and data on how they have cycled. Because this experiment was the first of its kind, it was decided to keep it small. 10 bicycles were selected and these bicycles could only be used on a Monday, since these bicycles are test bicycles from the Experience Center of Gazelle. The Experience Center is closed on Monday's, so this was the only day of the week we could use the bicycles. Also, because this experiment was never executed before, the number of participants is kept at a minimum. If this experiment showed not to work, it would be useless to have a huge number of participants. Because of the uncertainty of the outcome and no records of any experiment like this, it is decided to only select 10 participants. This would mean that 10 participants would each ride 10 different bicycles, so there are 100 data sets to start with. For a first-time study, this is an acceptable amount of data. If this proves to work, such experiments can be done with a larger number of participants to increase the reliability.

3.1.1. Equipment

As stated above, 10 bicycles were selected for the experiment. A questionnaire for the subjective data was already set up and measurements of how the participants have cycled should be done. There were several ways to collect these data. The first option was a device, created by SWOV. SWOV is a research institute in the Netherlands that focuses on road safety. They have designed the so called 'SWOV-box', a waterproof device that is equipped with a data logger, GPS and an accelerometer, that can be mounted on the rear rack of the bicycle. Connected with wires, there is an accelerometer/gyroscope that can be mounted onto the stem of the steer, to collect data on steering actions. It even has an event-button, which can be pressed in case of a critical event, which logs into the data. This device would be the perfect solution to gather the objective data, on what movements the bicycle makes. Unfortunately, these boxes were not available at the times, as they were in use for another experiment. Building new boxes would not fit within the time schedule, so another

solution was required. But the information on the SWOV-box gave a start on the data we needed to log.

Arend Schwab, supervisor of this project, has some connections in the research field of bicycles and contacted some of them. From that, an idea came up on using smartphones with an app to log the data. Sensors in modern day smartphones are quite accurate, although not as accurate as sensors designed for the specific purpose of measuring changes in speed and angle. But as long as the smartphones are the same brand and model, these data could be compared with each other. This meant that 10 identical smartphones were required to log the data for 10 different bicycles. After informing at Gazelle, they ensured us that they could provide 10 iPhone 6 for the experiment. The iPhones were all the same model, so suitable for this experiment. Finally, we did not use the iPhones from Gazelle, but from an external company of which Gazelle hired the iPhones. The following step was to find an app that provided data from the accelerometer, gyroscope and GPS from the iPhones.

The first option came by one of the contacts of Arend Schwab, Stefan Candefjord from Sweden. He developed, with other researchers from Chalmers University of Technology in collaboration with SAFER (Vehicle and Traffic Safety Centre), an app that is specifically designed to log data from the sensors within the smartphone. It logs data from available motion sensors (typically 3-axis accelerometer, 3-axis gyroscope, GPS, speed based on GPS, and 3-axis magnetometer)[14]. The downside of this app was that it was not yet released in the Netherlands in the Apple App Store. It was released, however, in on Google Play for Android smartphones. We did not have these type of smartphones, but the authors of the app tried to release the app in the Netherlands for iPhone as well. Again, unfortunately, this could not be done in time for our experiment. But this gave the opportunity to search for similar apps, not specifically designed for logging of vehicle movement, but with the same possibilities. After some trial and error, one app stood out. The app SensorLog was able to record the location by latitude and longitude together with the speed and distance, the heading in 3 directions, the data from a 3-axis accelerometer and a 3-axis gyroscope, together with the yaw, roll and pitch of the device[15]. This app collected all the data needed for the experiment, and therefore this app was suitable to use.

To mount the iPhones onto the bicycle, smartphone holders for bicycles were used. These could be placed on the steer, so the iPhone could track the steering actions of the rider. If the iPhone was attached to the frame, the actions of the steer could not be collected. Since most of the questions of the questionnaire are about steering actions, it is important to also collect the objective data from the steering actions, so these can be compared later on.

The last essential piece of equipment for logging objective data, is a photo camera. In order to collect all possible data, also for the geometry which is presented in chapter 4, the position of the rider on the bicycle needs to be recorded. In order to do so, every participant has to be photographed on every bicycle to determine their position. This gives the possibility to also take the rider position into account in a rider-bicycle model.

3.1.2. PILOT

3.1.2.1. CYCLING

Before the experiment took place, a small pilot study has been done, to see if the iPhone with the app provided the information that was expected. Also the distance provided the information that was expected and to determine the distance to be cycled. Beforehand was determined that the participants would need at least 10 minutes of cycling to really feel the bicycle and think about how they experience it. Just a short round of 3 minutes was thought to be not enough to get a complete picture of the handling qualities of the bicycle. Because the participants have to cycle 10 times, it could not take too long. The maximum was put to 15 minutes. The total time of cycling should therefore range from 10 to 15 minutes.

The pilot study was executed by the author of this report. An iPhone 6 was used with the SensorLog app installed to test the data-logging. The recording was set to 100 Hz, to collect as much data as possible. The iPhone was mounted on the steer with a holder, to see if this holder worked. The holder could be wrapped around the steer and tightened, and with a hinge on top the iPhone could be tilted in a preferred position. Also a powerbank was taped onto the steer, connected to the iPhone to see if this was a solution to keep the battery from dying.

The route to cycle was determined on forehand with Google Maps and was 3.8 km long. The prediction was that it should take about 13 minutes to cycle this distance, which was within the range of 10 to 15 minutes cycling. Figure 16 shows the predetermined route. This route holds traffic lights, different type of road surface, small and large corners and different types of road crossings. So, there are a variety of traffic situations included in the route. Within the route, the speed of the cyclist should be normal, as if cycling to work or to do

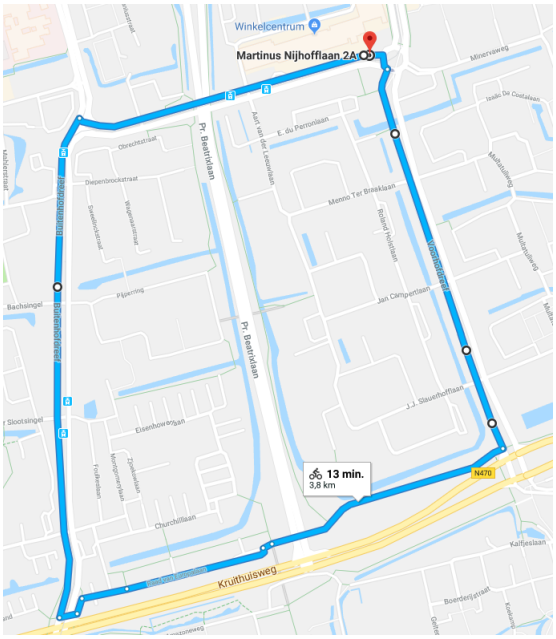

Figure 16: Pilot route of 3.8 km with a prediction of 13 minutes of cycling. Determined with Google Maps

some groceries. A self-determined speed. To also get information on cycling fast and cycling slow, two target speeds had to be implemented. In this pilot study, two speeds were chosen and checked if it was possible to ride at those speeds. For the slow speed, 2 m/s (7.2 km/h) was tried and for the high speed, 7 m/s (25.2 km/h) was tried.

The protocol for this pilot study should be the same as for the actual experiment. Therefore, the bicycle was equipped with the iPhone in the phone holder with the SensorLog app set up. The cyclists got into position, started the recording on the iPhone and started to cycle in a self-determined velocity. At the last part of the route, with a longer straight path, the two pre-determined speeds are tried. The speed could be monitored on the screen of the iPhone. When the route was completed, the SensorLog app was stopped and the data was saved onto the iPhone and could later be e-mailed for storage on a computer. After the route, the questionnaire was filled in and timed to see how long it took. This took about 5 minutes, when really reading the statements and thinking about the feeling of the bicycle.

3.1.2.2. DATA ANALYSIS

For the analysis of the data, the data could be retrieved from the iPhone in .csv format by e-mail. This file holds 57 different parameters and for each parameter it had 86860 data points. Not all parameters are useful for this experiment, so some of the parameters can be switched off during the actual experiment, to decrease the amount of data. The actual parameters used are the samples, sampling rate, longitude, latitude, yaw-, pitch- and roll angles and the x-, y- and z-axis of the gyroscope, which provides the angular velocity of the yaw, pitch and roll. The data is loaded in to Matlab and analysed using a script, displayed in Appendix C.

The amount of time cycled is calculated from the samples together with the sampling rate. There are 86860 samples in the pilot study with a sampling rate of 100 Hz.

$$\frac{samples}{samplingrate} = 868.6\ sec = 14.48\ min$$

This is close to the maximum time the total lap should take. Because of that, the final route can definitely not be longer than 3.8 km.

The longitude and latitude can be plotted against each other, to see if the cycled route is similar to the predefined route. Figure 17a shows the actual cycled route, based on the longitude and latitude data, and figure 17b shows the planned route. By comparing the two figures, it can be concluded that the intended route is cycled. This can also be done in the actual experiment, to see if the participants follow the intended route.

Figure 17: a. Actual cycled route. b. Intended route. Determined with Google Maps

From the time, longitude and latitude, the travelled distance and velocity are calculated. The GPS coordinated are translated to a distance on earth and corrected for the discrete values. The Matlab script in Appendix C shows the full translation. Distance and velocity are calculated and plotted against time, as shown in figure 18. From these figures can clearly been seen when the cyclists had to stop and for how long. This could be at a crossing or with traffic lights. As mentioned before, the last part of the route was used to see if a cyclist is able to cycle at 2 m/s and at 7 m/s. Figure 18 shows the velocity graph in the bottom and shows that almost the entire route is cycled at approximately 7 m/s. Therefore, it can be concluded that it is possible. At the very end, a short period of time is cycled at 2 m/s, seen where the blue line lies on top of the black line. This is seen more often in the plot, but when comparing the velocity to the travelled distance, this is at the points where the cyclists had to stop (flat line in travelled distance). So there is an error in measurement at those points, probably due to the discrete time line. However, this flat line does not occur at the end of the route, where there is actually cycled at 2 m/s. The travelled distance is increasing, so this part is correctly measured. Although this part is only a short period of time, it is possible to cycle at 2 m/s. Therefore, these speeds can be used in the actual cycle experiment.

Figure 19 shows the data retrieved from the gyroscope, angle and angular velocity, filtered with a low pass filter at 15 Hz to remove noise. 15 Hz is chosen, because the limit of motions by a human lies at 10 Hz. That means that any motion above 10 Hz is not executed by the person riding the bicycle, but by the road surface or other vibrations that can cause noise. To build in a safety range, to not filter out any human steering actions, the limit is set at 15 Hz.

The roll angular velocity is still very noisy. The angular velocity of the yaw shows the way the cyclists is steering. With a high angular velocity, there is a lot of fast steering, and with a low angular velocity, there is a lot of steering going on. Roll angular velocity describes the roll of the bicycle. The angles show the corners that are made and how far the bicycle is rolling over. On its own, there is not much to tell about the angular velocity, but in combination with the velocity and travelled distance, the moments of standing still and riding are very distinct. That is shown in figure 20, were all graphs are combined. There is no angular velocity when the cyclist is standing still (at 0 m/s) and there is some steering action when cycling. Of course, the most important part is the angular yaw velocity at cycling fast and cycling slow: are there a lot of steering corrections necessary to ride in a straight, or is a lot of steering unnecessary? At the end of the lap, when the velocity reaches 2 m/s, the yaw angular velocity increased with respect to the rest of the lap. This indicates more steering. This can also be seen when starting from a complete stop: higher angular velocities after a stop, than when during cycling for a longer period of time.

An actual number for the amount of steering can be gathered from the Power Spectral Density (PSD) of the yaw. The PSD shows the amount (power) of frequencies (Hz) of the steering actions. The more steering there is, the higher the power. The surface underneath the PSD is then a measure for the amount of steering that has been done while riding the bicycle. Figure 21 shows the PSD of the yaw from the pilot study, with a surface of 0.8411.

For the actual experiment, the segments with a speed limit, 7 m/s or 2 m/s, can be defined more accurately in the data. All this data can then be split up in different data segments for the high, low and self-chosen speed. This will provide more insight in the different speed ranges for the handling qualities.

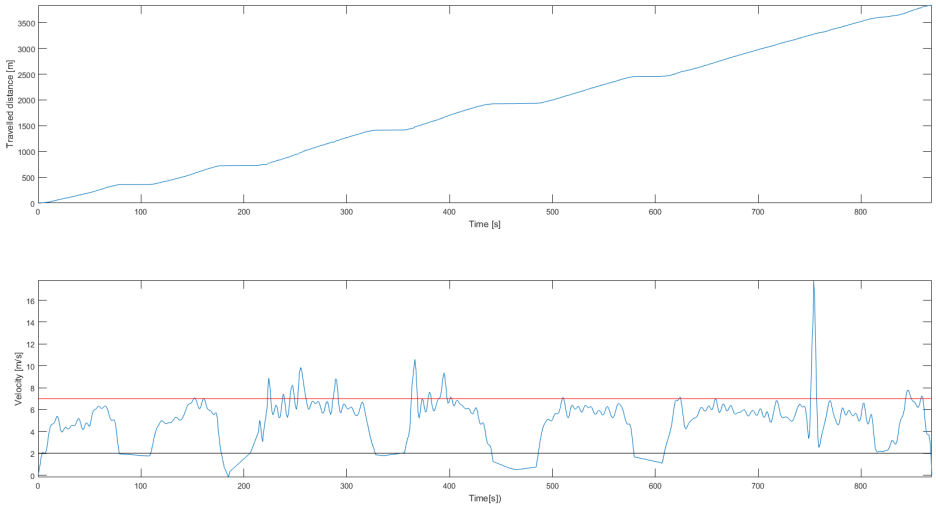

Figure 18: Distance and velocity against time. The red line marks 7 m/s, the black line marks 2 m/s

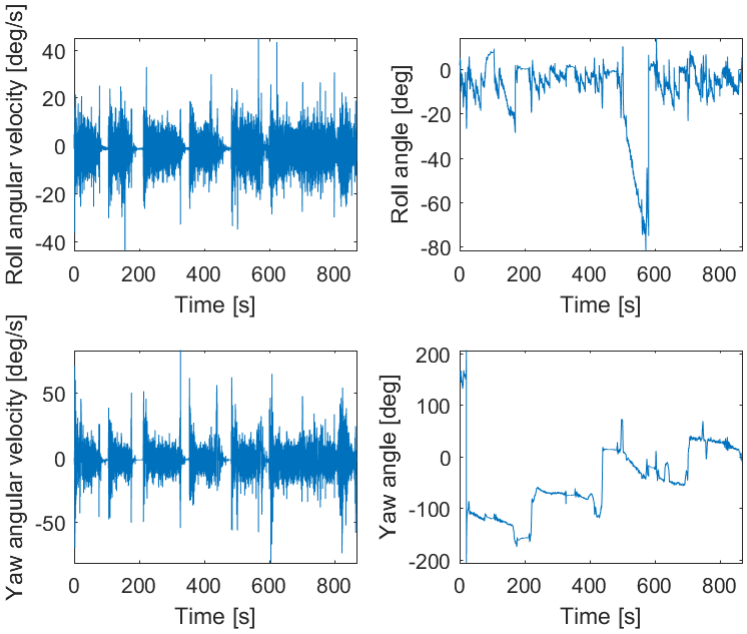

Figure 19: Roll and yaw angle and angular velocity against time

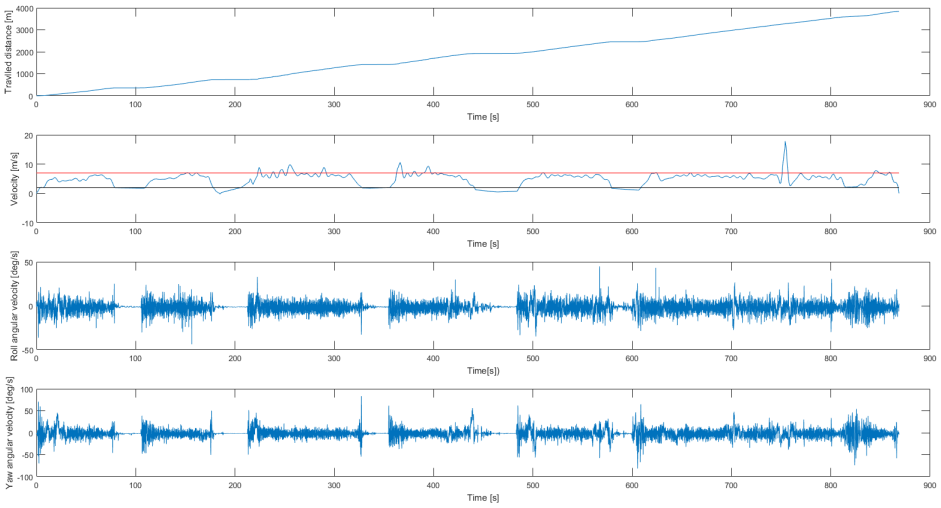

Figure 20: Distance, velocity, roll angular velocity and yaw angular velocity, normalized in time

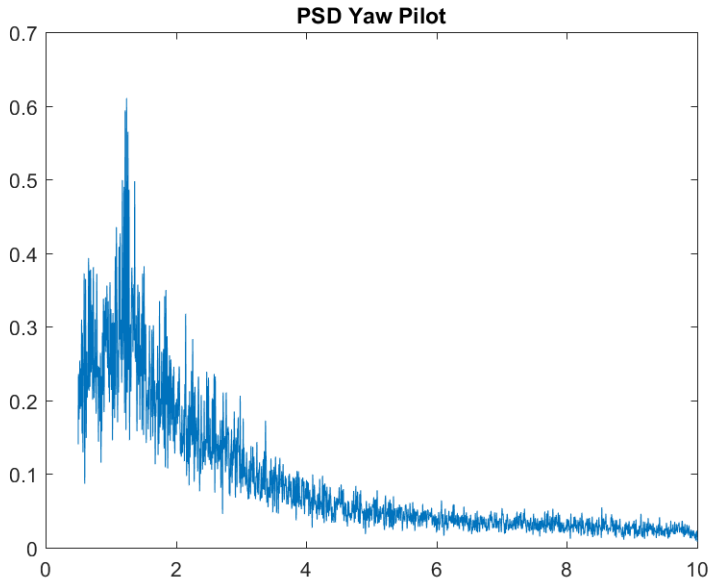

Figure 21: Power Spectral Density of the yaw angular velocity of the pilot study, with a surface of 0.8411

3.1.3. CONCLUSION

In conclusion, the pilot study showed that the total distance of the route should not be longer than 3.8 km, to stay within the time limit of 10 to 15 minutes. Filling in the questionnaire took about 5 minutes. The iPhone logs the required data and the data can be analysed in Matlab. Data such as time, travelled distance, velocity, angles and angular velocities can be used to provide insight in the steering actions the cyclists made. These numbers are objective, as they are not influenced by the opinion of the cyclist, but measured by sensors. The data might not be as accurate as a device specifically designed for this purpose, but sufficient enough to provide useful data. The data that is required does not need to carry very detailed information, as human cannot initiate a frequency higher than 10 Hz.

The equipment necessary for the bicycle experiment are the 10 bicycles, 10 identical iPhones with the SensorLog app installed and 10 smartphone holders for attaching the iPhone to the steer and a camera. In addition to these essential items, power banks with chargers are also added to the list, to make sure the batteries of the iPhones will last the entire duration of the experiment.

3.2. METHOD

3.2.1. BICYCLES AND PARTICIPANTS

In this cycling experiment, the 10 selected bicycles are all tested by 10 different participants. A recap of the bicycles: Ami, Balance, Orange, Orange HFP (motor in the front wheel), Orange HMB (motor in the cranks), Cityzen, Cityzen Speed (motor in the cranks), Tour Populair, Puur NL and Van Stael. These bicycles are discussed in chapter 2 and more detailed information on the bicycles can be found there.

To keep things easy and less complicated in logistics, it is decided to select one frame size for the bicycles. The bicycles had to be reserved before all participants were selected, so a frame size is chosen such that any possible participant would fit the bicycle. On suggestion of the supervisor of Gazelle, a lady's model with frame size 52-54 (depending on the available sizes for each bicycle) is used for the cycling experiment. Everyone should fit on this frame and size, and saddle height can be altered for each individual participant.

For the experiment, 10 subjects will participate. The original thought was to select 5 participants from the Royal Dutch Gazelle, with knowledge of the bicycles, and 5 independent participant, with no knowledge of the bicycles. There was one demand; the independent participant had to have affection with cycling and knowledge on dynamics, or a great understanding that different types of bicycles could have different feelings. They needed to know that they really have to pay attention to small differences in handling of the bicycles, in more detail than just 'it feels good' or 'it does not feel good'. The goal is not to get an impression of consumer views, but one of an experienced cyclist. The independent cyclists are selected to prevent a tunnel vision by the Gazelle employees. However, it was not possible to have 5 participants from Gazelle, only 4 had the time to participate. For that reason, an extra independent cyclist participated, resulting in 4 Gazelle cyclists and 6 independent cyclists. The independent cyclists included 4 cyclists who cycle for a hobby, 1 track cyclist with a minor handicap participating in the talent Paralympic group of the Netherlands and 1 bicycle mechanic.

The participants filled in an informed consent and all gave permission to use video and photo material. Unfortunately, it was found out a couple of days before the experiment, it is obligatory to have a driver's license for motor driven bicycles in order to cycle on the Cityzen Speed. One of the participants did not have this license, so he could not cycle on the Cityzen Speed. All other participants have cycled this bicycle and the participant without a license does have cycled at all the other bicycles.

The participants also filled out a form with some information about themselves. The information about the cyclist was to complete the picture of the participants. Age, gender, mass, height, cycling-hours per week and amount and types of bicycles. Most of this information was not used for the experiment, but gave some insight in the cycling experience of the cyclists. Only the mass and height are used to determine the moment of inertia of the participants (discussed in chapter 4).

3.2.2. ROUTE

The bicycle route is located in Dieren in the Netherlands, around the factory of the Royal Dutch Gazelle. From the pilot study was clear that the route should not be longer than 3.5 km. Because this study focuses on bicycle handling qualities of city bicycles, the route is located in an urban area to simulate a bicycle tour from home to work, for shopping, visiting a friend or family. This ensures different type of traffic situations and interaction and different type of road surfaces. This way, the bicycles can be experienced according to their purpose.

The author of this report is familiar in the area around the factory, and with that knowledge, the route is set up with the use of Google Maps. By using Google Maps, the start and end point are fixed at the Gazelle factory and a route of approximate 3.5 km is selected around it. The selected route runs through residential area with small brick roads and parked cars, along the main road through town on asphalt with cars moving at higher speeds, through industrial area with poorly maintained road, and through shopping area. This route also included traffic lights, crossing a train track and sharp and wide corners. This way a daily cycling route is simulated, such that the bicycle can be felt and tested in different situations. According to the prediction of Google Maps, this 3.5 km route should take about 11 minutes, with the range of 10 to 15 minutes. On forehand, the route is marked with arrows on clearly identifiable signs, so the cyclists can follow the route by the signs and they do not have to memorize it. At specific points at the end of the route, the signs show the prescribed speeds of 7 m/s and 2 m/s. Because it was not possible to have two long straight roads to let the participants cycle at the prescribed speeds, for the 7 m/s two smaller straight parts with one corner are selected. These parts are considered safe to cycle fast and long enough to reach the 7 m/s and hold it until the corner or until the sign to stop cycling at that speed. This part is longer than for 2 m/s, because the cyclists had to feel comfortable with the high speed. If they did not feel safe at the first part, they could reach the

speed at the second part. For the 2 m/s, the last straight road of the route is selected. Figure 22 shows the entire route (blue), with the two sections of prescribed speeds. 7 m/s is marked in red, 2 m/s is marked in green.

3.2.3. PROTOCOL

At the experiment, all 10 participants will cycle on each bicycle along the prescribed route. Only the participant without the proper license cannot ride the Cityzen Speed. Beforehand, the participants got the questionnaire e-mailed, so they could read it and ask questions.

Before the experiment starts, all bicycles are equipped with the smartphone holders, with the iPhone inserted and the settings in the SensorLog app are set to the right values by the leader of the experiment; a sampling rate of 100 Hz. Because the steers of all the bicycles were different and equipped with different accessories, the smartphone holders could not all have the same position and angle. At the moment nothing could be changed about that.

At the beginning of the experiment, the questionnaire was discussed with the participants, so there could be no mistakes on what was meant by the statements and they knew on what to pay attention. Then they were briefed about the events that would take place. The briefing was the same as this protocol. All participants cycle individually to prevent being influenced by others or changed the preferred speed. The participants start 2 minutes after one another, to ensure enough distance. The participants are asked to ride a self-chosen speed, a speed on which they would cycle as they go to work, school or shopping. That is to simulate a daily cycling tour.

The participants get ready, go to the appointed starting line and enable data logging in the app. The participants start the route and follow the directions along the route. At the last of the route, there will be a sign with 'start 7 m/s', where the participants should start cycling with 7 m/s until they reach the sign with 'end 7 m/s'. After that, a sign with 'start 2 m/s' shows up, indicating a speed of 2 m/s until the 'end 2 m/s' sign. This is to simulate cycling fast and slow. In the briefing the participants are made clear, that if there occurs any unsafe situation, they can stop cycling or change speed. Their safety goes first. When the participants have completed the route, the data logging is stopped and the data is saved. The file name is written down, together with the participant's name and bicycle, so the data can be connected to the participant and bicycle later on. The bicycle is stalled and the participant gets the questionnaire. Name and bicycle are written down on the paper, so the questionnaire can be connected to the data. After 15 minutes, to provide rest, the participant

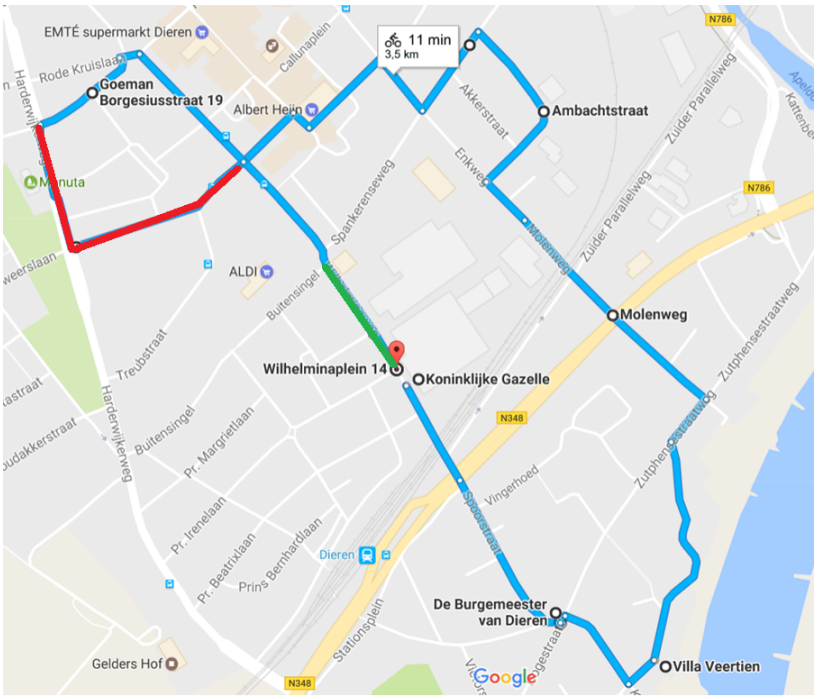

Figure 22: Route of the cycling experiment. Prescribed part of 7 m/s is marked in red, prescribed part of 2 m/s is marked in green. Determined with Google Maps

starts with the next bicycle and follows the same protocol. Each round should take about 15 minutes. There was a time schedule to provide a cycling order. Each participant starts and end with a different bicycle, to minimize the effects of the boredom or fatigue of the experiment. The bicycles are rotated in each round, so that all bicycles participate in each round and participants do not have to wait until there is a bicycle available. A special note on the bicycles with electrical support; if the bicycle has support, the support should be turned on.

At the lunch break, pictures will be taken from the participants on the bicycle. Because of logistics, it was not possible to capture the participants on the bicycle while cycling. The pictures are now taken by positioning each participant on each bicycle in the posture as they would have when cycling. The participants sit on the bicycle, very close to a wall, so that the bicycle stands straight up, with the participant leaning with the shoulder against the wall to prevent falling. The picture is then taken from a 5 meter distance, to prevent distortions by perspective. The spot from which the pictures will be taken is marked, to ensure the same perspective every time.

Is has to be noted that the protocol was not followed completely. Although the participants were instructed to cycle individually 2 minutes after each other, the participants started cycling together. Or they met each other while cycling, or they just started at the same time. There was decided to let it happen, because they had all very clear instructions on how to cycle and to what aspects they needed to pay attention. The cyclists knew what the goal was, so it is expected that the results are not actually influenced. They even reported that they tested the bicycle by hitting the steer, or making an 'avoiding move', just because they were interested. So, they were really paying attention to the handling qualities of the bicycle. The participants also did not wait for the entire 15 minutes, because they were not tired or sick of cycling. The 15 minutes was added to ensure they would not get tired, and as long as the participants were not tired or did not want to wait, they would not have to.

3.2.4. DATA COLLECTION AND ANALYSIS

During this cycling experiment, data is collected on two different parts. Data from cyclists and bicycle measured by sensors and photos and subjective data from the cyclists about the bicycle.

3.2.4.1. RIDER MEASUREMENTS

3.2.4.1.1 iPhone measurements The measured data that was collected about the rider behaviour during the 3.5 km cycling route, is already described in the previous section with the pilot study. An iPhone 6 was used, with an app SensorLog to log all data from the available sensors on the iPhone. Not all sensors could be disabled from logging, if the data was unnecessary, so the original data file held a lot of information. The files were saved with a time and signature on the iPhones. The file names were noted together with the participants name and bicycle, so they could be named properly after saving the data. The information ultimately used for analysis were the sample rate, amount of samples, roll-, pitch-, and yaw angles in radians, the roll-, pitch-, and yaw angular velocity in radians per second from the gyroscope and the longitude and latitude from the GPS. For each participant on each bicycle, a set of data is collected. This would be 99 data sets, 10 participants on 10 bicycles, minus the one without a driver's license for the Cityzen Speed.

Unfortunately, after examining the data for the first time, it appeared that some of the data was not collected properly. This is due to malfunctioning iPhones. Some of the iPhones' batteries were malfunctioning and empty very fast. Even charging and using powerbanks was sometimes not enough. With use of the iPhone 6 from one of the participants (same brand with the app installed), it was tried to solve the problem. This worked at the moment, but during analysis of the data, it was found out that the data was sampled at 20 or 10 Hz, and not on the required 100 Hz. So, these data files could not be used for the analysis. Doing the experiment again was no option, so the research had to continue with bicycles that did not have 10 different data sets. The failed measurements included 3 times the Orange HFP, 4 times the Tour Populair and 2 times the Puur NL. This means that for 99 data sets 9 were unfit, 9% of the data could not be used. All the other data is analysed as mentioned below.

Based on the sample rate and amount of samples a time line was constructed. The longitude and latitude coordinates are converted to a distance, by a discrete function. With the time line and the distance from the GPS, a velocity profile is created. Due to noise in the recording of the data, it is filtered with a low-pass filter at 15 Hz. Speed at a bicycle does not change very fast, and 10 Hz is the limit of human movement, so 15 Hz was high enough to filter any noise but to preserve the necessary data. From GPS and velocity profiles, the cycled route could be examined. Have they followed the directions, and what was their speed at the different

segments of the route? The data from the angles and angular velocity is filtered with a low-pass filter at 20 Hz, to make sure no steering actions of the participant is lost. Figure 23 shows an example of the filtered data as used for the analysis. This figure shows the same graphs as in figure 20 of the pilot study.

Based on the GPS data, segments of the route are selected to examine closer on specific velocity prescriptions. The GPS coordinates are searched for manually, based on the prescribed segments. These segments are shown in figure 24. Blue 'o' is the free segment, black '+' marks the 7 m/s segment and red '*' the 2 m/s segment. A specific coordinate is taken along the route, with a deviation of 10^-3, for the start and ending of each section. The section of 2 m/s and 7 m/s second were prescribed. The section for the free, self-chosen, velocity is based on the routes that each individual has cycled. There were some mistakes in the route for the first round, and these mistakes are considered when selecting the free-section. The section is chosen such that different traffic situations and road surfaces are within the segment, so holds as much information as possible from a daily cycling tour. When the sections for the specific velocities were selected, the same sections are used to define the velocity, angles and angular velocities for the three speeds, 2 m/s, 7 m/s and the free speed. For these sections the average speed is calculated, to check if they actually have reached the prescribed speed and what their average self chosen-speed was.

The angular velocities are analysed in a Power Spectral Density (PSD) graph. For each velocity segment, for each angle, the peak frequency and the surface underneath the graph are collected. The peak frequency of the PSD shows the frequency in which the participant steers the most. The surface shows the overall amount of steering and describes the amount of steering necessary to keep the bicycle straight. Figure 25 shows an example of the PSD for the yaw, cycling at 2 m/s. Because it was found most interesting, as it shows the turning of the steer by the cyclists, only the yaw is used for the PSD-graphs. The data is analysed for yaw and roll, as the pitch does not change. The analysis is done in Matlab, the same way as in the pilot study. The files can be found in Appendix D. In the next section, the results of the all the bicycles and participants are presented.

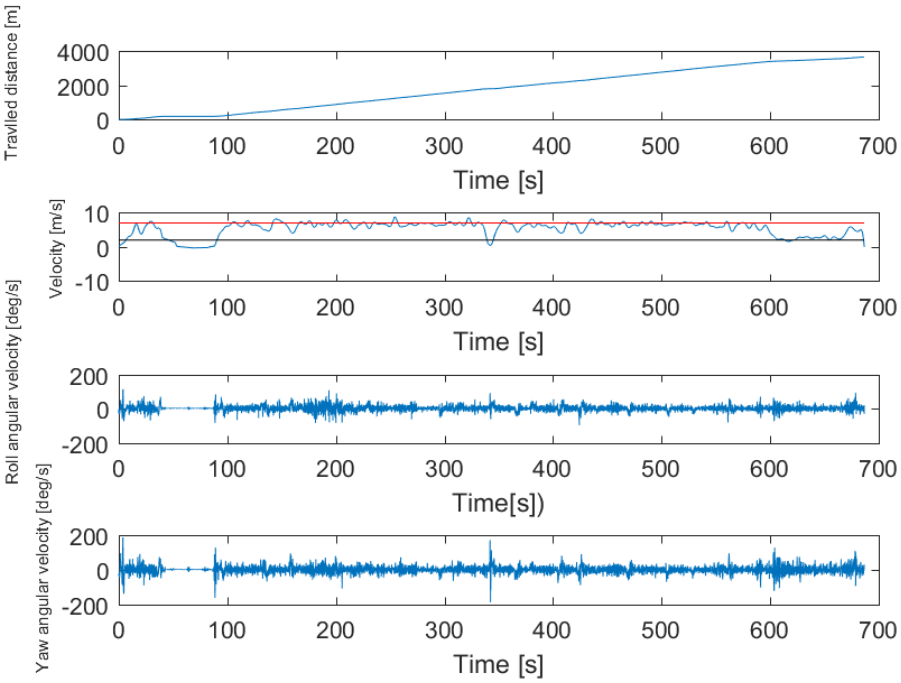

Figure 23: Example of the data. Distance, velocity, roll angular velocity and yaw angular velocity, normalized in time

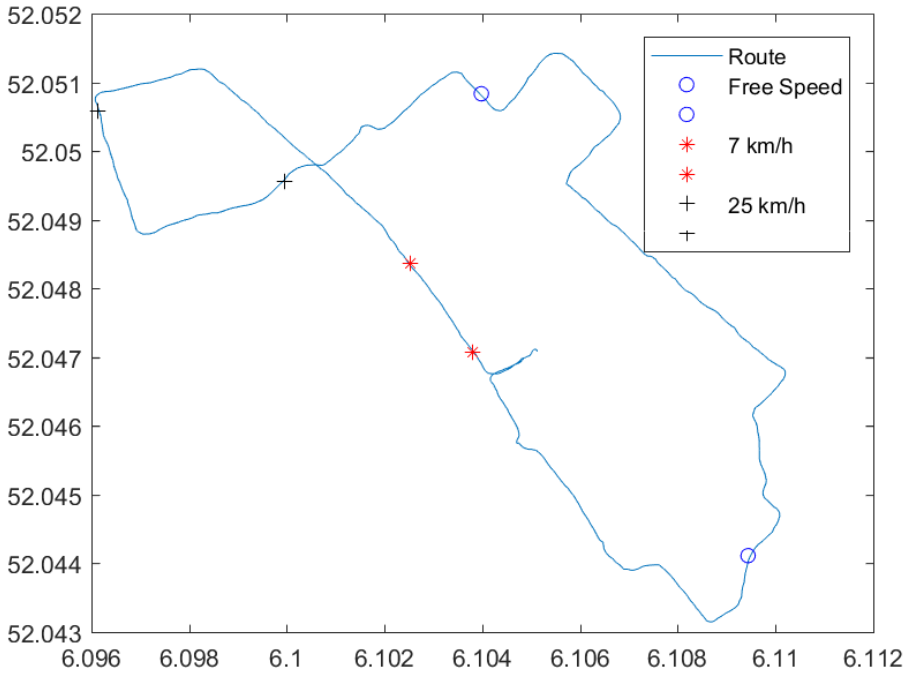

Figure 24: Example of a cycled route, with markers for the speed sections. Between blue 'o': free speed, black '+': 7 m/s, red '*':2 m/s

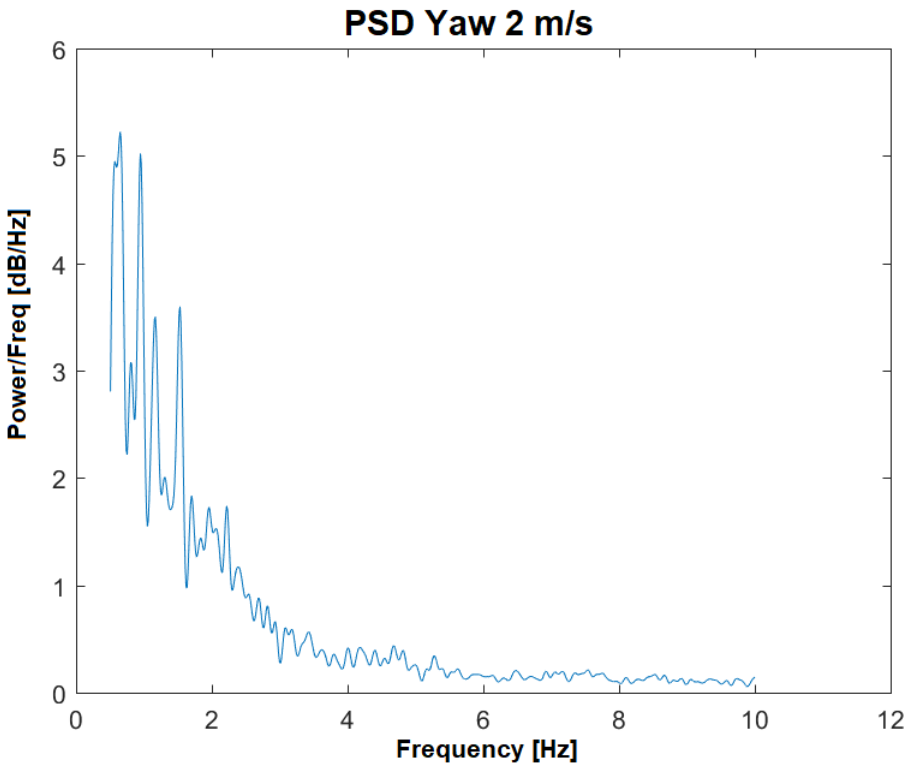

Figure 25: Example of a filtered PSD, for the yaw at 2 m/s

3.2.4.1.2 Posture The second rider measure from the experiment is the posture of the participant on each bicycle. As was mentioned by the Gazelle employees, the geometry of the bicycle results in leaning more forward (sportive) or backwards (lazy) on the bicycle. It is thought that the posture of the rider on the bicycle influences the behaviour. The JBike6 program includes the posture of a rider, in a very simple manner. The rider is added to the bicycle as a point mass with a moment of inertia around a principle axis. In order to complete the model for comparison with subjective data from the experiment, the information of the rider's posture during the experiment is required. The protocol of collecting the pictures is described above. One participant did not get the picture taken on two of the bicycles (Cityzen and Orange), but those were bicycles with the same geometry as other bicycles (Cityzen Speed and Orang HBM/HFP), so the angles of those pictures are takes, as they should be the same. The pictures are taken from a distance, so that there is almost no effect of perspective in the picture.

Every single picture is analysed with Kinovea[16], an open source program that is able to measure within photographs and videos. From the pictures, the centre of mass (COM) is estimated, around navel height and at the front of the body. This estimation is based on the knowledge that the centre of mass lies at 55% of the persons height, measured from the floor, and just in front of sacral vertebrae S2 when standing. Since the rider is seated and the arms and legs are moved to the front of the body, the COM moves more to the front and slightly upwards. Because the participants where not marked, the COM is estimated solely on the pictures and is not very accurate. In Kinovea, the COM is marked and then measured in x- and y-direction, with the origin of the axis system is the ground contact point of the rear wheel. The measurement is based on a calibration of a known distance, the wheelbase. This information was provided by Gazelle and will be further discussed in chapter 4. The wheelbase was measured from two clearly visible points, the wheel axes, and then moved downwards until it reaches the ground contact points. This line was given a length in mm, and this would be the calibration point of all other lines that would be drawn. With the use of a grid, the distances from the COM to 0-x and 0-y were measured. In addition, the angle of the participant on the bicycle was taken, with respect to the horizontal. A virtual line through the torso of the participant was followed, and the angle with the horizontal was taken as the angle of the participant of the bicycle. Figure 26 shows an example of these photo-analyses, the original in 26a and the analysed one in 26b. Also these results are presented for all participants and bicycles in the next section.

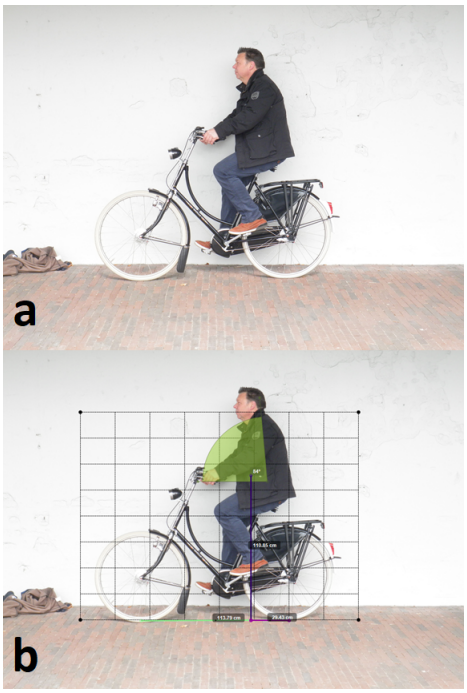

Figure 26: Example of a picture analysed with Kinovea: a. Original picture, b. Analused picture with location of COM and rider angle

3.3. RESULTS

The complete set of data can be found in Appendix D: measures from the iPhone sensors and subjective opinions on the bicycles, for each participant on each bicycle. The lines marked in red are the data sets that could not be used due to a wrong sample rate. Not all 90 figures of each measured variable are provided, that would be too much. Instead, the routes of the cyclist are discussed without all the figures present, the average speed and PSD peak and -surface of the segments are provided. The same accounts for the subjective data. The average data is provided in the text, the rest can be found in Appendix D. The analysis

3.3.1. MEASUREMENTS

From the data can be seen that most of the time the participants have cycled the determined route and thus could follow the directions. Only a few participants have made mistakes in the first rounds. This could be seen from the GPS data, one example is shown in figure 27. The green encircled part shows multiple lines crossing at a wrong section of the route. This indicates the participant was lost. The route took a little longer, and for some others the coordinates that are supposed to be in the data are missing. This gave some complications with selecting the data for the free speed segment. But by closely examining each data set on the cycled route, suitable coordinates could be chosen, such that there was enough data and multiple situations on the road are incorporated in the data. And as the data is averaged over the section, there is not a large effect of taking a wrong route in the free speed segment.

For the iPhones measurement, the rider COM, mass and angle are presented in the general data set in Appendix D. The rider COM, mass and angle will only be used for the rider-bicycle model. From the raw data could be seen that the values are different for each participant on the same bicycle. The differences between the participant's angle are larger for one bicycle than for the other. The average (with standard deviation (STD)) velocity, peak frequency of steering (yaw) and the surface of the PSD (yaw and roll) over the three segments are presented in figure 28. For each segment, the mean for one bicycle is calculated, so averaged over the participants. From this data can be seen that the prescribed speeds are not always reached on average, but also not as individual participant (results in Appendix D). This is the average data, so they might have cycled at some points below and at some points above 2 m/s. In general, the deviation from the target speeds are small. However, the deviation from 2 m/s to the actual cycles speed is higher than for the deviation of 7 m/s. The STD for each bicycle is small for most, so there are no large differences between the participants on one bicycle. The same trend of a small STD occurs for the free speed. This suggest that some bicycles tend to induce a slower cycling speed and others a higher speed. Otherwise there would be a larger STD when the participants all have a preferred speed and stick to that speed for each bicycle. Also interesting to note is the free speed of the Cityzen Speed: 7.9 m/s. This is faster than the prescribed 7 m/s. This is probably due to the electrical support, up to 45 km/h (12.5 m/s). Therefore it is easy to cycle at high speeds, so the bicycle encourages to cycle really fast.

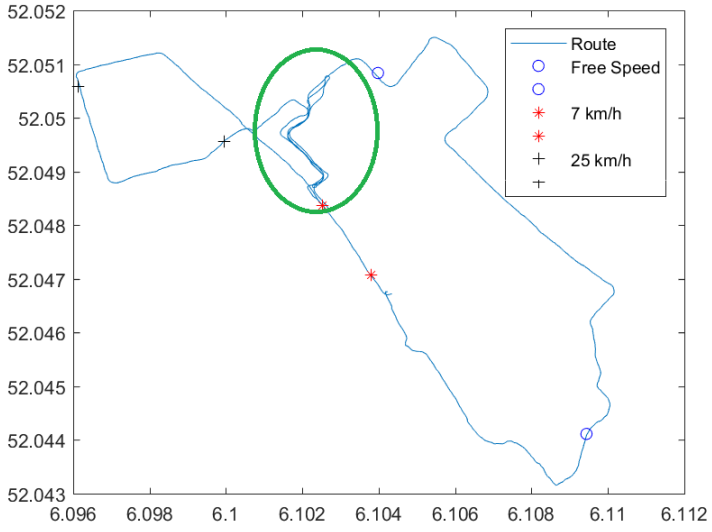

Figure 27: Route from GPS data. Green encircled: wrong route by a lost participant.

Bicycle	Velocity Free [m/s]	Velocity 2 [m/s]	Velocity 7 [m/s]	Peak Freq Free [Hz]	Peak Freq 2 m/s [Hz]	Peak Freq 7 m/s [Hz]	PSD Surface Yaw Free	PSD Surface Roll Free	PSD Surface Yaw 2 m/s	PSD Surface Roll 2 m/s	PSD Surface Yaw 7 m/s	PSD Surface Roll 7 m/s
Ami	6.35	3.15	6.63	1.12	0.77	1.22	2.83	2.38	4.87	1.60	3.88	3.01
STD	*0.44*	*0.30*	*0.20*	*0.16*	*0.30*	*0.18*	*0.61*	*0.79*	*1.48*	*0.44*	*0.59*	*0.82*
Balance	6.30	3.17	6.46	1.02	0.76	1.08	2.85	2.31	4.53	3.32	3.54	2.87
STD	*0.54*	*0.39*	*0.26*	*0.21*	*0.20*	*0.23*	*1.05*	*0.47*	*2.19*	*1.35*	*0.65*	*0.33*
Orange	5.11	3.18	5.80	0.89	0.79	1.12	2.96	2.55	4.04	2.54	4.42	3.23
STD	*0.42*	*0.54*	*0.37*	*0.25*	*0.32*	*0.28*	*1.47*	*2.40*	*1.15*	*0.52*	*0.67*	*0.42*
Orange HFP	6.46	3.45	7.24	0.92	0.70	1.04	2.70	2.07	4.66	2.78	4.60	3.12
STD	*0.59*	*0.41*	*1.65*	*0.25*	*0.14*	*0.33*	*0.76*	*0.60*	*1.22*	*0.70*	*2.08*	*1.26*
Orange HMB	6.17	3.30	6.41	1.06	0.67	1.06	3.13	1.79	4.28	1.92	4.02	2.46
STD	*0.63*	*0.43*	*0.27*	*0.26*	*0.13*	*0.23*	*1.01*	*0.54*	*1.00*	*0.45*	*1.00*	*0.46*
Cityzen	6.08	3.72	6.42	1.27	0.76	1.44	3.10	1.60	4.44	1.28	5.27	2.78
STD	*0.70*	*0.66*	*0.33*	*0.32*	*0.26*	*0.49*	*0.68*	*0.44*	*1.03*	*0.26*	*0.75*	*0.41*
Cityzen Speed	7.89	3.59	6.84	1.25	0.73	1.06	3.40	1.90	4.45	1.66	4.69	2.58
STD	*0.69*	*0.76*	*0.55*	*0.23*	*0.20*	*0.16*	*0.61*	*0.33*	*0.93*	*0.30*	*2.14*	*1.20*
Tour Populair	5.23	3.03	6.16	0.96	0.60	1.18	2.18	1.48	2.90	1.78	4.48	3.02
STD	*0.31*	*1.42*	*0.21*	*0.24*	*0.38*	*0.21*	*0.37*	*0.29*	*1.63*	*1.00*	*0.53*	*0.26*
Puur NL	5.53	3.46	6.24	0.95	0.82	0.96	2.34	1.73	4.17	2.48	4.31	3.07
STD	*0.44*	*0.57*	*0.21*	*0.31*	*0.26*	*0.24*	*0.27*	*0.18*	*1.10*	*0.72*	*0.70*	*0.50*
Van Stael	5.97	3.68	6.32	1.18	0.75	1.72	3.04	1.69	4.96	1.82	5.19	3.02
STD	*0.58*	*0.64*	*0.47*	*0.44*	*0.20*	*0.73*	*0.71*	*0.32*	*1.15*	*0.56*	*1.57*	*0.84*

Figure 28: Rider measurements. Mean for each bicycle with STD

The peak frequency of the yaw gives an idea about steering control from the participants. If the peak frequency of the yaw is very high, there are faster corrections than when the yaw is lower. With a low frequency, slower corrections are made to control the bicycle. The peak frequency when cycling at 2 m/s is lower than when cycling at the free speed or t 7 m/s. The peak frequency for the free speed and for 7 m/s are similar. The surface underneath the PSD graph gives an indication of the amount of steering. The larger the surface, the more corrections are made. The yaw surface of the free speed is lower than both the surfaces for 2 m/s and 7 m/s. The differences in yaw surface between 2 m/s and 7 m/s differ within each bicycle. For the Ami and the Balance, the surface is higher, so more steering when cycling at 2 m/s. The Tour Populair has more steering, a larger surface, at 7 m/s. The roll surface shows the same trend. This can be explained by the fact that turning the steer has an effect on the roll of the bicycle and therefore on the roll of the steer. The amount of roll is not as present as the amount of yaw, so the differences are not as large as in the yaw, but still present and proportional to the yaw. So, when cycling at 2 m/s there is slower but more steering. The van Stael requires the most steering action at 2 m/s, at 7 m/s the Tour Populair shows the most steering actions.

3.3.2. SUBJECTIVE DATA

3.3.2.1. SCORE ANALYSIS

The subjective data were the answers to the questions from the questionnaire with the handling qualities. Each participant filled out the form for each bicycle they had cycled on. No statements were unanswered, so there were no gaps in this data set (except for the participant who did not cycle on the Cityzen Speed). This data was collected after each round and digitized for analysis after the experiment. The questionnaire was already presented in chapter 2 by figure 15 and the raw data of the questionnaire is shown in Appendix D, by the last 14 columns of the results. This data is averaged over the participants, so there is a mean score for each bicycle. These values are presented in figure 29.

Although not all data from the iPhone measurements could be used due to recording problems, all data from the questionnaire is used for the subjective analysis. All data was present and the recording problems were not of influence of the cycling perception of the participant. By looking to the mean subjective data, it shows from the STD values that the participants did not always agree with each other on the handling quality.

The STD's are reaching values of 1 or higher for a number of bicycle-statement combinations. This is of course due to the small number of participants. There are always differences between the opinion of participants and with only 10 scores per bicycle, these differences in opinions can be easily seen in the results. It is also interesting to see whether these differences occur between the Gazelle-employees and the independent participants. The scores of the Gazelle-participants and independent-participants are separated and again analysed. These values are then compared with each other, to see if one group scores the bicycles different from the other group. Appendix D holds the figures with the values for the Gazelle- and independent-participants and the differences between the two groups.

To start with the scores of the Gazelle-participants, they agree on most of the bicycles. Agreeing and disagreeing with each other is based on the STD value. The higher the value, the more the score of the Gazelle employees differ from each other. For the Balance, Orange HFP and Cityzen speed, they disagree most about the handling qualities. For the Orange HMB, but also for the Ami, they disagree in the same amount as the agree. This is not always for the same questions, so it is not one handling quality that they cannot define very well. They data also shows that the Gazelle-participants are agreeing on the questions about steering the most. Only question 1,5,6 and 9 show some different scores. This suggests that they can experience the amount of, and how they steer better than they can experience straight riding and the general feeling the bicycle gives.

For the independent-participants, the results are not as clear. They disagree more with each other than the Gazelle-participants do. The independent-participants have experienced the bicycles very differently. It is unclear if this is because the Gazelle-participants are biased, or because the independent-participants are not as sensitive for their actions as the Gazelle-participants. This suggestion is backed up by the differences within the questions. The independent group is showing larger and more differences within each question, where the Gazelle-participants agreed more with each other. This holds for questions 11, 12 and 14 and in a lesser degree for 1,5,6 and 13. Questions 1,5 and 6 also came forward in the Gazelle-group, indicating a handling quality that is difficult to rate or experience (lazy, forgiving and stability at low speeds).

However, when the results between the groups are compared, it shows that the groups agree a lot more with each other than they do within their group. The two groups agree mostly on 8 of the 10 bicycles, except for the Tour Populair and the Puur NL. Also the questions scores are similar, except for 8 and 7. So, the

	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14
Ami	1	-0.7	0.8	1.3	0.2	-0.4	-0.7	1	-0.1	0.8	1.1	1	1	1
STD	*0.77*	*1.27*	*0.98*	*0.64*	*0.87*	*1.02*	*1.19*	*0.63*	*0.83*	*0.87*	*0.54*	*0.89*	*0.89*	*0.89*
Balance	1.2	-1.7	1.2	1.2	0.8	-0.6	-0.9	0.7	-0.9	1	0.5	0.7	0.5	0.8
STD	*0.98*	*0.46*	*0.87*	*0.75*	*1.08*	*0.92*	*1.04*	*1.10*	*0.83*	*1.00*	*1.36*	*1.10*	*1.50*	*1.08*
Orange	1	-1.4	1.4	1.3	1.3	-0.3	-1.1	0.9	-0.6	1.2	0.7	0.5	1	0.9
STD	*0.77*	*0.80*	*0.49*	*0.64*	*0.64*	*0.90*	*0.54*	*1.04*	*1.43*	*0.75*	*1.00*	*1.12*	*0.77*	*1.04*
Orange HFP	0.5	-1.5	-0.1	0.2	0.1	-0.3	-1.2	0.6	-1	0.6	0.2	0.1	0.3	0.4
STD	*1.02*	*0.50*	*1.14*	*0.98*	*1.45*	*1.27*	*0.98*	*0.80*	*0.77*	*0.80*	*1.17*	*1.30*	*1.27*	*1.28*
Orange HMB	1.4	-1.1	1	1.1	1.3	-0.3	-0.6	0.7	-0.6	1.3	0.8	0.9	1.1	1
STD	*0.66*	*0.70*	*0.89*	*0.83*	*0.90*	*1.00*	*1.11*	*1.27*	*1.28*	*0.46*	*0.87*	*0.83*	*0.54*	*0.89*
Cityzen	0	1.4	1.2	1.2	0	-0.8	-1.6	1.1	-0.7	0.9	1.3	1.1	1	1.4
STD	*1.00*	*0.92*	*0.87*	*0.98*	*1.10*	*0.60*	*0.49*	*0.70*	*1.00*	*0.70*	*0.90*	*1.14*	*1.10*	*0.49*
Cityzen Speed	0.1	1.6	0.4	1.0	0.4	0.0	-1.2	0.9	-0.6	1.0	0.6	0.8	1.0	0.9
STD	*1.29*	*0.50*	*0.96*	*0.67*	*0.96*	*1.15*	*1.03*	*0.74*	*1.17*	*0.82*	*0.68*	*0.79*	*0.47*	*0.74*
Tour Populair	1.2	-1.7	0.8	1.3	1.1	-0.6	-0.4	0.6	-0.4	0.8	0.4	0.4	0.8	0.7
STD	*0.75*	*0.64*	*0.98*	*0.64*	*1.14*	*1.02*	*1.28*	*1.20*	*1.11*	*1.17*	*0.92*	*1.02*	*0.98*	*0.90*
Puur NL	1.3	-1.5	1.1	1.1	1	-1.1	-0.4	0.5	-0.2	0.5	0.9	0.8	0.8	0.8
STD	*1.00*	*0.92*	*0.54*	*0.94*	*1.00*	*0.94*	*0.92*	*1.12*	*1.08*	*0.67*	*0.83*	*0.75*	*0.75*	*0.40*
Van Stael	0.6	0.6	1.2	1.4	0.4	-1.2	-1.1	0.9	-0.5	1	1.1	1.3	1.5	1.4
STD	*1.28*	*1.11*	*0.60*	*0.66*	*1.28*	*0.87*	*0.94*	*0.83*	*0.81*	*0.77*	*0.54*	*0.46*	*0.50*	*0.66*

Figure 29: Subjective data. Mean for each bicycle with STD

Gazelle-group agrees more with each other than the independent-group does. However, when averaging out, the scores for the bicycles and questions are similar. The groups do agree with each other, indicating that there is no real bias from one of the groups. Only the Puur NL and Tour Populair are perceived differently over the two groups.

3.3.2.2. ASSIGNING HANDLING QUALITIES

With the scores from the participants on the bicycle handling qualities, these qualities can now be assigned to the bicycles. The questions of the questionnaire corresponded with the selected handling qualities. In figure 30 a transformation table is presented that shows how a score on a question corresponds to the handling quality. In the first column are the numbered questions, in the second column are the corresponding handling qualities and in the third and fourth columns are the explanations of what a high or low score means. Note that the questions 6, 7 and 8 have an opposite transformation than the other questions. They are highlighted in the figure. Question 8 is transformed to nervous only, because in this case nervous and stable are convertible. Question 14 is transformed to direct only, since 11, 12 and 13 also correspond to maneuverable.
To provide a better representation on which bicycle scores the highest on which handling quality, figure 31 shows a ranking of the mean scores from the bicycles to the questions expressed as handling quality. The translation to handling quality gives a high ranking when there is a high score. If the mean scores are equal, the ranking is based on the STD, where a low STD has a higher ranking than a high STD. When even those are equal, the bicycles are put in the same cell.

The two main geometries and handling qualities, lazy and sportive, are expected to be opposite. When a bicycle is considered sportive, it should not score high on lazy. This is about right. When a bicycle is rated high on sportive, it is rated low on lazy and the other way around. The two handling qualities are not exact opposites, but generally follows this trend.

Some outstanding results can be seen for the Orange HFP, Tour Populair, Puur NL and Balance. Those bicycles are rated continuously as least direct, least maneuverable, least nervous and also scored low on controllable. Orange HFP is scored also low on forgiving, secure and safe. Interestingly enough, the Balance was designed as a stable bicycle for elderly who couldn't cycle anymore. The Balance was supposed to provide safety and give the cyclists a secure feeling. But, other bicycles not designed for elderly are rated higher at secure and safe. The Balance is located in the middle on the scale, where it is expected to be in the higher rankings. For the Cityzen Speed can be said that the bicycle is considered to be sportive and at the same time unsafe, uncontrollable and unstable in the lower speed range, but stable in the higher speed range and moderated in maneuverability and directness. When looking at the Cityzen, the non-electrical version, it is also sportive, but considered more safe and more stable in the lower speed range. It is also more maneuverable and direct. That indicates that the electrical support adds to the handling qualities of the bicycle. The same

	Statements	Handling Quality	High score	Low score
1	The bicycle gives me a relaxed feeling	Lazy	Lazy	Not lazy
2	The bicycle gives me a sportive feeling	Sportive	Sportive	Not sportive
3	I feel safe at all times riding the bicycle	Safe	Safe	Unsafe
4	I can control this bicycle at any time	Controllable	Controllable	Controllable
5	The bicycle is forgiving	Forgiving	Foriving	Unforiving
6	I have the feeling of tipping over when I ride **slowly**	Stable (Weave)	***Unstable***	***Stable***
7	I have the feeling the bicycle starts swaying across the road at **high** speeds	Stabe (Capsize)	***Unstable***	***Stable***
8	The bicycle easily holds a straight line	Stable / Nervous	***Not Nervous***	***Nervous***
9	I have to make steering corrections to follow a straight line	Nervous	Nervous	Not nervous
10	The bicycle is under control when mounting and dismounting	Controllable	Controllable	Uncontrollable
11	The bicycle easily steers around an obstacle	Maneuverable	Maneuverable	Not maneuverable
12	The bicycle easily steers into a corner	Maneuverable	Maneuverable	Not maneuverable
13	I do not have to put in effort to turn the steer	Maneuverable	Maneuverable	Not maneuverable
14	I does not take much effort to change the heading of the bicycle	Direct / Maneuvrable	Direct	Not direct

Figure 30: Transformation from question-score to handling quality. Statement 6, 7 and 8 are opposite to the other transformations

Ranking	1	2	3	4	5	6	7	8	9	10
Most Lazy	Orange HMB	PuurNL	Tour Populair	Balance	Orange & Ami		Van Stael	Orange HFP	Cityzen Speed	Cityzen
Most Sportive	Cityzen Speed	Cityzen	Van Stael	Ami	Orange HMB	Orange	Orange HFP	PuurNL	Balance	Tour Populair
Most Safe	Orange	Van Stael	Balance & Cityzen		Puur NL	Orange HMB	Ami & Tour Populair		Cityzen Speed	Orange HFP
Most Controllable	Van Stael	Ami & Orange & Tour Popluair			Balance	Cityzen	Orange HMB	Puur NL	Cityzen Speed	Orange HFP
Most Forgiving	Orange	Orange HMB	Tour Populair	Puur NL	Balance	Cityzen Speed	Van Stael	Ami	Orange HFP	Cityzen
Most Unstable (2 m/s)	Cityzen Speed	Orange	Orange HMB	Orange HFP	Ami	Balance	Tour Populair	Cityzen	Puur NL	Van Stael
Most Unstable (7 m/s)	Puur NL	Tour Populair	Orange HMB	Ami	Balance	Orange	Van Stael	Orange HFP	Cityzen Speed	Cityzen
Least Nervous	Cityzen	Ami	Cityzen Speed	Van Stael	Orange	Balance	Orange HMB	Orange HFP	Tour Populair	Puur NL
Most Nervous	Ami	Puur NL	Tour Populair	Van Stael	Cityzen Speed	Orange HMB	Orange	Cityzen	Balance	Orange HFP
Most Controllable	Orange HMB	Orange	Van Stael	Cityzen Speed	Balance	Cityzen	Ami	Tour Populair	Orange HFP	Puur NL
Most Maneuverable	Cityzen	Ami & Van Stael		Puur NL	Orange HMB	Orange	Cityzen Speed	Balance	Tour Populair	Orange HFP
Most Maneuverable	Van Stael	Cityzen	Ami	Orange HMB	Puur NL	Cityzen Speed	Balance	Orange	Tour Populair	Orange HFP
Most Maneuverable	Van Stael	Orange HMB	Cityzen Speed	Orange	Ami	Cityzen	Puur NL	Tour Populair	Balance	Orange HFP
Most Direct & Maneuverable	Cityzen	Van Stael	Orange HMB & Ami		Cityzen Speed	Orange	Puur NL	Balance	Tour Populair	Orange HFP

Figure 31: Bicycle ranking to statement. Based on mean score per bicycle. If equal score, the ranking continues on STD from low to high

trend can be seen with the Orange bicycles. The HFP with front wheel support scores lower on all qualities compared to the HMB with crank support. The non-electric Orange scores similar to the Orange HMB, so in these bicycles the location of the support is important for the handling qualities. But this figure shows again that rating the bicycles on handling qualities is difficult. Where lazy and sportive are supposed to be opposites, question 8 and 9 should also be opposites. Question 8 rates least nervous with a high score and question 9 most nervous with a high score. The questions ask for similar qualities, but opposite; *'8. The bicycle easily holds a straight line'* and *'9. I have to make steering corrections to follow a straight line'*. Yet, the rating is not completely reversed. The Ami even scores high on both questions.

To get an overall picture of the handling qualities based on the questions, questions about the same handling qualities are clustered. Question 8 includes stable and nervous as handling quality. Because there is a question about stability in the lower speed range and about stability in the higher speed range, it is unclear which one to cluster with question 8. Therefore, the decision is made to cluster question 8 only with 9, within the handling quality nervous. However, when reviewing this handling quality with the clustered scores, it has to be taken into account that the rating is not completely reversed as was expected. This also shows when analysing the questions with Cronbach's α. $\alpha = 0.64$ for 8 and 9 on nervousness, which is below the 0.7 mark of reliable. So, when reviewing the handling quality nervous, it has to be taken into account that the results might not be completely reliable. The same accounts for clustering question 4 and 10 for controllable. These questions do not ask exactly the same, but it is expected that when mounting and dismounting is difficult to control, the participants also have answered that the bicycle is not in control at all times. Again, analysis with Cronbach's α shows that this is not the case. The participants have not answered the questions in the same way, as $\alpha = 0.52$. Nonetheless, these questions are clustered, because evaluating them separately does not add to the understanding of controllable. When evaluating the handling quality controllable, the reliability of the results has to be questioned. For combining question 11, 12 and 13 on maneuverable is no doubt. $\alpha = 0.83$, so these can be clustered without any doubt of reliability. Question 14 also covered maneuverable partially, but since there are already 3 other questions about maneuverability, question 14 is assigned to direct only. The other questions ask about only one handling quality and do not have to be clustered with another. Figure 32 shows the values of the clustered handling qualities for each bicycle. Question 6, 7 and 8 are transformed, such that a high score corresponds to more of that quality. This way, the values are comparable to the others. From these values, a radar plot is constructed for each of the bicycles, to display a handling quality profile. These are presented in figure 33. The more towards the center, the less the handling quality is present. The other way around, the more outwards the more the handling quality is present.

The handling quality profiles show that some bicycles have the same type of handling qualities. Just by the shape of the radar plot, similar bicycles can be matched. Features that stand out are the 'dip' at sportive, the 'sharp point' at safe and the curves along the top left and bottom right. This handling quality profile accounts

Handling Quality	Lazy		Sportive		Safe		Stable (weave)		Stable (capsize)		Controllable		Forgiving		Nervous		Maneuverable		Direct	
Question	1		2		3		6		7		4,10		5		8,9		11,12,13		14	
Bicycle	Mean	STD	Mean	STD	Mean	STD	Mean	STD	Mean	STD	Mean	STD	Mean	STD	Mean	STD	Mean	STD	Mean	STD
Ami	1.0	0.775	-0.7	1.269	0.8	0.980	0.4	1.020	0.7	1.187	1.1	0.805	0.2	0.872	-0.6	0.865	1.0	0.795	1.0	0.894
Balance	1.2	0.980	-1.7	0.458	1.2	0.872	0.6	0.917	0.9	1.044	1.1	0.889	0.8	1.077	-0.8	0.980	0.6	1.334	0.8	1.077
Orange	1.0	0.775	-1.4	0.800	1.4	0.490	0.3	0.900	1.1	0.539	1.3	0.698	1.3	0.640	-0.8	1.260	0.7	0.998	0.9	1.044
Orange HFP	0.5	1.025	-1.5	0.500	-0.1	1.136	0.3	1.269	1.2	0.980	0.4	0.917	0.1	1.446	-0.8	0.812	0.2	1.249	0.4	1.281
Orange HMB	1.4	0.663	-1.1	0.700	1.0	0.894	0.3	1.005	0.6	1.114	1.2	0.678	1.3	0.900	-0.7	1.276	0.9	0.772	1.0	0.894
Cityzen	0.0	1.000	1.4	0.917	1.2	0.872	0.8	0.600	1.6	0.490	1.1	0.865	0.0	1.095	-0.9	0.889	1.1	1.056	1.4	0.490
Cityzen Speed	0.1	1.286	1.6	0.497	0.4	0.956	0.0	1.155	1.2	1.030	1.0	0.745	0.4	0.956	-0.7	0.989	0.8	0.685	0.9	0.737
Tour Populair	1.2	0.748	-1.7	0.640	0.8	0.980	0.6	1.020	0.4	1.281	1.1	0.973	1.1	1.136	-0.5	1.162	0.5	0.991	0.7	0.900
Puur NL	1.3	1.005	-1.5	0.922	1.1	0.539	1.1	0.943	0.4	0.917	0.8	0.872	1.0	1.000	-0.4	1.108	0.8	0.778	0.8	0.400
Van Stael	0.6	1.281	0.6	1.114	1.2	0.600	1.2	0.872	1.1	0.943	1.2	0.748	0.4	1.281	-0.7	0.843	1.3	0.526	1.4	0.663

Figure 32: Scores for each individual handling quality, based on clustered statements from the questionnaire. Question 6, 7 and 8 are transformed such that a high score corresponds with a high amount of that quality

for the Balance, Orange, Orange HMB, Tour Populair and Puur NL. The Orange HFP has a similar profile at the top, but a more pointy profile at the bottom resulting from a decrease in stable and forgiving. The Ami shows also a similar profile , but with a small 'dip' at forgiving. From the Ami, there is a transition via the Van Stael to the Cityzen Speed and the Cityzen. Those bicycles show a decrease in lazy and forgiving and develop higher peak for sportive. All profiles show a 'dip' at the handling qualities about stability and even more in the high speed range (capsize) than in the low speed range (weave). Except for the Tour Populair and Puur NL, these show a higher value for the stability in the higher speed range, so a better capsize handling quality. All bicycles are rated 'not nervous' (a score below zero). It has to be mentioned that the results on nervous might not be reliable based on the Cronbach's value.

These handling qualities are solely based on the subjective experience of the participants, so these profiles do not say anything about the objective qualities the bicycles have. These plots show that there are bicycles with similar handling quality profiles, that can be put into a group fitting the description of lazy. Other bicycles can be put into a group of sportive bicycles. Within these groups, small differences in the other handling qualities define each individual handling quality profile and the characteristics of the bicycle. This fits the description of the Gazelle employees, that there are two main geometries (lazy and sportive), with small adjustments within these geometries.

3.4. DISCUSSION

During the cycling experiment, the participants were instructed to cycle a prescribed route at a self-chosen speed and a prescribed speed at two sections. The instructions also included cycling 2 minutes apart from each other and 15 minutes of rest in between cycling the different bicycles. The complete route was recorded by an iPhone mounted on the steer and afterwards the participants filled out a questionnaire.

The first round the 2 minutes-apart starting rule was followed. Halfway the first round some of the participants met in front of traffic lights or while getting lost. After that, the participants started to cycle together from the start. They also did not take 15 minutes rest in between. Cycling one after another was introduced to prevent the cyclist from not cycling their own preferred speed or getting distracted from 'feeling and testing' the bicycle. However, most of the cyclist that cycled together were in the same age- or expert-group, so their cycling speeds would probably have been quite the same. For the Cityzen Speed, that is way faster than all the other bicycles, every participant wanted to try out its speed. Therefore, the speed of that bicycle is not influenced, everyone cycled a fast speed, all alone. About getting distracted while cycling, that is probably not the case. Every participant mentioned something about putting the bicycle to the test, by pretending to avoid a bicycle, cycling with hands off the steer or hitting the steer while cycling with one hand and even getting the bicycle to shimmy. Afterwards they also discussed the bicycles with each other out of interest. So, despite not following instructions, it did probably not influence the results a great deal. The participants did follow the directions on which bicycle to cycle when, so the order of bicycles is not altered. The risk of boredom or fatigue is averaged out with all bicycles. Because there was not enough time to ride the route one time with all the participants, the first round some took a wrong turn. But, eventually they have found the route and it did not influence the sections with a prescribed speed. In the end, all participants filled out all the questionnaires about the bicycles, so there were no gaps in the data on the subjective part.

The rider measurements from the iPhone, on the other hand, had some missing data. Due to a problem with the app, the iPhones from Gazelle could not be used and they had to be rented last minute from another

company. The iPhones met the specifications and the app was installed correctly. They were a setup properly, extra powerbanks and chargers were present at the cycling experiment to make sure the iPhones would last the entire test-day. However, some phones appeared to have a really bad battery and the powerbanks were not strong enough to charge them faster than they were drained. During the experiment two iPhones did not hold up. As a back-up, the iPhone of one of the participants was used. This should not have been a problem, except that the app was setup wrong. The sampling rate was set a 10 Hz and the other time 20 Hz. This was not enough to capture all the actions from the rider and a lot of data points were missing. Unfortunately, it was decided to not use these data set at all.

Because of the missing data, some bicycles have less data points and are more sensitive to outliers when averaging. This was the case for the Puur NL (2 missing), Tour Populair (4 missing) and Orange HFP (3 missing). But, because the data is not analysed on average per bicycle, but with all data together, it does not mind that some bicycles are in there more often than others. The average data is only used to compare the bicycles with each other, and will not be used to construct the correlations between the handling qualities and objective measures. This data will not be affected by the 9 missing rider-bicycle combinations.

It was remarkable to see that a self-chosen speed by the participants differed per bicycle. Everyone cycled the bicycle a different time of day, with different traffic interactions, but it seemed that for one specific bicycle, there is a preferred speed. One bicycle has a higher preferred speed than the other, that is not completely participant dependent. What almost did not differ at all, were the peak frequencies of steering. For the lower speed, 2 m/s, there was a lower frequency for all participants on all bicycles. Since the free speed and high speed were often close together, the peak frequency was similar at both speeds. For the low speeds the peak frequency of steering lies between 0.65 Hz and 0.8 Hz, and for the high speed and free speed between the 1.0 and 1.1 Hz. Only for bicycles that had a lower self-chosen speed, the frequency dropped little below 1.0 Hz. This is interesting to keep in mind when modelling an average rider, when a specific rider is unknown. The frequency of steering is found to be close around 1.0, depending on the speed. So, for an average speed, an average peak frequency of steering should be around 1 Hz.

Another remarkable results came from the questionnaire. Those results showed that not all questions were answered as expected. The results for lazy (Q1) and sportive (Q2) are almost opposites, but other questions are not. For example, question 8 and 9 should have been opposites, as they ask almost the same but the other way around. It appeared not to be so, and it is likely that the questions are interpreted differently than was meant. The questions that ask for the same handling qualities were evaluated with Cronbach's α and it showed that only the questions about the maneuverability of the bicycle (Q11-13) are answered the same, as they show $\alpha > 0.7$. The other clustered-questions are less reliable (Q4&Q10 and Q8&Q9), but because of lack of a possibility to do another test, they are taken together anyway. This might have been due to unclear questions or different interpretation of the questions, as explained in the previous chapter. In a following study, the questionnaire should be reviewed and revised to construct questions that describe the handling qualities better, so there is no room for interpretation of the questions.

While looking at the results of the questionnaire, it has to be kept in mind that some of the Gazelle-participants were the same people as are interviewed in the beginning. Those participants had more knowledge on the bicycle and could therefore be biased. The results of the Gazelle-participants are therefore compared to the results of the independent-participant. That showed that the Gazelle-participants agree more with each other than the independent-participants agree with each other. But, on average, the two groups do agree on almost all bicycles, except for the Tour Populair and Puur NL. There is no explanation why those two bicycles are different. Although there are some differences between the two groups, they are not that outstanding, that there would have been a bias. They would have probably a better understanding of the meaning of the questionnaire, but they have probably not filled in the questionnaire based on what they thought on forehand. The results of this experiment were of interest of them, so they would probably have done their best to score the bicycles as how they have experienced them.

Another interesting feature from the questionnaire, was the rating of the Balance. The Balance should provide for elderly people that are afraid of cycling or cannot do it with a normal bicycle. The Balance should be a safe and secure bicycle. However, in the rating the Balance is not rate most safe or most reliable. It is ranked in the middle range, while it is supposed to be in the higher range. Although this study is not about customer appreciation, it is an interesting result, because they bicycle is not rated for the handling qualities it should have.

On the other hand, the Cityzens show a result as is expected. The Cityzen Speed was rated sportive, unsafe and uncontrollable at low speeds, but more stable in the higher speed range. The non-electric version is also

sportive, but more safe and stable in the lower speed range. The electrical support thus has influence on the handling qualities, especially when riding slow. It invites to go faster with a support, it is just easier. The same is observed in the Oranges, but in a lesser amount. The Oranges are supported up to 27 km/h, while the Cityzen Speed is supported up to 45 km/h, so there is a different 'fast speed range'. While the support does not really affect the handling qualities (Orange vs Orange HMB), the location of the support does (Orange HFP). With a motor in the front wheel, the bicycle is rated lower on all qualities. So less stable, less controllable, less maneuverable and so on. This shows that electrical support does have influence, depending on the supporting speed, and that location is also very important.

3.5. SUMMARY

This part of the report discussed the experiment that is conducted in order to collect data about the bicycle when being used. The data that was collected included information on how the bicycle is steered, by iPhone measurements, and about how the bicycle is experienced by the rider, subjective data. 10 participants (4 Gazelle employees, 6 independent participants) have each tested 10 bicycles (1 participant tested only 9) on a route of 3.5 km through urban area, so 99 data sets were collected. From these 99 sets, 9 sets were unfit for analysis due to failing iPhone recordings. From the measured data the rider COM, mass and angle, as well as the average velocity, peak frequency of steering (yaw) and the surface of the PSD (yaw and roll) are analysed. From this data is found that the bicycles induce different cycling speeds, the frequency of steering is lower at 2 m/s and the amount of steering is the least when cycling at a self-chosen speed. Depending on the bicycle there is more steering at 2 m/s than at 7 m/s, for others it is the other way around.

The subjective scores on the questionnaire show that the participants experience the bicycles differently. It might occur, when one participant answers the question with +2, other might answer it with -1. Those differences are for some bicycles on some questions larger than for others, but there is no solid trend to be found. Also, a bias among the Gazelle-participants is unlikely to be present. They do agree more with each other than the independent group, but there is an agreement between the groups about the handling qualities of the bicycles. Except for the Tour Populair and the Puur NL, those are scored differently.

From the mean scores on the bicycle per question, a handling quality profile is created by clustering the scores of questions with the same handling qualities. That showed that the bicycles can be divided into two groups with matching profiles, lazy and sportive. Within these groups, small differences are present that define each individual bicycle.

In the next part, a rider-bicycle model will be constructed based on the geometry of the bicycle and information from the experiment about the posture and steering actions of the rider. From this model, objective measures will be calculated. These objective measures are unique for each rider-bicycle combination, due to specific dynamic combinations. These objective measures are in chapter 5 matched with the subjective measures from the cycling experiment.

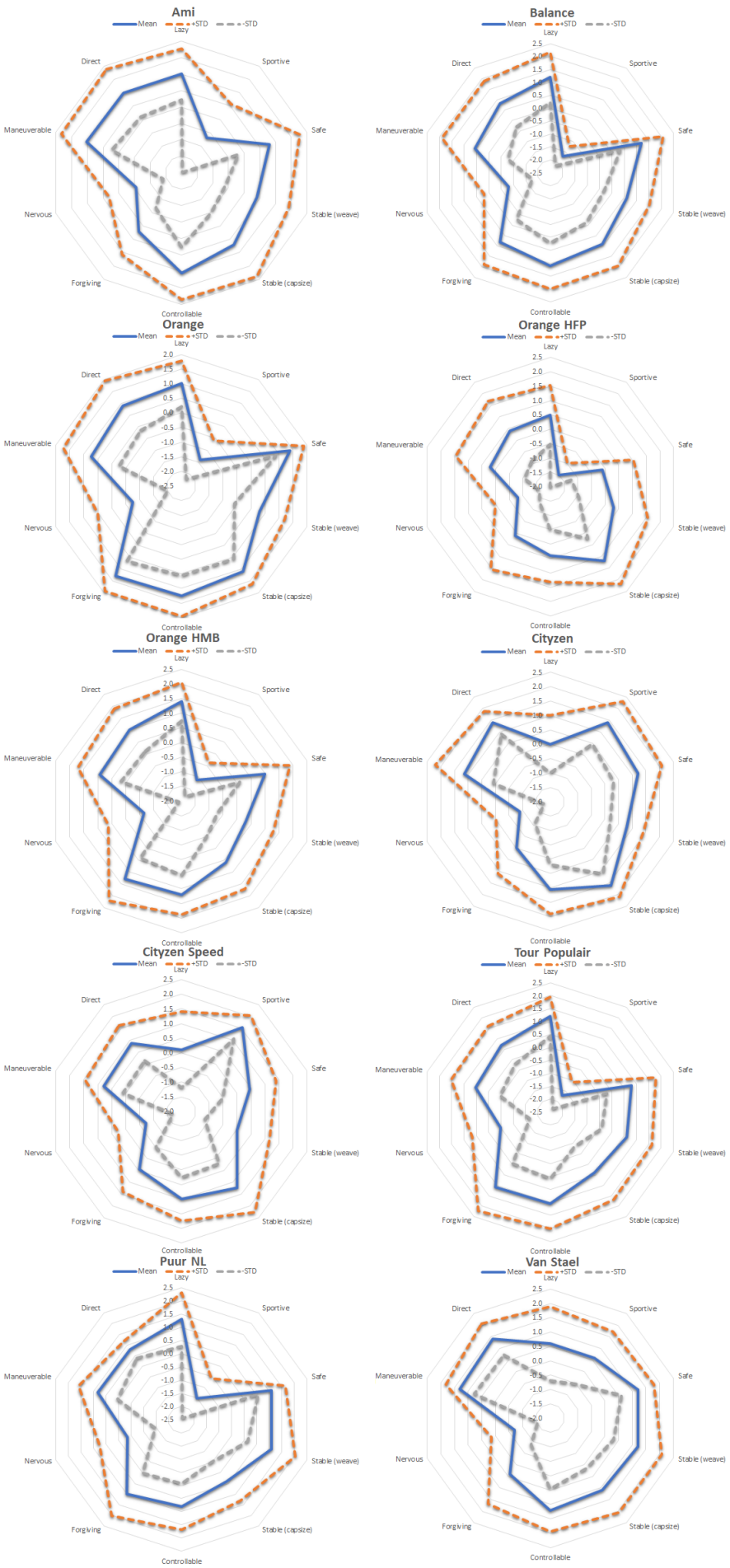

Figure 33: Handling quality profiles for all bicycles

4

RIDER-BICYCLE MODEL: OBJECTIVE MEASURES

The previous part explained the cycling experiment and the collection of the subjective data and rider measurements from on the cycling experiment. This part continues with the collection of objective data, based on a rider-bicycle model. With information about the geometry of the bicycles from Gazelle and measurements from the participants of the cycling experiment, each bicycle with each participant can be modelled. These models are constructed following the JBike6 computer program[4]. The collection of the data for the geometry and mass properties, the translation to the bicycle model and the objective measures based on the model will be discussed. In addition to the JBike6 model, an already existing rider-bicycle model is used to assess the handling qualities of the bicycles. This model evaluates the effort to control the bicycle and calculates a measure for the handling quality from it. This measure is discussed as well.

4.1. RIDER-BICYCLE MODEL

To analyse the bicycle's geometry and calculate objective measures that can be retrieved from a rider-bicycle model, JBike6 was used as modelling program. This program requires the following input: head angle λ, wheelbase w, trail c, rear wheel diameter d_R, real wheel mass m_R, real wheel moment of inertia $I_{xx,R}$, $I_{yy,R}$ and $I_{zz,R}$, front wheel diameter d_F, front wheel mass m_F, front wheel moment of inertia $I_{xx,F}$, $I_{yy,F}$ and $I_{zz,F}$, rear frame centre of mass $COM_{x,B}$ and $COM_{y,B}$, rear frame mass m_B, rear frame moments of inertia $I_{11,B}$, $I_{22,B}$ and $I_{zz,B}$, and principle axis of the rear frame α_B, rider centre of mass $COM_{x,C}$ and $COM_{y,C}$, rider mass m_C, rider moments of inertia $I_{11,C}$, $I_{22,C}$ and $I_{zz,C}$ and principle axis of the rider α_C, front assembly centre of mass $COM_{x,H}$ and $COM_{y,H}$, front assembly mass m_H, front assembly moments of inertia $I_{11,H}$, $I_{22,H}$ and $I_{zz,H}$ and principle axis of the front assembly α_H (figure 34). The program also asks for the same values for the rear rack and front basket, but because there are no extra added masses to the two, these two are to be neglected and zero in the model. The actual rear rack is part of the rear frame, and the front basket is part of the steering assembly.

4.1.1. MODELLING THE RIDER

The rider is modelled as a passive point mass with moments of inertia around a principle axis. At the cycling experiment data about the mass and length of the rider are determined, as well as an estimation of the centre of mass (COM) and the trunk angle when seated on the bicycle. JBike6 asks for the COM, mass, moment of inertia and the principle angle, where the principle angle is the trunk angle of the rider. Therefore, only the moments of inertia are unknown. These moments of inertia can be calculated with the use of an existing rider model from Moore et al. (2009)[17]. The rider model from this paper used anthropomorphic data to make an estimation of the human parameters. This model has the rider moment of inertias already determined and can be used as reference to scale the properties of the participants. From the paper, the moments of inertia of the complete rider I_{rm} and the mass m_{rm} of the rider model were known, and after contact with the author, Jason Moore, also the length of the model l_{rm} was known.

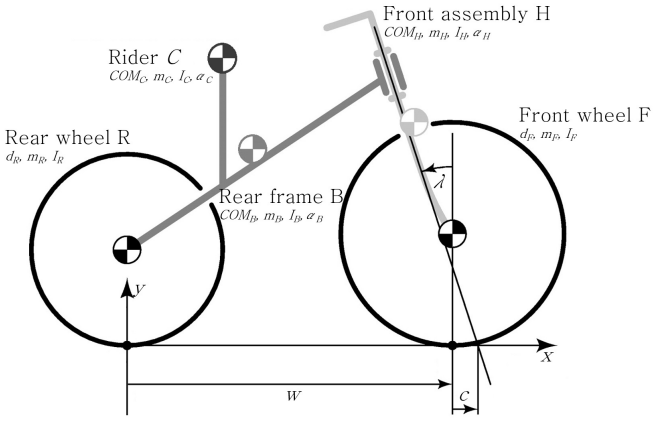

Figure 34: Schematic figure of the bicycle with the parameters for the JBike6 model

$$m_{rm} = 72\ kg$$

$$l_{rm} = 1.83\ m$$

$$I_{rm} = \begin{bmatrix} 8.00 & 0 & -1.93 \\ 0 & 8.07 & 0 \\ -1.93 & 0 & 2.36 \end{bmatrix} kgm^2$$

After calculating the eigenvalues I^*_{rm} from the matrix I_{rm} and rotating the axis to the right configuration (from x - -z coordinates to x-y coordinates), the moments of inertia from the rider model can be scaled to the moments of inertia of the participants with the length and mass from the measurements during the experiment.

$$I_C = I^*_{rm} \frac{m_C}{m_{rm}} \frac{{l_C}^2}{{l_{rm}}^2}$$

with m_C the mass, l_C the length and I_C the moments of inertia of the participant, corresponding with the JBike6 values for rider C. This is done for each participant, so each participant can be modelled with each bicycle. This resulted in 90 sets of data (only for the useful data sets), with a different angle and COM for each participant on each bicycle. The mass and moments of inertia are the same for each individual participant on each bicycle. Figure 35 shows an example of the values from one participant for each bicycle.

4.1.2. MODELLING THE BICYCLE

The parameter for the bicycle model can be divided in three categories: general geometry, wheel properties and bicycle frame properties. These three categories will be discussed one after another.

Bicycle	Rider COM X	Rider COM Y	Rider mass	Rider I11	Rider I22	Rider Izz	Rider Angle
Ami	0.3985	1.034	70	7.3838	1.514	6.931	-16
Balance	0.3809	1.0675	70	7.3838	1.514	6.931	-6
Orange	0.3639	1.1367	70	7.3838	1.514	6.931	-11
Orange HFP	0.3439	1.095	70	7.3838	1.514	6.931	-10
Orange HMB	0.3496	1.1241	70	7.3838	1.514	6.931	-11
Cityzen	0.4216	1.1064	70	7.3838	1.514	6.931	-25
Cityzen Speed	0.4331	1.1257	70	7.3838	1.514	6.931	-26
Tour Populair	0.3032	1.1159	70	7.3838	1.514	6.931	-3
Puur NL	0.3217	1.1284	70	7.3838	1.514	6.931	-4
Van Stael	0.3885	1.078	70	7.3838	1.514	6.931	-25

Figure 35: Example of the rider data from one participant for each bicycle

4.1.2.1. GEOMETRY

The basic geometry of the bicycle defines the general shape. It includes the head angle λ, wheelbase w, trail c and wheel diameter d. The Royal Dutch Gazelle provided the geometry documents of the bicycles, which hold information about the tube lengths and the angles between them. Some of these files had all the information about the head angle, wheelbase and trail, but some missed one or more parameters. Gazelle has a Solid Works model of each of their bicycles as well. Some are more detailed than others, however, the main information about the head angle, wheelbase and trail are incorporated in all of them. For the bicycle that did not have all the information in the geometry document, the Solid Works files are used to collect the information. It is taken into account that all bicycles used at the cycling experiment had a lady frame size of 52-54, so the files of these bicycle sizes are used. The diameters of the wheels are provided in a direct conversation. In Appendix E, an example of a geometry file can be found, from the Puur NL frame size 54. Figure 36 shows the geometry values of the head angle, wheelbase, trail and wheel diameter for each bicycle.

4.1.2.2. WHEELS

Wheels have an effect on the steering behaviour of the bicycle. The mass distribution has effect on the moment of inertia, especially for the bicycle with an electric motor in the front wheel. To make sure the moment and masses of the wheels are modelled as accurate as possible, moments of inertia of the wheels are determined from an experiment.

A bicycle wheel can be modelled as a thin disk, for which the moments of inertia are

$$I_{zz} = 0.5 I_{xx}$$

$$I_{xx} = I_{yy}$$

where the z-axis is the disk's rotation axis. The moment of inertia around the axis of rotation of the disk can be determined by measuring the period of oscillation. For the period applies

$$T = 2\pi \sqrt{\frac{I_P}{dmg}}$$

were T is the period of oscillation, I_P the moment of inertia around the point of rotation P, d the distance from axis of rotation of the disk to rotational point P, m the mass of the disk and g the gravitational acceleration 9.81 m/s^2. When data of the mass, distance d and the period of oscillation are measured, the equation can be rewritten to

$$I_P = \frac{T^2 dmg}{2\pi^2}$$

To determine the moment of inertia around the z-axis, the parallel axis theorem is used

$$I_{zz} = I_P - md^2$$

Bicycles	Head angle λ [deg]	Wheelbase w [m]	Trail c [m]	Front wheel diameter d [m]	Rear wheel diameter d [m]
Ami	69.0	1.072	0.068	0.661	0.661
Balance	66.0	1.201	0.075	0.609	0.609
Orange	68.5	1.120	0.080	0.704	0.704
Orange HFP	68.5	1.120	0.080	0.704	0.704
Orange HMB	68.5	1.120	0.080	0.704	0.704
Cityzen	70.5	1.114	0.060	0.700	0.700
Cityzen Speed	70.5	1.114	0.060	0.700	0.700
Tour Populair	65.5	1.138	0.086	0.723	0.723
Puur NL	65.0	1.121	0.126	0.730	0.730
Van Stael	73.0	1.051	0.047	0.686	0.686

Figure 36: Geometry values for all bicycles

In the experiment to determine the moments of inertia of the wheels, the wheel is removed from the bicycle and weighed to determine the mass m. Then it is suspended on a rod fixed to a rack by its rim, so the wheel can swing like a pendulum around point P. The distance d is measured with a measuring tape. For the actual test, the wheel is pulled out of its equilibrium and released, so it starts oscillating. 10 oscillations are manually timed with a stopwatch and this is done 5 times for each wheel, to increase the reliability of the results for one period T. Figure 37 shows the test-setup.

Not all bicycles were present at the testing location. Therefore only both wheels of the Ami, Balance, Cityzen Speed are tested and the only the front wheels of the Puur NL and Van Stael because time was limited. For the wheels of the Oranges, an unpublished graduation project is consulted, which included the Orange HMB and HFP[18]. The wheels on these bicycles are the same as the Oranges in this report. The wheels of the other bicycles, the Orange (non-electric), Cityzen and Tour Populair, are compared visually based on the photos taken at the cycling experiment. In addition, Gazelle provided information about the naves and brakes that are included in the wheels. This is also used for comparison, as this influences the weight of the wheels. The wheels are compared, and the values of known wheels are used for the unknown wheels that have the best match. The values for the moments of inertia and are scaled, based on the diameters of the wheels by

$$I_{unknown} = \frac{d_{known}}{d_{unknown}} I_{known}$$

For the unknown masses, the ratio between the front and rear wheel is used to scale the mass if the wheels could not be transferred directly. This is the case for the rear wheels of the Puur NL and the Van Stael. The ratio between the front and rear wheels that are known are applied to the wheels that are unknown.

$$m_{rear,unknown} = \frac{m_{front,known}}{m_{rear,known}} m_{front,unknown}$$

Appendix E includes the elaborate comparison for the moment of inertia and mass scaling with figures that show which wheels are used to determine the others. Figure 38 shows the moment of inertia and the masses of all wheels after the experiment and scaling to other bicycle wheels.

4.1.2.3. BICYCLE FRAME

Initially, it was meant to retrieve the mass and moment of inertia properties of the bicycle frame from the Solid Works files from Gazelle. Because not all bicycles had the same details of the assembly and not all properties of all components were known, it was decided to strip the entire bicycle down to just the naked frame. This means that everything, up to the nuts and bolts (if they were modelled) are removed, until just the frame with rear rack, the tube of the steer, steer stem and front fork were left. If the bicycle had a motor in the frame, the

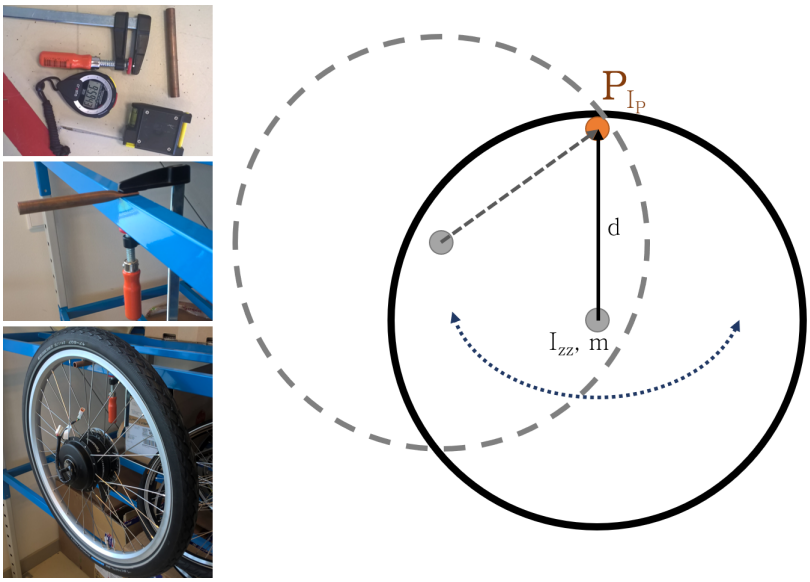

Figure 37: Test setup for the moment of inertia of a wheel. The photos on the left show the actual setup, the schematic drawing on the right shows the principle

Bicycles	Front wheel mass m [kg]	Front wheel inertia I_{xx} & I_{yy} [kgm^2]	Front wheel inertia I_{zz} [kgm^2]	Rear wheel mass m [kg]	Rear wheel inertia I_{xx} & I_{yy} [kgm^2]	Rear wheel inertia I_{zz} [kgm^2]
Ami	2.10	0.07323	0.14645	3.60	0.07337	0.14674
Balance	5.45	0.05632	0.11264	3.50	0.06149	0.12298
Orange	2.25	0.08345	0.16691	2.63	0.07710	0.14460
Orange HFP	4.71	0.08960	0.16330	2.63	0.07710	0.14460
Orange HMB	1.99	0.08160	0.15660	4.18	0.07640	0.14030
Cityzen	2.25	0.08393	0.16691	2.75	0.07724	0.15449
Cityzen Speed	2.25	0.08345	0.16691	2.75	0.07724	0.15449
Tour Populair	3.10	0.10595	0.21190	3.79	0.09751	0.19502
Puur NL	2.55	0.09894	0.19787	2.98	0.11562	0.23124
Van Stael	1.75	0.06718	0.13436	2.22	0.08528	0.17055

Figure 38: Moment of inertia and mass values for all bicycle wheels. Values for the Orange HFP and HMB are retrieved from [18]

motor is kept in the model, as well as a battery if a bicycle should have one. 2 of these models has issues with the rear rack. The rear rack of the Balance and Tour Populair were missing. To compensate for that, pictures of the bicycles are compared to find the closest match for both racks. The rear rack of the Ami was found to match the Balance best and the rear rack of the Puur NL fitted the Tour Populair. The material properties were adjusted to match the original bicycles. The pictures of the rear racks can be found in Appendix E.

After the bicycles were stripped, the right materials were added to the components to add mass and moments of inertia properties to the Solid Works model. However, after adding the material properties and checking the masses, the masses showed strange values. After consulting the supervisor from Gazelle, the values appeared not to be right. This was a huge problem, because if this way of modelling the bicycle does not work, all the bicycles have to be measured by hand. To take one step in between, three bicycles were going to be measured for their mass and moment of inertia. The obtained masses then are put into Solid Works, to see if with these changes, the moments of inertia from the model are equal to the moments of inertia that are measured. If that is the case, the bicycle components only have the be weighted and not fully measured for the moments of inertia. That would save a lot of trouble and time. The following two sections will cover the measurements of the bicycle frame, one part about the steering assembly and one part about the rest of the frame. The three bicycles selected for the measurements are the Ami, Balance and Van Stael.

4.1.2.3.1 Steering assembly For the measurements on the steering assembly, the masses of the components need to be determined. The components of the steering assembly are the front fork, the steering tube and the steer stem. These components had to be weighted at Gazelle, as they did not have a record with the weights. The masses of the front fork and a combination of the stem and tube of the steer, with handgrips and brake levers included, were manually measured by an employee of Gazelle. With total mass of the steering assembly, the COM and the moment of inertia can be determined. This is done by hand for three bicycles: Ami, Balance and Van Stael.

First of all, the front wheel is removed from the steering assembly. This ensures that only the steering assembly is measured and that there is no interference from the wheel that than has to be subtracted later. The front assembly remains attached to the rest of the bicycle. Every equipment on the steer remains on the steer. The tuning of the steer is slightly loosened, so the steer can freely rotate with a minimum amount of friction from the head tube.

The first measurement is to determine the COM of the steering assembly. This should be located just in front of the steering axis. JBike6 has a separate axial system for the front assembly, with the origin at the intersection of the ground and the steering axis, the u-axis along the steering axis and the v-axis perpendicular to this, as shown in figure 39.

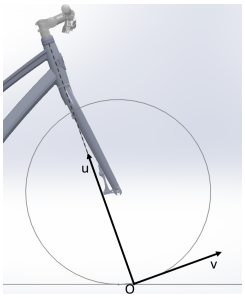

Figure 39: u-v system for the front assembly

The COM_v can be determined by a moment equilibrium. The bicycle laid flat on a table, with the head tube horizontal (aligned with a leveller) and such

that the steering assembly can rotate freely. The steering assembly should 'fall', or rotate downwards, by gravity pulling at the centre of mass. By lifting the steering assembly up at a fixed position, a certain amount of force is required. When the steering assembly is held in an equilibrium, the COM_v can be calculated by

$$F_{lift} r = F_g v$$

$$v = \frac{F_{lift} r}{F_g}$$

with F_{lift} the force required to hold the steering assembly in equilibrium and r the distance from the steering axis to the virtual wheel axis aligned with the lifting force, F_g the gravitational force and v the distance from the steering axis to the origin of the gravitational force, the COM.

In the experiment, F_{lift} is measured with the use of an analogous push/pull gauge, model SN-50, with an accuracy of 0.1 N, range from 0 N to 50 N. The assembly is lifted at one of the ends of the front fork, with the gauge pulling in vertical direction, in the line of the wheel axis, until the front fork was horizontal and held in equilibrium (figure 40). The amount of force necessary to keep this equilibrium is read from the gauge. This is done three times, to increase the reliability. F_{lift} is known, r is provided by the geometry of the bicycle (it is the offset of the front fork) and F_g can be calculated with the mass of the bicycle. By using the equilibrium equation, the COM_v can be calculated.

The COM_u cannot be calculated that easy. Based on the information of the COM of the bicycles that have been evaluated by Kalsbeek(2016)[18], an educated guess can be made. The COM should lie approximately half way the head tube of the bicycle. When the front fork is very heavy, for example a telescope fork, this might be a little lower. This is measured with a measuring tape, with the bicycle standing on the ground, with the wheel included. The results of the measurements of the COM are shown in figure 41.

The next step was to determine the moment of inertia around the steering axis, also without the wheel. This is done similar to the moment of inertia of wheel: an oscillation test. By adding a spring to the steering assembly, a mass-spring system is created that can be described with an oscillation:

$$I\ddot{\phi} + C\phi = 0$$

$$-I\omega^2 + C = 0$$

$$I = \frac{C}{\omega^2}$$

$$\text{with} \quad \omega = \frac{2\pi}{T}$$

where I is the moment of inertia of the system around the axis of rotation, C the torsional stiffness and T the period of oscillation. This way, a moment of inertia I around the axis of rotation can be calculated by

$$I = \frac{C}{(\frac{2\pi}{T})^2}$$

Torsional stiffness C and the period of oscillation T have to be found experimentally. For this experiment, the bicycle is positioned on top of a table so that the head tube (or steer axis) is vertical and there are no gravitational influences. Two elastic bands connect both ends of the handlebar with the seat post, to create an oscillating system. T can be found by timing the oscillations, C has to be measured in a static manner. Torsional stiffness is the deviation of moment M by the angular rotation. By pulling the steer, equipped with the elastic bands, out of its equilibrium with the push/pull gauge parallel to the virtual line between the seat post and the steer axis, the force F_{spring} required can be measured. The perpendicular distance L to the axis of rotation can also be measured. The angular rotation ϕ_Δ resulting from this pulling, can be determined by measuring the elongation, $l_1 - l_0$, of the elastic bands. There is only a minor angular rotation, so linearity can be assumed. Figure 42 shows the bicycle system with the springs, and the points of measurement for F_{spring}, L, ϕ_Δ, l_1 and l_0.

With these measurements, C can be calculated by

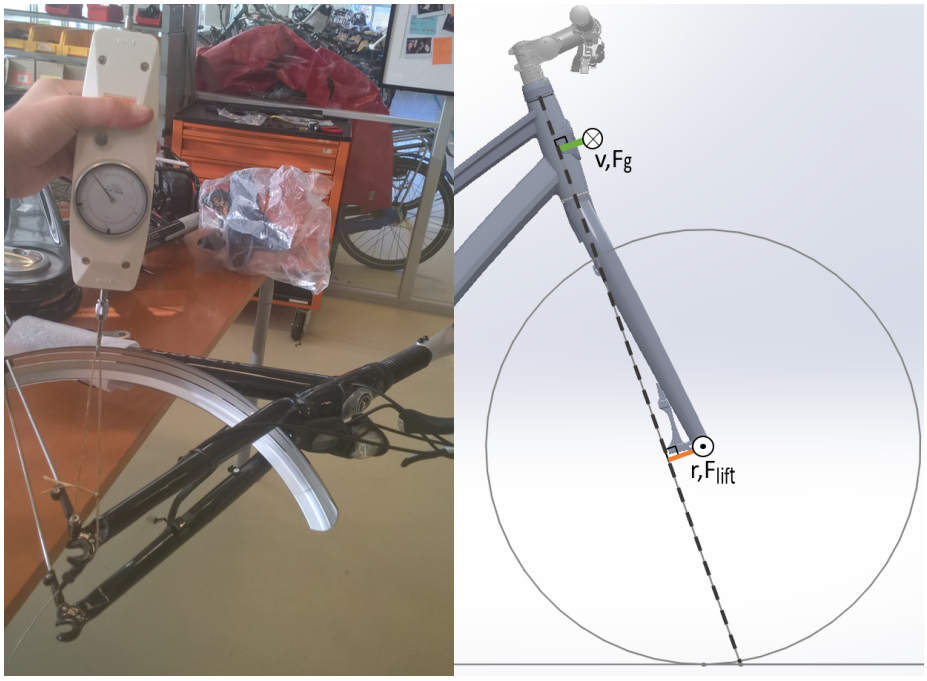

Figure 40: COM-experiment. On the left the actual setup and measurement are shown, on the right a schematic of the measurement. F_g is directed into the paper, F_{lift} comes out of the paper

Bicycle	Steering assembly [kg]	r [m]	F_{lift} [N]	v [m]	u [m]
Ami 1	3.43	0.055	10.8	0.0177	0.85
Ami 2	3.43	0.055	9.1	0.0148	0.85
Ami 3	3.43	0.055	10.0	0.0163	0.85
Ami average	*3.43*	*0.055*	*10.0*	*0.0163*	*0.85*
Balance 1	3.67	0.05	14.0	0.0194	0.78
Balance 2	3.67	0.05	14.5	0.0201	0.78
Balance 3	3.67	0.05	15.2	0.0211	0.78
Balance average	*3.67*	*0.05*	*14.6*	*0.0202*	*0.78*
Van Stael 1	2.66	0.055	7.1	0.0150	0.83
Van Stael 2	2.66	0.055	6.6	0.0139	0.83
Van Stael 3	2.66	0.055	6.8	0.0143	0.83
Van Stael average	*2.66*	*0.055*	*6.8*	*0.0144*	*0.83*

Figure 41: Results of the COM experiment

$$M = F_{spring} * L$$

$$\phi_\Delta = \frac{L}{l_1 - l_0} \quad \text{with linearity}$$

$$C = \frac{M}{\phi_\Delta}$$

During the actual experiment, the force to pull the system out of equilibrium and the elongation of the elastic bands are measured 3 times for reliability. The elongation of the spring was measured by a tape measure and the push/pull gauge was the same as with the COM-experiment. The elastic bands were equipped at the far end of the handle bars and at that position the gauge was attached. In figure 42, the end of the handlebar is in line with the steering axis, perpendicular to the seatpost-steeraxis line. This was not the case for the three measured bicycles. The perpendicular distance from line of action of the force to the steering axis was measured by using a straight rod positioned on top of the steering axis perpendicular to the seatpost-steeraxis line, to make sure the right distance was measured.

For measuring the period of oscillation T, a camera was positioned underneath the test-setup. The system was pulled out of equilibrium by hand and released to induce an oscillation. The camera captured the oscillation and the video was analysed afterwards with Kinovea[16] to determine T. This process was repeated 3 times to ensure reliability. Figure 43 shows two situations of the test-setup. 43a shows the position of the bicycle where the head tube is vertical and 43b shows the system from the point of view from the camera. These measurements led to the following results, shown in figure 44.

With the results from the experiment and the known parameters on the masses of the steering assembly from Gazelle, the model can be set up and the modelled results can be compared with the results from the experiment. While modelling the three measures bicycles (Ami, Balance and Van Stael) in Solid Works, it appeared that the moments of inertia of the front assembly did not match the measured results. With some trial and error, it appeared that handgrips and brake leavers at the end of the steer are of large influence. So, to cover for that, handgrips and brake levers are added to the model. A random combination of a handgrip and brake lever was weighted at Gazelle (heavy duty) and another combination (small and simple) by the author of this report. This gave a range of masses that could be assigned to the steering assemblies for the handgrips and brake levers. The masses were guessed for each bicycle based on the looks and within the range of the two measurements; large and heavy or small and light weighted. These masses were included in the mass

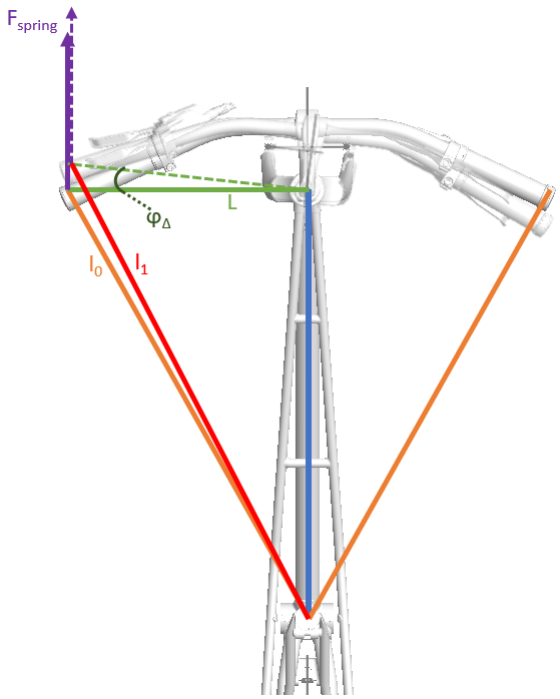

Figure 42: Schematic test setup

of the steer tube (they were equipped when the steers were weighed), so they are subtracted from that and added separately.

This in total resulted in a modelled moment of inertia (MOMI) for the steering assembly, that could be compared to the measured moments of inertia (MEMI) from the experiment. Figure 45 shows the MOMI and the MEMI around the steering axis for the three bicycles. The Ami and Balance have a 0.03 kgm^2 difference between the MOMI and the MEMI. The Van Stael has a difference of 0.004 kgm^2. For these small values, the differences for the Ami and Balance seem large. However, the range of measurements in the experiment is similar, there are differences of 0.023 kgm^2 within one bicycle. In addition, it has to be kept in mind that the moment of inertia of the wheels have to be added to the steering assembly to get the full picture of the total front assembly. These values are in the order of 0.13 to 0.17 kgm^2. Because of those two factors, the range of measurement and the addition of the wheel, the moments of inertia from the model are used, as they are reliable enough for this purpose. The moment of inertia for the other bicycles can be retrieved from the improved Solid Works models. The values will be presented in the next section, as the input for JBike6.

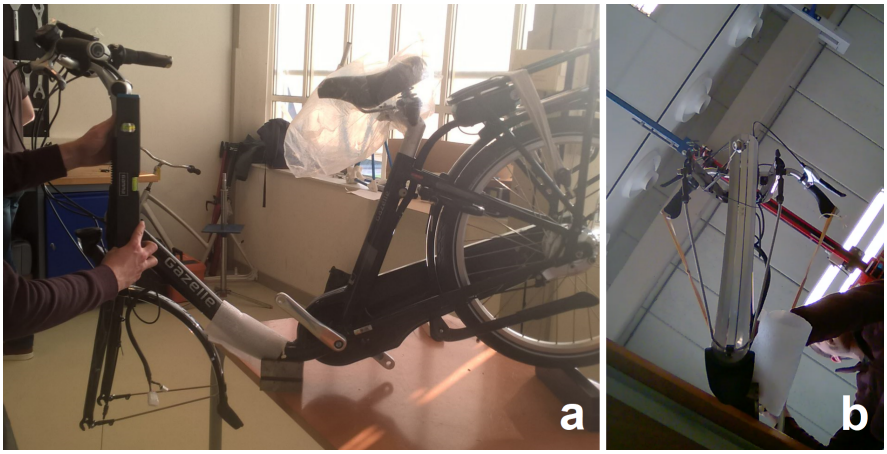

Figure 43: a. Position of the bicycle with a vertical head tube. b. Test-setup with elastics from camera view

Bicycle	L [m]	l_0 [m]	l_1 [m]	Δl [m] = l_1-l_0	F_{spring} [N]	M [Nm] = F*L	φ_Δ [rad] = L/Δl	C [Nm/rad] = M/φ_Δ	T [s]	I [kgm^2] = C / $(2\pi/T)^2$
Ami 1	0.288	0.663	0.738	0.075	6.95	1.998	0.261	7.659	0.565	0.062
Ami 2	0.288	0.663	0.725	0.062	6.85	1.969	0.216	9.132	0.600	0.083
Ami 3	0.288	0.663	0.721	0.058	6.85	1.969	0.202	9.762	0.585	0.085
Ami average	**0.288**	**0.663**	**0.728**	**0.065**	**6.88**	**1.979**	**0.226**	**8.753**	**0.583**	**0.075**
Balance 1	0.296	0.745	0.84	0.095	6.90	2.042	0.321	6.364	0.745	0.089
Balance 2	0.296	0.745	0.85	0.105	5.70	1.687	0.355	4.756	0.745	0.067
Balance 3	0.296	0.745	0.835	0.090	6.50	1.924	0.304	6.328	0.745	0.089
Balance average	**0.296**	**0.745**	**0.842**	**0.097**	**6.37**	**1.885**	**0.327**	**5.771**	**0.745**	**0.081**
Van Stael 1	0.272	0.646	0.702	0.056	2.90	0.789	0.206	3.831	0.550	0.029
Van Stael 2	0.272	0.647	0.698	0.051	2.90	0.789	0.188	4.207	0.550	0.032
Van Stael 3	0.272	0.648	0.693	0.045	2.80	0.762	0.165	4.603	0.550	0.035
Van Stael average	**0.272**	**0.647**	**0.698**	**0.051**	**2.87**	**0.780**	**0.186**	**4.186**	**0.550**	**0.032**

Figure 44: Results of the moment of inertia measurements of the steering assembly

Bicycle	Experiment	Model	Difference
Ami	0.075	0.043	0.032
Balance	0.081	0.050	0.031
Van Stael	0.032	0.037	-0.004

Figure 45: Comperison of the modelled and measured moment of inertia

4.1.2.3.2 Rear frame As the masses of the wheels are already determined, and the Royal Dutch Gazelle provided the masses of the steering assembly, only the mass of the rear frame had to be measured. This way each component can be modelled in Solid Works with the correct masses, and a correct moment of inertia for the rear frame can be obtained. By weighing the entire bicycle and subtracting the known masses of the wheels and steering assembly, only the mass of the frame is left. Gazelle also provided information of the masses of the motors and batteries of the bicycles, so the model could be as accurate as possible. Since this weighing does not require much, all bicycles that were present in the storage when conducting the experiments on the front assembly, were weighed. The non-electric Cityzen was not present, but the frame is almost the same as from the Speed-version. With the masses of the motor and battery subtracted, the mass of the Cityzen's frame should be accurate. Also the Orange HMB was not present, but that data could be retrieved from Kalsbeek (2016)[18]. And the non-electric Orange was not present in the right size, only in a larger size. But due to the lack of a right bicycle and no option to let it weigh somewhere else, this mass is used for the Orange. The difference in size will not have a really large effect on the mass, according to a Gazelle engineer. Figure 46 shows the masses of all components of the bicycles, which will be used on modelling the bicycles in Solid Works to obtain the modelled moment of inertia's. The wheels are not put into the Solid Works model, and the mass of the rear frame is without the motor and battery, as they will be put into the model separately. The complete overview of the values for the moments of inertia, mass and other bicycle parameters are presented in the next section, as the input for JBike6.

4.2. OBJECTIVE MEASURES FROM A RIDER-BICYCLE MODEL

In the previous section is described how all the bicycle parameters are determined. These parameters were necessary to create a bicycle model, from which objective measures can be retrieved. The following section describes two ways on obtaining these measures: by the JBike6 program and by a handling quality measure from Hess et al. (2012)[6].

4.2.1. JBIKE6

JBike6 is a computer program that calculates the stability of a bicycle. That is done by calculating the eigenvalues of the uncontrolled bicycle for a range of speeds with the use of the linearized equations of motion (EOM) of the bicycle. This results in an open loop stability plot with three real eigenvalues and one imaginary eigenvalue. Figure 47 shows a screen shot of the eigenvalues from JBike6. The real eigenvalues represent the weave mode, capsize mode and caster mode. The caster mode is for these bicycles always negative, thus stable. The weave mode is often unstable at low velocities (a positive eigenvalue) and has a corresponding imaginary eigenvalue that indicates the oscillation of the weave mode. This means the bicycle is weaving across the road, and with a low imaginary eigenvalue, the weave oscillation is not enough to keep it stable. At higher speeds, the oscillation disappears as the real eigenvalue goes to negative and the bicycle reaches the stable speed range. The capsize mode is a mode that is often stable (negative) at lower speeds, but gets marginally unstable at higher speeds. This mode indicates a roll to the side of the bicycle, meaning that an uncontrolled bicycle tips over to the side when it becomes unstable.

Different parameters are put into the model, thus resulting in different values. From these EOM's, the stability range of the bicycle and the eigenvalues are calculated. The calculations are extensively described

Bicycle	Rear Frame	Steer Assembly		Front wheel	Rear Wheel	Motor	Battery
		Fork	Steer+Stem				
Ami	9.34	1.54	1.89	2.10	3.80	3.03	2.51
Balance	11.50	1.39	2.28	5.45	3.50		3.43
Orange	11.72	1.14	1.88	2.25	2.63		
Orange HFP	13.41	1.41	3.05	4.71	2.63		3.43
Orange HMB	10.21	1.38	3.05	1.99	4.18	3.03	2.51
Cityzen	8.26	1.36	1.41	2.25	2.75		
Cityzen Speed	8.26	1.30	2.03	2.25	2.75	3.98	2.39
Tour Populair	11.25	2.20	2.01	3.10	3.79		
Puur NL	11.42	1.57	2.68	2.55	2.98		
Van Stael	7.74	1.04	1.62	1.75	2.22		

Figure 46: Masses of all parts of the bicycles. The rear frame mass is without motor and battery

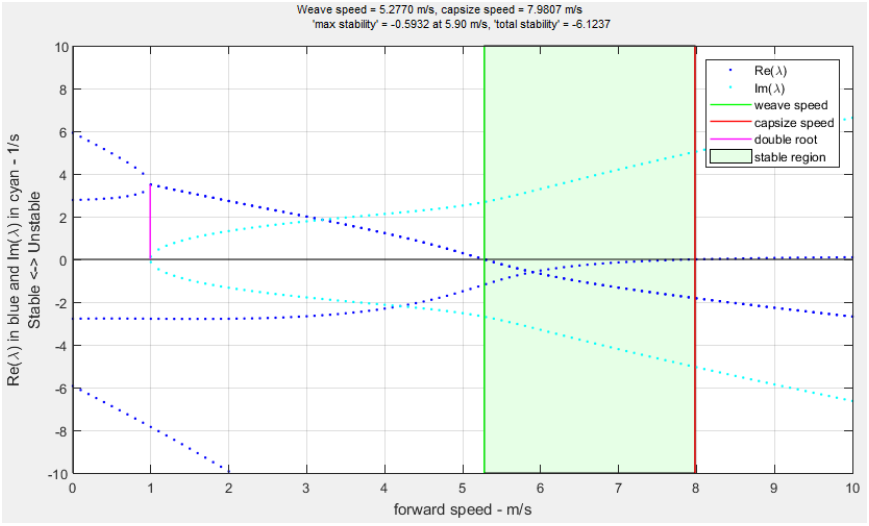

Figure 47: Screen shot of an eigenvalue plot example of the open loop stability from JBik6

by Meijaard et al. (2007)[5]. The basic EOM is described by

$$M\ddot{q} + vC\dot{q} + (K_0 + v^2 K_2)q = 0$$

In addition, the program was slightly adapted for the purpose of this study, to examine the objective measures at three different speeds: 2 m/s, 7 m/s and a free speed. The eigenvalues for these three speeds are extracted from the program, as well as the steer stiffness at these speeds. The steer stiffness refers to the stiffness of the steering assembly, while turning the steer. It is determined by the mass and inertia properties of the bicycle. The amount of stiffness of the steering assembly might also be an indicator of a handling quality, when the handling quality covers the steering actions of the bicycle. Therefore, this is also considered.

The steer stiffness is calculated with the use of the frequency of steering at the tree different speeds. In the previous chapter, the peak frequency of steering was explained. This frequency is used to determine the steer stiffness, as well as a frequency of 0 Hz that should resemble the feeling of the steer when there are no steering actions. With the equations of motion at a given frequency ω at a given speed v and the variables $q = \begin{bmatrix} \phi \\ \delta \end{bmatrix}$ (roll and yaw), the complete equation will be

$$T = M\ddot{q} + vC\dot{q} + (K_0 + v^2 K_2)q$$

or rewritten to a Laplace transformation

$$T = (M\omega^2 + vC\omega + K_0 + v^2 K_2)q$$

$$T = A(\omega)q$$

The steer stiffness can be found from the yaw of the steer, δ. By applying a unit torque on the steering system, the response of δ can be found.

$$T = \begin{bmatrix} 0 \\ T_\delta \end{bmatrix} \quad \text{with} \quad T_\delta = 1$$

$$\begin{bmatrix} \phi \\ \delta \end{bmatrix} = A^{-1} \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

This results in a value for δ at a given torque of 1 Nm. The stiffness k of the steer can then be determined by dividing the torque over the angle of δ, since rotational stiffness is expressed in Nm/rad

$$k = \frac{1}{\delta}$$

This is done for each bicycle-rider combination, resulting in a data set for the steer stiffness. The adapted Matlab files can be found in Appendix E. The other function that are used in the script can be downloaded from the website of JBike6[4]. The next section will discuss the input and the results of the eigenvalues and steer stiffness from JBik6.

4.2.1.1. INPUT

The parameters that have to be put into JBike6 are described in the section 'Rider-Bicycle Model'. In addition, also the three speeds and the peak frequency for each speed for each rider bicycle combination has to be put into JBike6. Appendix E holds all the parameters for each rider specific on each bicycle, including the mass, moments of inertia, torso angle, free speed and peak frequency for all three speeds, and all parameters for each bicycle. These values are loaded into JBike6, to create a set of measures with the eigenvalues and steer stiffness for each rider-bicycle combination.

4.2.1.2. OUTPUT

JBike6 provided two types of output, the eigenvalues and the steer stiffness. Figure 48 shows the average value for each bicycle. The data that could not be used are left out in the average. The complete data sets can be found in Appendix E. The **X**'s mark the unusable data. The eigenvalues will now be discussed first.

For each speed, there is only one real eigenvalue presented. The value of highest real eigenvalue shows if the bicycle is stable or unstable, it does not matter which eigenvalue that is. The 2 m/s eigenvalues are all positive, meaning all bicycles are unstable at low speed. This positive eigenvalue is the weave mode, with an imaginary eigenvalue as measure for the amount of oscillation. The average real eigenvalue for 2 m/s lies between 2.78 and 3.10 and the imaginary eigenvalue between 1.24 and 1.51. It is not the case that a higher real eigenvalue also has a higher imaginary eigenvalue. For the free speed, the stability of the open loop varies between and within the bicycles. There is a critical point where the weave eigenvalue, based on the dynamics of the rider-bicycle system, becomes negative and stable when it is uncontrolled. Within one bicycle, some participants have cycled above that critical point, in the stable speed range, and some have cycled below that point, were the bicycle is unstable in the open loop. When comparing the real eigenvalues to the cycled speeds, it is clear that the positive eigenvalues have lower speeds than when there are negative eigenvalues.

At 7 m/s almost all bicycles are stable. The capsize mode becomes positive around 8 m/s for most bicycles, except for the Van Stael and Tour Populair. Those two bicycles have a lower speed in which the capsize mode becomes positive and the bicycle system unstable. Some of the participants have cycled above the critical capsize speed, so when the bicycle is open loop unstable.

However, the differences between positive and negative values within one bicycles are very small, the eigenvalues are only just positive or just negative. It might be due to the averaging of the speed over the total distance, but it can also be due to the preference of the cyclist. An open loop unstable bicycle can be controlled by a human, and it might just be that this was a more comfortable speed for the cyclists. As already discussed in the previous chapter, there are differences in the free speeds for each bicycle. It seems that a bicycle induces a higher or lower cycling speed. The same trend is visible in the stability of the bicycles. The bicycles that had a lower average speed are also more likely to be unstable, because of that lower speed. Therefor it can be stated, that the chosen cycling speed for that specific bicycle is more preferred than a speed in which the bicycle is open loop stable at all times.

The imaginary eigenvalues are not presented for the free speed and 7 m/s, because not all bicycles are unstable. The unstability is only marginally, so the effect of the oscillation can be neglected.

Continuing on the steer stiffness, for each speed, there are two steer stiffness's presented. One with the peak frequency of steering (peak) and one with 0 Hz (0), implying there is no steering at all. At the low speed of 2 m/s, the difference between the peak- and 0 Hz stiffness is very small. Also the peak frequency at 2 m/s is closer to zero than in the other speeds. The differences increase when the speed increases. At the free speed and at 7 m/s, the differences between the peak- and 0 Hz stiffness are significant. The stiffness at 0 Hz

Bicycle	Real Eigenvalue 2m/s	Imaginary Eigenvalue 2m/s	Real Eigenvalue Free	Real Eigenvalue 7m/s	Steer Stiffness 2m/s (peak)	Steer Stiffness 2m/s (0)	Steer Stiffess Free (peak)	Steer Stiffness Free (0)	Steer Stiffness 7 m/s (Peak)	Steer Stifness 7 m/s (0)
Ami	3.1000	1.5085	-0.4685	-0.2301	7.6620	7.6611	6.3844	3.3182	6.5157	2.3136
Balance	3.0783	1.4149	-0.0750	-0.7717	10.3014	10.2952	5.6124	6.7775	5.5446	5.8916
Orange	3.1008	1.4019	0.2817	-0.2709	8.3790	8.3743	5.2990	5.5791	6.6627	2.7306
Orange HFP	2.6370	1.3530	-0.4769	-0.4896	8.7111	8.6857	5.1547	4.0361	5.0098	3.1729
Orange HMB	2.9947	1.3749	-0.2923	-0.3890	8.5562	8.5440	5.7966	4.4877	5.9610	3.2501
Cityzen	2.9915	1.3698	-0.1134	-0.1298	6.7120	6.6985	6.2555	2.7886	6.8038	1.4301
Cityzen Speed	3.0177	1.5064	-0.0799	-0.1827	7.2071	7.2086	14.2549	1.4801	6.8193	1.9840
Tour Populair	2.8201	1.3579	-0.2019	-0.0214	8.1186	8.0949	4.2711	4.0129	7.5071	0.7452
Puur NL	2.9759	1.2397	0.4831	-0.6700	13.5127	13.4598	8.4922	9.4735	8.2906	6.7508
Van Stael	2.8139	1.4642	-0.1943	-0.0233	4.2912	4.2840	5.0424	1.4116	6.3385	0.5899

Figure 48: Average eigenvalues and steer stiffness values for each bicycle

decreases drastically in respect to the stiffness at 2 m/s and the stiffness at the peak Hz decreases only a little for almost all bicycles. This can be seen quite well with the average stiffness of each bicycle (figure 48). When looking at just the peak-stiffness, since that resembles the actual steering, the values for the free speed and 7 m/s are almost the same. Except for the Cityzen Speed. That bicycles shows a huge difference, twice as high in the free speed. The free speed of the Cityzen Speed is also a lot higher than all the other speeds and higher than the prescribed 7 m/s (7.8 m/s). This might have influenced the large difference. The Tour Populair shows a larger difference than the other bicycles as well, where it is almost twice as small with the free speed, compared to the stiffness at 7 m/s. However, this bicycle did not have the lowest average free speed. When looking at the values between the participants within one bicycle, there are differences as well. The Puur NL has some major differences between the participants, as well as the Cityzen Speed at 2m/s (peak and 0). These differences are up to 5 Nm/rad, where the other bicycles have a maximum of 3 Nm/rad. The values for the steer stiffness for each participant are compared to the velocity and the frequency during cycling, but there is no direct relationship.

Between the bicycles, there are huge differences. The range with the peak frequency at 2 m/s lies between 4.29 and 13.51 (Van Stael and Puur NL), for the free speed it lies between the 4.27 (Tour Populair) and 14.25 (Cityzen Speed) and for 7 m/s it lies between 7.51 (Tour Populair) and 8.29 (Puur NL). For the free speed, those 2 are the only outliers, the rest is closer together, as well as the stiffness at 7 m/s. Those values are all close together. At the free speed, the Cityzen Speed has the highest velocity and shows a higher steer stiffness. At 2 m/s and 7 m/s, the Puur NL shows the highest stiffness. This is the only bicycle with a front rack, increasing the mass and the distance from the COM of the steering assembly to the steering axis. On the other hand, the HFP has a front wheel motor, but does not have different results than the HMB or non-electric Orange without a front wheel motor. So, it seems, a motor in the front wheel has not influenced the steer stiffness of the bicycle.

Together with the different results of mass distribution and differences between participants, it seems like there are multiple factors within the bicycles that influence the stiffness of the bicycle. After some trials with the JBike6 parameters, the program showed that the stiffness can be changed by tuning various parameters. Thus, there is a combination of factors that results in the steer stiffness of a bicycle.

4.2.1.3. AVERAGE RIDER

The last part of the objective measures from the bicycle model, is a model with one average rider. For the eigenvalues and steer stiffness, each bicycle is evaluated with 10 different participants. These participants might have ridden each bicycle different from the other. It is not possible to rule out fluctuations, it are still human beings riding a bicycle in traffic. To really compare the bicycles with respect to each other, and average rider is created and put on each bicycle. This rider has the average properties of all the participants together, cycles at given speeds op 2.0 m/s, 5.5 m/s and 7.0 m/s with a peak frequency of steering of 1 Hz. The free speed differed for every bicycle, so to keep everything the same, a fixed free speed had to be chosen. The average speed of all trials was 6.1 m/s. But, because that is really close to the high speed of it 7 m/s and is quite high on average, it is decided to take a speed a little lower, to see if there are really differences within the three speeds. The only thing that differs for each bicycle, is the angle of the rider and the COM of the rider. The angle and COM of the rider are determined by the geometry of the bicycle, and thus belongs with the bicycle properties. All angles and COM of all participants on one bicycle are averaged to determine one angle and one COM for one specific bicycle. The bicycle properties did not change, so figure 49 only shows the rider properties for each bicycle, were only the angle and COM are different.

These values are again loaded into JBike6, with the same calculations as for all the other data. Except that there is only one rider per bicycle, so one output for the eigenvalues and steer stiffness per bicycle. The results for the bicycles with an average rider are presented in figure 50.

Because all the average riders 'acted' the same on each bicycle, except for the posture, these values are solely about the bicycle. The real eigenvalues at 2 m/s are very close together and all positive, therefor all unstable at 2 m/s. At a 'free speed' of 5.5 m/s only the Orange and Puur NL are unstable and at 7 m/s all bicycles are stable. These results are the same as in the average of all riders, and even the values are almost the same. They differ around 0.02 from each other. These results show that that Orange and the Puur NL have a higher speed at which the system becomes open loop stable than the other bicycles, and that all bicycles have a higher speed than 7 m/s when the capsize mode becomes positive and the bicycles becomes open loop unstable again.

Also the steer stiffness results are similar, although the values differ more than the eigenvalues do. The only real difference is the highest value at 7 m/s. With an average rider, the Tour Populair has the highest

Bicycle	Rider COM X	Rider COM Y	Rider mass	Rider I11	Rider I22	Rider Izz	Rider Angle	Peak Hz	Free Speed
Ami	0.3422	1.0605	82.2	9.7182	1.9926	9.1222	-10.9	1.0	5.5
Balance	0.3572	1.0918	82.2	9.7182	1.9926	9.1222	-8.5	1.0	5.5
Orange	0.3353	1.1351	82.2	9.7182	1.9926	9.1222	-10.4	1.0	5.5
Orange Voor	0.2784	1.1321	82.2	9.7182	1.9926	9.1222	-7.1	1.0	5.5
Orange Mid	0.3158	1.1270	82.2	9.7182	1.9926	9.1222	-9.9	1.0	5.5
Cityzen	0.3956	1.1208	82.2	9.7182	1.9926	9.1222	-25.8	1.0	5.5
Cityzen Speed	0.3901	1.1324	82.2	9.7182	1.9926	9.1222	-24.4	1.0	5.5
Tour Populair	0.2520	1.1337	82.2	9.7182	1.9926	9.1222	-5.2	1.0	5.5
Puur NL	0.1758	1.1139	82.2	9.7182	1.9926	9.1222	-0.6	1.0	5.5
Van Stael	0.3569	1.1021	82.2	9.7182	1.9926	9.1222	-26.2	1.0	5.5

Figure 49: Rider properties for an average rider on each bicycle

Bicycle	Real Eigenvalue 2m/s	Imaginary Eigenvalue 2m/s	Real Eigenvalue 5.5 m/s	Real Eigenvalue 7 m/s	Steer Stiffness 2m/s (peak)	Steer Stiffness 2m/s (0)	Steer Stiffess 5.5 m/s (peak)	Steer Stiffness 5.5 m/s (0)	Steer Stiffness 7 m/s (Peak)	Steer Stifness 7 m/s (0)
Ami	3.1091	1.5131	-0.3881	-0.2255	7.6837	7.6603	4.6383	4.5379	9.1685	2.3076
Balance	3.0823	1.4234	0.5871	-0.7447	10.3539	10.3052	6.0382	7.7329	4.9507	5.8956
Orange	3.1122	1.4069	-0.1726	-0.2649	8.4154	8.3754	4.9610	5.0802	9.1997	2.7264
Orange HFP	2.6540	1.3572	0.1668	-0.4854	8.9294	8.8001	3.9205	5.5788	6.4326	3.2778
Orange HMB	3.0036	1.3861	0.0607	-0.3795	8.6094	8.5397	4.7101	5.4488	7.8198	3.2410
Cityzen	2.9990	1.3763	-0.2037	-0.1302	6.7627	6.6913	4.4826	3.6322	9.7092	1.4472
Cityzen Speed	3.0072	1.5190	-0.5504	-0.1704	7.1177	7.1021	4.5637	4.0534	9.7366	1.8758
Tour Populair	2.8460	1.3568	-0.5079	-0.0311	8.3680	8.2508	4.4147	3.6665	10.9603	0.3920
Puur NL	2.6877	1.1687	0.4010	-0.4518	11.3440	11.0109	5.3818	6.8754	7.8835	3.9215
Van Stael	2.8233	1.4706	-0.4599	-0.0209	4.3169	4.2746	3.8621	1.9107	9.3119	0.2223

Figure 50: Eigenvalues and steer stiffness for the average rider on each bicycle

stiffness, instead of the Puur NL. These results show that the Balance and Puur NL have a high stiffness at 2 m/s and the Van Stael a low stiffness, the Cityzen Speed exceeds all bicycles at 5.5 m/s with approximately 10 Nm/rad and that the Balance has a low stiffness at 7 m/s compared to the other bicycles.

Where the eigenvalues do not differ at all from the average results of all riders on a bicycle, there are some differences in value in the steer stiffness. This implicates that the eigenvalues are not influenced that much by the rider on the bicycle, but the steer stiffness is. And that the actual equations of motion, from which the eigenvalues arise, or not as distinct that the eigenvalues are spread over a wide range.

4.2.2. HQM

The third modelled objective measure is the handling quality measure (HQM) from Hess et al. (2012)[6]. This handling quality measure is designed to asses handling for different vehicles, independent of the task. This model is more widely explained in the literature study of the author, prior to this report[3] and can also be found in the original paper[6]. The basic principle of the HQM is the idea of an inner and outer loop control model (figure 51). The outer loop controls the tracking task, like following a path, and the inner loop (figure 52) controls the balancing of the bicycle, to prevent it from falling over. Next to the model, a measure of handling quality was constructed, based on the amount of effort that has be put into the system to control it and that can be adapted for any kind of task or vehicle.

$$HQM = \left|\frac{\dot{M}}{C}\right| \frac{1}{K_p}$$

with $\dot{M}$ the primary loop rate variable and C as the set point, normalized by $\frac{1}{K_p}$ to match the unit of $\dot{M}$. The ratio between C and $\dot{M}$ represents the amount of effort that has to be put into the system, to match the set point. The higher the ratio, the higher the HQM, the more difficult it is to control the vehicle. Moore et al. (2016) has further developed the rating scale, resulting in 3 levels. Level 1 defines as 'little rider compensation required' (HQM 1 to 5), level 2 as 'moderate rider compensation' (HQM 5 to 8) and level 3 hold the scores of 8 and higher with 'significant rider compensation'.

This HQM can be used for a bicycle model, to assess the stability of the bicycle: How much effort has to be put into the bicycle to control it? The outer loop tracking task remains the same, but the inner loop has to be adjusted to match a bicycle model. Based on the inner loop from figure 52, the general HQM can be adapted. The goal is to keep the bicycle straight up, so the set point would be a roll angle ϕ_c. The primary loop rate is defined by $\dot{\phi}$ and δ, since both influence the roll of the bicycle. δ has to be normalized by $K_{\dot{\phi}}$ to a roll angle velocity. Also the set point ϕ_c has to be normalized to a roll angle velocity by K_{ϕ}. This way, the amount of

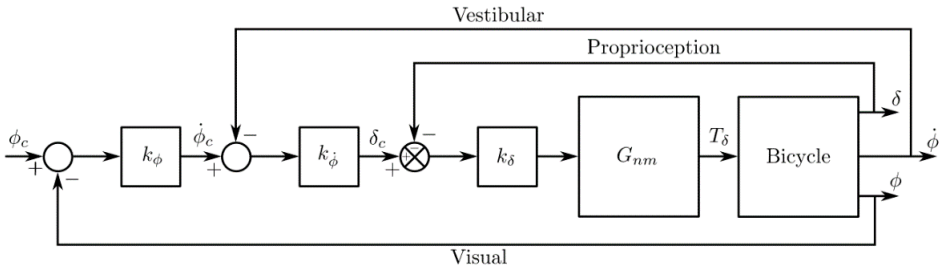

Figure 51: The inner loops of the manual control system for balancing tasks from Hess et al. (2012)[6]

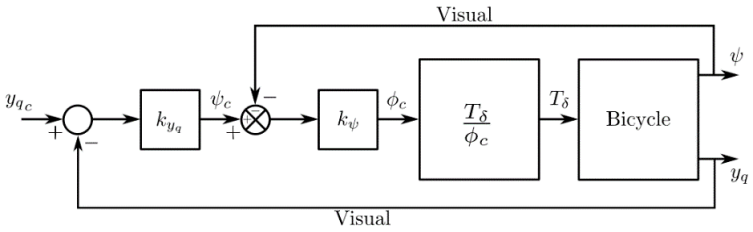

Figure 52: The complete manual system, showing the outer loops of the manual control system for tracking tasks. The inner loops are represented by the $\frac{T_\delta}{\phi_c}$-block from Hess et al. (2012)[6]

input from the controller ($\dot{\phi}$ and δ) can be compared to the set point to determine the amount of effort.

$$HQM = \left| \frac{\dot{\phi} + \frac{\delta}{K_{\dot{\phi}}}}{\phi_c} \right| \frac{1}{K_\phi}$$

Within the model, a controller is responsible for the input of the system, G_{nm} in figure 52. This is a simplified neuromuscular model, which is based on a human controller by experiment. The reasoning behind this model can be found in Hess et al. (2012)[6].

$$G_{nm} = \frac{30^2}{s^2 + 2(0.707)30s + 30^2}$$

The model is completed with the equations of motion from the bicycle and the outer loop. The complete model is provided in Matlab by one of the authors, Jason Moore. The model is adapted for the purpose of this report, to assess the HQM for each bicycle at each of the three speeds from the cycling experiment. The adapted part of the Matlab files can be found in Appendix E, the other files can be retrieved from a Github[19]. The HQM tells in which level of control the bicycle fits for each speed, and thus given an idea about the subjective handling qualities.

4.2.2.1. INPUT

The input for the HQM-model are the already existing neuromuscular model, the bicycle model and the desired speeds. The neuromuscular model is exactly the same as used in Hess et al. (2012)[6]. The bicycle model is also already existing, as it was needed for JBike6, but the configuration of the coordinate system is different. This had to be rewritten from x - y to x - $-z$

The HQM-model required an input of the head angle λ, wheelbase w, trail c, rear wheel diameter d_R, real wheel mass m_R, real wheel moment of inertia $I_{xx,R}$, $I_{yy,R}$ and $I_{zz,R}$, front wheel diameter d_F, front wheel mass m_F, front wheel moment of inertia $I_{xx,F}$, $I_{yy,F}$ and $I_{zz,F}$, rear frame centre of mass $COM_{x,B}$ and $COM_{z,B}$, rear frame mass m_B, rear frame moments of inertia $I_{xx,B}$, $I_{yy,B}$, $I_{zz,B}$ and $I_{xz,B}$, front assembly centre of mass $COM_{x,H}$ and $COM_{z,H}$, front assembly mass m_H, front assembly moments of inertia $I_{xx,H}$, $I_{yy,H}$, $I_{zz,H}$ and $I_{xz,H}$. Important to be noted, the body of the rider is not included in this model. It is just the bicycle frame with a virtual controller, without mass or other properties. In order to rewrite the bicycle system from the JBike6-model to the HQM-model, first the principle axes of inertial for the rear frame and front assembly have to be corrected. In the HQM-model, they are defined within the coordinate system, not by a principle

angle. The inertia matrices $I_{JB,\alpha}$ with a separate principle angle α are rotated by a rotational matrix R_α to inertia matrices with the angle incorporated in the Jbike6-system I_{JB}.

$$R_\alpha = \begin{bmatrix} \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$I_{JB} = R'_\alpha \, I_{JB,\alpha} \, R_\alpha$$

After this rotation all separate bodies from the bicycle, both wheels, rear frame and front assembly, are rotated with rotational matrix $R_{J/H}$ from the JBike6-system (JB) to the HQM-system (HQM). This is done for the COM and the inertia matrix.

$$R_{J/H} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & -1 & 0 \end{bmatrix}$$

$$COM_{HQM} = R_{J/H} \, COM_{JB}$$

$$I_{HQM} = R'_{J/H} \, I_{JB} \, R_{J/H}$$

This is done for every bicycle, which resulted in a set of parameters for the HQM-system of every bicycle without rider. These are the same as described in the previous part, but rotated to the right system.

The only missing inputs are the gains of the system. Within the model, there is a build in function to guess the gains for the bicycles. These are different for every speed. For each speed, the gains for the system, $K_\delta, K_{\dot{\phi}}, K_\phi, K_\psi$ and K_y, are guessed by the model. Because there is no reference on what these gains should be, it cannot be stated with certainty that these gains are correct. The gains for the example bicycles in the program are also very distinct, so these could not be used as reference. The gains that are used in the model can be found in Appendix E.

All this data is loaded into the HQM-model, together with the three speeds. Because the free speed was undetermined, and this model needs a fixed speed, an average speed was chosen to resemble the free speed of the cycling experiment. This speed is set at 5.5 m/s, just as with the average rider.

4.2.2.2. OUTPUT

The results for the HQM can be best shown by the HQM-plots of the three speeds. Figure 53 shows the HQM for all bicycles at 2 m/s, figure 54 at 5.5 m/s (the 'free speed') and figure 55 presents the HQM at 7 m/s. The figures show the HQM versus the frequency resulting from the transfer function of the model. The most important is the peak of the HQM, that gives in indication of how much effort it takes to control the bicycle.

For the results at 2 m/s, it seems a bit odd that some bicycles go to infinity at 0 Hz, and some to zero. After consulting the creator of the program, Jason Moore, it became clear that the program cannot handle velocities below 2.5 m/s. So the model was run again, but with speeds of 2.5 m/s and 3.0 m/s and new gains that fitted those speeds. Also these speeds gave unclear results with strange values. The gains that were found by the program were not stable. After multiple trials, the program still could not find gains that created a stable system. This means that the data from the HQM-model is probably invalid.

Despite that probability that the data is invalid, one more statement about the HQM at the higher speeds, 5.5 m/s and 7.0 m/s, can be made. Those results looked more reliable by eye, so there were looked into nonetheless. The figures show the peak HQM all around the same value. Also this was discussed with Jason Moore by e-mail, and it is concluded that probably the handling of all these bicycles are not different enough to show large differences in the HQM. All these bicycles are available on the market, so are probably all quite well controllable. The dynamics of the bicycle are too similar, and although it might feel different for the rider of the bicycle, the HQM values them all similar. This can be related to the conclusion about the eigenvalues: they do not differ that much from each other, so probably the dynamics of the system are not distinct enough to show real differences.

So, the HQM has provided two insights. In the higher speed range, where the results look more accurate by eye, the values are not different enough to make a real distinction between the bicycles. And, especially for the lower speed range, the results might be invalid because of wrong gains. There are no references on what those gains should be, so the gains cannot get more accurate than the program provides. Therefore, the results of the HQM will not be used to assess the handling qualities of the bicycles from this study.

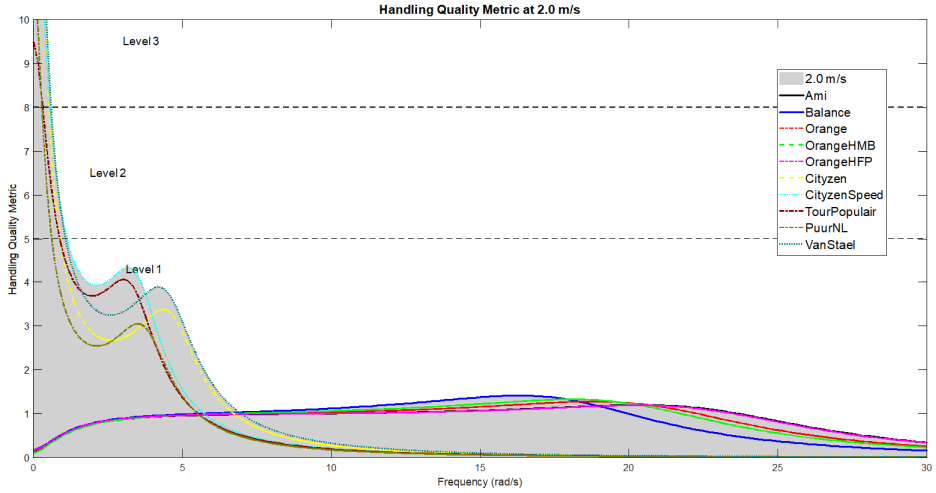

Figure 53: HQM for all bicycles at 2.0 m/s

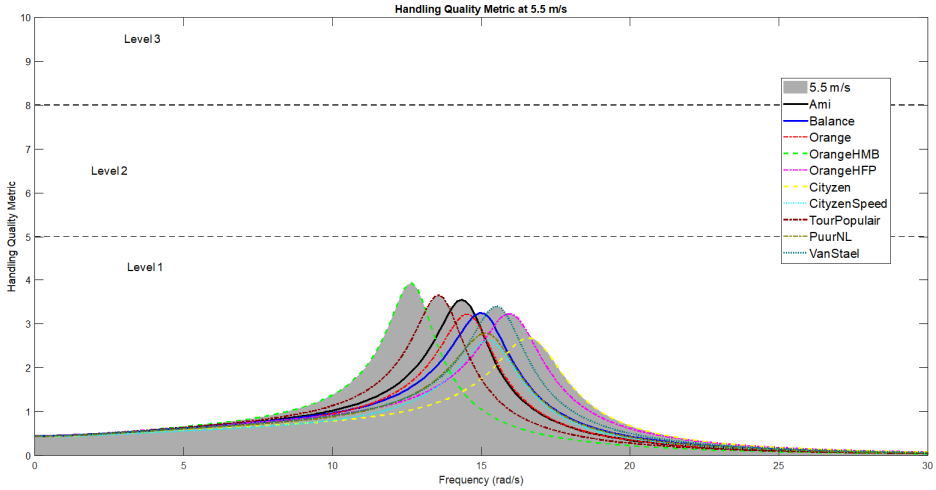

Figure 54: HQM for all bicycles at 5.5 m/s

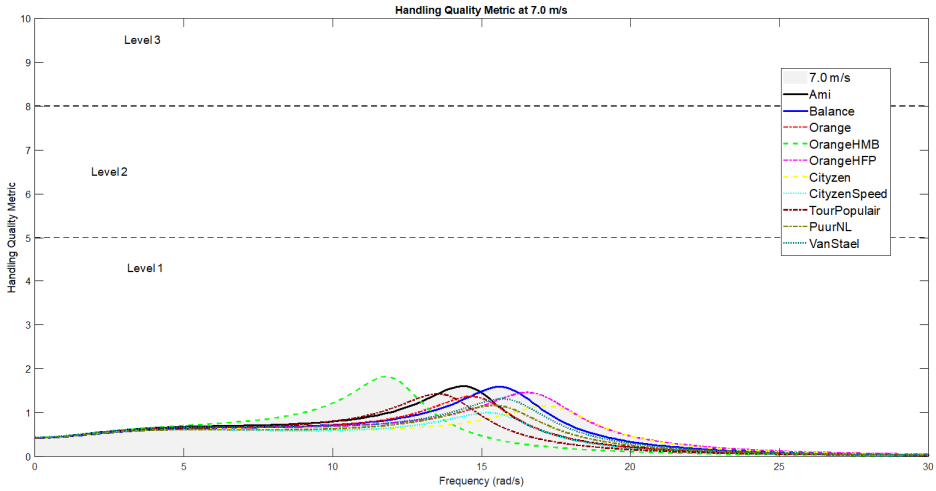

Figure 55: HQM for all bicycles at 7.0 m/s

4.3. DISCUSSION

In finding the objective measures, the properties of the bicycle had to be defined. During this process, not all bicycles or bicycle parts were available. Due to these missing data, assumptions had to be made to fill all bicycle properties.

Starting with the wheel, not all bicycles were present at the day of measuring and taking out the rear wheel of the bicycle was a time-consuming job. From all bicycle present, the front wheels are measured and only the 'odd' rear wheels were measured. The Ami and Balance both have a different wheel size, so difficult to compare to the other and had to be measured. Because the Cityzen Speed had a rear wheel what was easy to get out, also this one was measured. The wheels of the Orange HFP and HMB could be retrieved from Kalsbeek (2016)[18], and with this data, the other wheels are scaled. This might have led to values that are not completely accurate. But, since there were no values that looked really different from the others and with the knowledge that the wheels are not that different from each other, the values that are scaled are used nevertheless. There was no other option to get the actual data.

The same problem occurred in defining the properties of the bicycle front assembly and rear frame. The Solid Works file from Gazelle provided not the outcome that was expected and another solution in finding the moments of inertia had to be found. Three bicycles were measured, to test if this provided reliable outcomes. The results were close to what was expected, but it still had a range of values, that were relatively large for the dimensions of those values for 2 of the three bicycles. With the bicycles manually weighed and a reference point, the new masses were put into the Solid Works models and compared to the measured data. Still, the outcomes were not similar, but within range of the measurement-range. The differences between the values were the same. Because the difference from Solid Works were the same as in the actual measurement and the wheel still had to be included in the complete assemble, the Solid Works values are assumed to be correct. This is an assumption and probably not all values for the moments of inertia are correct, but it is probably close enough. There were no really weird results in the eigenvalue analysis that indicate that something in the dynamics is wrong. It might have led to minor differences in the eigenvalue analysis that have influenced the strength of the correlations.

The masses of the bicycle were measured by hand, so those are correct. The only difficulties lie within the steer. The steer and steer stem were measured as one, so it had to be guessed how to divide the weight over the two components in Solid Works. Depending on the size of the stem, a higher or lower weight was added. Also the hand grips and brake levers were equipped when weighing the steers. As those appeared to be of great influence of the moment of inertia of the steering assembly, it had to be added separately in the Solid Works model. The hand grips and brake levers are not weighed for each bicycle. Only two sets, a small and a large set, are measured and based on the looks of the sets on the available photo's, a mass within the range of the two was assigned to each bicycle. Since the grips and levers are of great influence, it might be possible that also this have influenced the actual moment of inertia of the steering assembly.

So, while constructing the bicycle model, a lot of assumptions had to be made. All these assumptions are based on actual measurements and within the range of the actual measurements, but it is not fully reliable. There might be some errors in the data. Unfortunately there was no other possibility to obtain the data more accurate. There was no data base of all the components of each bicycle and it was too time consuming to do it all by hand with the knowledge that it might not be more accurate. The batteries and motors of electrical bicycles have been taken into account. Those are also weighed manually and implemented separately into Solid Works. This adds to the accuracy of the model.

This model is loaded into JBike6. The results coming out of it are calculated numbers for the eigenvalues and steer stiffness. The complete rider-bicycle model is a simplified model. A rider is modelled as passive point mass on top of a bicycle without a controller. It is an open loop system and the results do not say anything about a controlled system. But, this is a reliable start to analyse the rider-bicycle system. Simple calculations to evaluate a handling quality. As pointed out in a previous literature study, there are no validated rider models and thus the results that would come from such a model are also not reliable. This open loop system is of course simplified and not accurate to the real world, but it does give solid values for the uncontrolled system.

A model that had a controlling rider was the model of Hess et al. (2012)[5]. This model is still under development, but it provided a measure for the handling of a bicycle: control effort. This was an interesting measure, as it covered the stability of keeping the bicycle straight up while following a modelled path. One number comes out of the model, indicating a good, moderate or bad handling bicycle. Despite the value that it would have had to this study, the results of the model were unreliable in this case. The gains that the program provide did not result in a stable closed loop system. Even after multiple trials, the right gains for the

system could not be found, not for any bicycle. Because there was no reference on what those gains should be, a valid gain could not be found. The model in its form right now was not suitable for our bicycle system. To still say something about the results that came from it, although unreliable, all bicycles were found within the good-handling range. Actually, this could have been expected, because all these bicycles are sold and in use in the Netherlands. All bicycles are 'conventional' bicycle, with a conventional geometry. They are not distinct enough to show real differences between the bicycles. The dynamics are largely the same.

The minor difference in dynamics also showed from the objective measures. The rider does not have much of an influence on the eigenvalues. The eigenvalues are defined by the equations of motion of the rider-bicycle system. The rider is included in that, but that does not result in very large differences within and between the bicycles. On the other hand, the steer stiffness does show a lot of differences within and between the bicycles. The steer stiffness is calculated with the peak frequency of steering or with 0 Hz. The differences between the peak frequency and 0 Hz in the free speed and 7 m/s are really large, while it is a lot smaller in 2 m/s. When comparing these results to an average rider on each bicycle, the same trend is visible. Where the eigenvalues do not differ at all from the average results of all riders on a bicycle, there are some differences in value in the steer stiffness. This implicates that the eigenvalues are not influenced that much by the rider on the bicycle, but the steer stiffness is.

It is interesting to look at the eigenvalues, because they do not differ that much between different riders. When looking at the steer stiffness is it more difficult because those are more rider dependent. A solution would be an average rider for each target group. That should be a rider model, based on the target group for a specific bicycle. For instance a child, a commuter, an elderly man, a mom or a student. A peak frequency of steering is unknown would still be unknown. But, as stated above, it showed that the frequency depends on the speed of the bicycle. For an average speed the frequency of steering lies around 1 Hz. For some slower cyclists (elderly) a lower frequency could be chosen and for a commuter at really high speeds a higher frequency would be suitable. This way, a steer stiffness can still be calculated for each bicycle with an average rider representing a specific target group. There are then still differences within each person actually riding the bicycle, but there is a guideline to work with.

4.4. SUMMARY

This chapter covered the objective measures from a rider-bicycle model; eigenvalues, steer stiffness and HQM. First the JBike6 model was explained.

The rider was constructed based on an existing model from Moore et al. (2009)[17]. The properties of all participants were collected at the cycling experiment and scaled with the existing rider model to create a passive rider with a principle angle for the moment of inertia. The bicycle model was constructed in three parts. First, the geometry of the bicycle was provided by Gazelle, which outlines the basic shape of the bicycle. Next, the dynamic properties of the bicycle had to be found. The moments of inertia and masses of most wheels were collected experimentally or from other literature, and the wheels that could not be tested were scaled with the other based on their looks and information about the nave and brake system from Gazelle. The bicycle frame was a bit more complicated. The first Solid Works files from Gazelle appeared not to provide the right numbers. After adding material properties, the weight of the bicycle was not correct. Parts of the bicycle are weighed by hand separately (motor, battery, steer tube and stem, front fork and wheels), as well as the complete bicycle, so all components could be subtracted from the complete mass of the bicycle, to also get the mass of the rear frame. A test was set up, to measure three bicycles for their centre of mass and moment of inertia of the steering assembly and compare that with the Solid Works data after implementing the correct mass. These values were found to be reliable enough, so all moments of inertia are determined by Solid Works, after all the masses were corrected. With these values, the bicycle model with passive rider could be implemented in JBike6 for analysis of the objective measures.

The analysis in JBike6 resulted in four eigenvalues and six steer stiffness values. For each speed, 2 m/s, a free speed and 7 m/s, there is a highest real eigenvalue to assess the open loop stability of the bicycle, and an imaginary eigenvalue at 2 m/s for the amount of oscillation in the weave mode. Also, for each speed there is a steer stiffness with the peak frequency of steering and with 0 Hz steering (no steering at all). The eigenvalues showed that all bicycles are open loop unstable at 2 m/s, and that every bicycle on average is stable at 7 m/s and only two at the free speed are not. But, within the bicycles there are differences between the participants, some were cycling at open loop stable and some unstable. The bicycles that had a lower average speed are also more likely to be unstable, because of the lower velocity. Therefor it can be stated, that the chosen cycling speed for that specific bicycle is more preferred than a speed in which the bicycle is open

loop stable at all times. The steer stiffness at 2 m/s shows only minor differences between the peak and 0 Hz, were at the free speed and 7 m/s are larger differences. The peak frequency at 2 m/s is lower, so more close to 0, than the frequencies at the free speed and 7 m/s. For the peak-stiffness, the values at the free speed and 7 m/s are almost the same, except for the Cityzen Speed. The speed in the free section of this bicycle was way higher than all the others, including the 7 m/s. This high speed has probably added to the steer stiffness. However, when comparing the cycled speeds to the steer stiffness, there is no one-on-one relationship. The same accounts for the frequency of steering. Also within the bicycles, between the participant, some large differences show up. This indicates that a rider does have influence on the steer stiffness of the bicycle.

To check for the differences between the bicycles without influences of the rider, an average rider was created and the same analysis in JBike6 was performed. This gave the same results for the eigenvalues, with almost the exact same values, and approximately the same values for the steer stiffness as well. However, the values with an average rider did differ from the average values of all rider per bicycle. That is an indication that the rider does not have that much of influence on the eigenvalues, but does influence the steer stiffness.

The last part covered a handing quality metric, designed by Hess et al. (2012)[6]. This metric assesses the amount of effort required to control a vehicle. The more effort, the higher the metric, the worse the handling. This model is provided by one of the authors and slightly adapted for our purpose. Although the model provided results, the results are unreliable because of an unstable closed loop system. The required gains are estimated by the program, but after some trial and error, none of the gains could provide a stable system for any of the bicycles. So this metric is not used for further analysis. One remark about the results that is interesting. The results for 5.5 m/s and 7 m/s seemed more reliable by the eye and showed that the values for the HQM are all close together in the level were the bicycle is ought to be controllable. After consulting the authors, it is thought that the differences in controllability are not large enough to result in a different handling quality metric. The dynamics of the bicycles are not that different, and all bicycles are on the market and should be controllable for that sake.

The next chapter will discuss the correlations between the subjective measures from the participants and the objective measures from JBike6. Can a handling quality be predicted by a rider-bicycle model?

5

SUBJECTIVE AND OBJECTIVE MEASURES: CORRELATIONS

The previous two chapters have covered the subjective handling qualities and from the experiment, and the objective measures from the rider-bicycle model. This chapter will combine the two, to see if there is any correlation between one of the subjective handling qualities and an objective measure.

A quick recap on the available data: subjective answers from participants on 14 questions that covered 10 handling qualities, rider measurements from the cycling experiment (speed, peak frequency of steering and amount of steering) and objective measures from a rider-bicycle model (eigenvalues and steer stiffness). The velocity and peak frequency of steering from the cycling experiment are used to create the rider-bicycle model, as those are different for each rider on each bicycle. Figure 56 shows a recap of the numbers of the questions from the questionnaire and the corresponding handling qualities.

The Power Spectral Density is correlated with the subjective handling qualities, to compare the actual rider steering behaviour to the opinion of the participants on the steering behaviour. This will point out if they were able to judge the steering behaviour as it was executed, or that is only a 'feeling' they get when riding the bicycle. After that, the subjective handling qualities and objective measures are analysed on correlations. Can a handling quality be predicted by an objective modelled measure?

5.1. CORRELATIONS

The raw data, for each participant on each bicycle is analysed per question per objective measure per speed in search for a correlation between the subjective and objective data. The analysis is done by a Spearman's ρ ranked correlation, because this type allows for correlations on an ordinal scale, like the answers to the questionnaire. This is done with the use of Matlab, and the data set that were unusable are not taken into the correlation analysis. The Matlab files can be found in Appendix F. A correlation of $\rho = 1$ describes a perfect linear relationship between the two variables, with a correlation $\rho = 0$ there is none and with $\rho = 0.5$ there is a moderate correlation. The results are found to be significant when $p < 0.05$. Only then, there is a correlation between a handling quality and an objective measure. All other results are discarded. An example of a correlation with all data, for one question and one variable is shown in figure 57. Spearman's ρ and p are provided in the header of the figure, as well as the variables. The data in the figure are all participants on all bicycles, where each colour represent a bicycle and each figure a participant. All correlation figures are based on this principle. The data used for the objective measures can vary. A rider measure can also be used to correlate with. The rider measures of peak frequency and speed are not correlated, since these are measures that are used to build the model. The PSD, however, has been used to assess the quality of the subjective results.

Handling Quality	Lazy	Sportive	Safe	Controllable	Forgiving	Stable (Weave)	Stable (Capsize)	Nervous	Maneuverable	Direct
Question	1	2	3	4,10	5	6	7	8,9	11,12,13	14

Figure 56: An overview of the questions from the questionnaire corresponding to the handling qualities

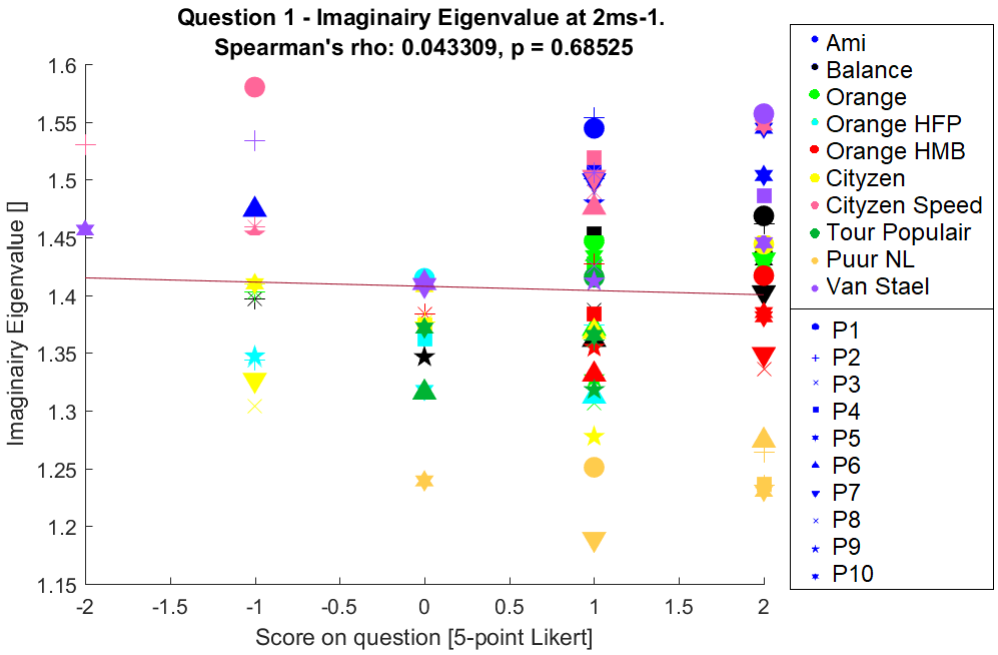

Figure 57: Example of a correlation figure, where each colour represents a bicycle and each figure a participant. Question 1 with the imaginary eigenvalue at 2 m/s. $\rho = 0.68525$, $p > 0.05$

5.1.1. POWER SPECTRAL DENSITY

The power spectral density (PSD) has been correlated for the three speeds. Not because it might predict a handling quality (this is very participant dependent), but because it can give an indication how well the participants have answered the questions. For instance, if they have answered that they have to make a lot of steering corrections to follow a straight line (score +2 on question 9), then there should be a higher value for the PDS, more steering. Appendix F holds the correlation figures for the PSD.

The PSD only correlates significant at the free speed with 'Sportive'($\rho = 0.3799, p < 0.05$) and with 'Stable (capsize)' ($\rho = -0.2186, p < 0.05$). The correlation with sportive at the free speed is a positive correlation. With the question 'The bicycle gives me a sportive feeling', a higher score would indicate more sportive. So a positive correlation means that with a higher PSD, more steering, the bicycle is rated sportive.

The question for the stability at capsize (higher speeds) was stated 'I have the feeling the bicycle starts swaying across the road at high speeds'. That means that with a higher score, the bicycle starts to sway more, indicating a less stable bicycle. The correlation of the PSD is a negative correlation, indicating a lower PSD, less steering, correlates with a less stable bicycle. This result is found to the significant, although with a weak correlation. However, this is opposite of what is implied by the question, more swaying across the road would require more steering actions from the rider. Therefore, it is likely that the participants had difficulties with identifying their own steering actions. This might also be an explanation why there are not more correlations. For example, the questions about the amount of steering 'I have to make steering corrections to follow a straight line' (question 9, corresponding to nervous) does not show any correlation with all of the three speeds. The participants have failed to identify their own amount of steering. The means that the results of the correlations with questions about the amount of steering (6,7,8 and 9) are probably not reliable. This also came forward from Cronbach's α when the questionnaire was analysed for clustering the questions.

5.1.2. EIGENVALUES AND STEER STIFFNESS

5.1.2.1. RESULTS

The eigenvalues and steer stiffness are correlated the same way as the PSD. For each speed, there are 2 steer stiffness's and 1 real eigenvalue and for 2 m/s there is an additional imaginary eigenvalue, resulting in 10 possible correlations per question. Appendix F holds all the figures with correlations. Figure 58 shows an overview of all significant correlations ($p < 0.05$) with their ρ. In addition, the specific question number is given when more questions correspond the handling quality. The separation of 0 Hz and Peak Hz at each speed only accounts for the steer stiffness. For each handling quality, the correlating measure at a specific

Handling quality	Lazy	Sportive	Safe	Controllable	Forgiving
Question	1	2	3	4,10	5
2 m/s 0 Hz		stiffness < (-0.54) imaginary > (0.42)		imaginary > (0.25 (**10**))	
2 m/s Peak Hz		stiffness < (-0.54)			
7m/s 0 Hz	stiffness > (0.21) real < (-0.22)	stiffness < (-0.43) real > (0.44)			
7 m/s Peak Hz					
Free speed 0 Hz	stiffness > (0.23)	stiffness < (-0.58)			
Free speed Peak Hz		stiffness < (-0.28)			

Handling quality	Stable (Weave)	Stable (Capsize)	Nervous	Maneuverable	Direct
Question	6	7	8,9	11,12,13	14
2 m/s 0 Hz		stiffness < (0.29) imaginary > (-0.25)		real > (0.24, (**12&13**)) imaginary > (0.26 (**12**), 0.23 (**13**))	real > (0.26) imaginary > (0.22)
2 m/s Peak Hz		stiffness < (0.29)			
7m/s 0 Hz		stiffness < (0.22)			
7 m/s Peak Hz					
Free speed 0 Hz		stiffness < (0.27)			
Free speed Peak Hz				stiffness > (0.26 (**11**), 0.22 (**12**))	

Figure 58: Significant correlations between a handling quality and an objective measure for each speed, with an indication < (decrease) or > (increase) of the measure for an increase of the handling quality and ρ (...)

speed is provided, with the consequence, < or >. When > is given with the measure, it means that the handling quality increases with an increasing measure. When < is given, the handling quality increases with a decreasing measure.

Is it immediately clear that there are only a few significant correlations, 24 of the possible 140. Furthermore, the correlations are only moderate to weak. There are the most correlations with the steer stiffness, fewer for the real and imaginary eigenvalue. The strongest correlations are found with the handling quality sportive, for the steer stiffness at 2 m/s and the free speed ($\rho = 0.54 - 0.58$). For all the other correlations accounts $\rho < 0.3$. This is probably due to the small group of participants. The few number of correlation might be due to the fact that the participants were unable to recognize their own steering behaviour. They have answered on how they felt the bicycle, but that did not correspond to what they actually did (as shown by the PSD) and also the objective measures showed different results than what the participants answered.

To provide a more clear picture, the correlations are displayed as an average with the standard deviation of the objective value per bicycle. It is sorted from low to high on the correlating handling quality. These figures can be found in Appendix F and figure 59 shows an example. It has to be noted that the bicycles are only ranked from low to high, and not on the actual average subjective value of the handling quality. A perfect correlation should show an increasing (or decreasing when negative) average value form left to right. Because the bicycles are not positioned on the x-axis by value, but by rank, the trend line does not have to be straight.

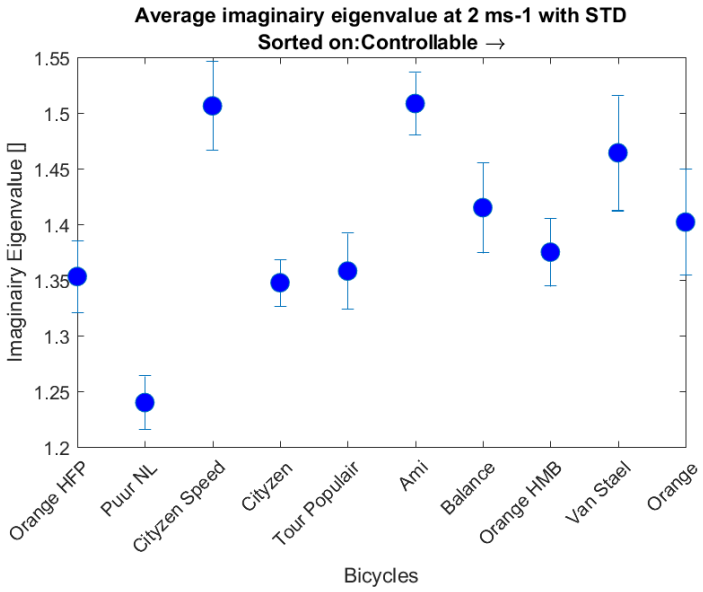

Figure 59: Example of bicycles sorted on a handling quality. The bicycles are ranked on the x-axis based on their average value on controllable, from low to high. Correlation between controllable and imaginary eigenvalue at 2 m/s

It might have some steps, but it should always go up (or always go down with a negative correlation). This is clearly not the case. Due to averaging and only a weak correlation, the increase of value from left to right is not as clean as would be preferable. There is often a visible trend, but the objective values are jumping around this trend line. Also the STD's of the objective values are large for some, indicating that there are large differences within one bicycle, due to the participants. The objective data with the average rider can be found in Appendix F. The same figures are created, with the same subjective ranking, but with the objective measures from the average rider. The 'lines' in the graph do not improve. They even get worse, indicating that the rider does have influence on the bicycle objective measures and that it can be felt by the riders. There is a stronger trend line than with the average rider, showing that these handling qualities can be felt and judged by the participants. The handling qualities with significant correlations:

- **Lazy** ; The bicycle gives the rider a lazy feeling, with a high *steer stiffness* at a self-chosen speed and at 7 m/s, and when the *real eigenvalue* is small at 7 m/s.
- **Sportive** ; The bicycle gives the rider a sportive feeling, with a low *steer stiffness* at all speeds, with a high *imaginary eigenvalue* at 2 m/s and a high *real eigenvalue* at 7 m/s.
- **Controllable** ; The bicycle is controllable with a low *imaginary eigenvalue* at 2 m/s.
- ***Stable (Capsize)*** *; The bicycle does not sway across the road at high speeds with a low* steer stiffness *at all speeds and a high* imaginary eigenvalue *at 2 m/s.* (Unreliable result)
- **Maneuverable** ; The bicycle is rated maneuverable with a high *real and imaginary eigenvalue* at 2 m/s and with a high *steer stiffness* at a self-chosen speed.
- **Direct** ; The bicycle is rated as direct with a high *real and imaginary eigenvalue* at 2 m/s and with a high *steer stiffness* at a self-chosen speed.

The handling qualities that have no significant correlation:

- **Safe** ; There is no correlation between a safe feeling while riding the bicycle and any objective measure.
- **Forgiving** ; There is no correlation between forgiving bicycle behaviour and any objective measure.
- **Stable (weave)** ; The stability of the bicycle at low speed does not correlate to any objective measure.
- **Nervous** ; The amount of steering to keep a steady line does not correlate to any objective measure.

5.1.2.2. HANDLING QUALITY PROFILES

As shows from the handling quality correlations, when one objective measure is adjusted, it affects multiple handling qualities. For some bicycle this may be beneficial, but for others there might be some fine tuning necessary. For instance, a more controllable but less direct bicycle. With these set of correlating handling qualities, a new handling quality profile is created for each bicycle (figure 60). Only the handling qualities that have a significant correlation with one of the objective measures is included. This means that for the quality controllable, only question 10 has a significant correlation. Question 4 is removed from this quality, because it shows no correlation and the scores were conflicting as shown by Cronbach's value. Questions 11, 12 and 13 all show a correlation with one of the objective values and had a good Cronbach's α value, so there remain clustered in the handling quality profiles. These profiles can be used when designing a new bicycle. The other qualities are left out, because they show no correlation with an objective measure, and therefore they cannot be modelled with the used of objective measures. The list below provides the consequences for the handling qualities of an altered objective measure.

- **Steer stiffness** ; When increasing the steer stiffness at 7 m/s or the self-chosen speed, the bicycle becomes more *lazy* and more *maneuverable*. With a decrease of the steer stiffness, at all speeds, the bicycle becomes more *sportive* and more *stable* (unreliable) in the capsize range (high speeds).
- **Real eigenvalue** ; When the real eigenvalue increases at 2 m/s, the bicycle becomes more *maneuverable* and more *direct*. When it is increased at 7 m/s, the bicycle becomes more *sportive*. When it is decreased at 7 m/s, the bicycle becomes more *lazy*.
- **Imaginary eigenvalue** ; With an increased imaginary eigenvalue, the bicycle becomes more *sportive*, *controllable*, *stable* (unreliable), *maneuverable* and more *direct*.

It appears from the handling quality profiles, that the bicycles can be put into groups with matching profiles. The profiles show three categories of bicycles; lazy bicycles with a dip at sportive, lazy bicycles with a straight line crossing sportive and bicycles that are sportive with a flat top at lazy. In the first category, from most lazy (top) to less lazy (bottom), belong the Balance, Tour Populair, Orange HFP, Orange and Puur NL. The second category is a transition from lazy to more sportive, including the Orange HMB and the Ami. The third category, from least sportive and more lazy to most sportive and less lazy, hold the Van Stael, Cityzen and Cityzen Speed. The groups with matching profiles also have similar geometries or are classified in similar groups when interviewing the Gazelle employees. These fit the basic lazy and sportive geometry. The categories are shown in figure 61, 62 and 63. These figures also include a profile of the objective values. From top to bottom: 2 m/s, free speed and 7 m/s with left the steer stiffness with 0 Hz and right the eigenvalues, with the imaginary eigenvalue on top. Because the steer stiffness with 0 Hz shows the most correlations, and the peak frequency not, the steer stiffness with 0 Hz is chosen as leading in this objective profile. To create a readable plot, the values in the profile range from -1 to 1, where all the steer stiffness's and the real and imaginary eigenvalue at 2 m/s are divided by 10.

It shows that also these objective profiles have specific shapes in each category. Because the correlations are not very strong, there are some differences with the order of the objective values. These do not correspond completely with the handling quality profiles. This division in categories can help with the development of a specific bicycle for a specific target group. Desired qualities can be found within a category and objective values can be matched with these bicycles to create similar handling qualities.

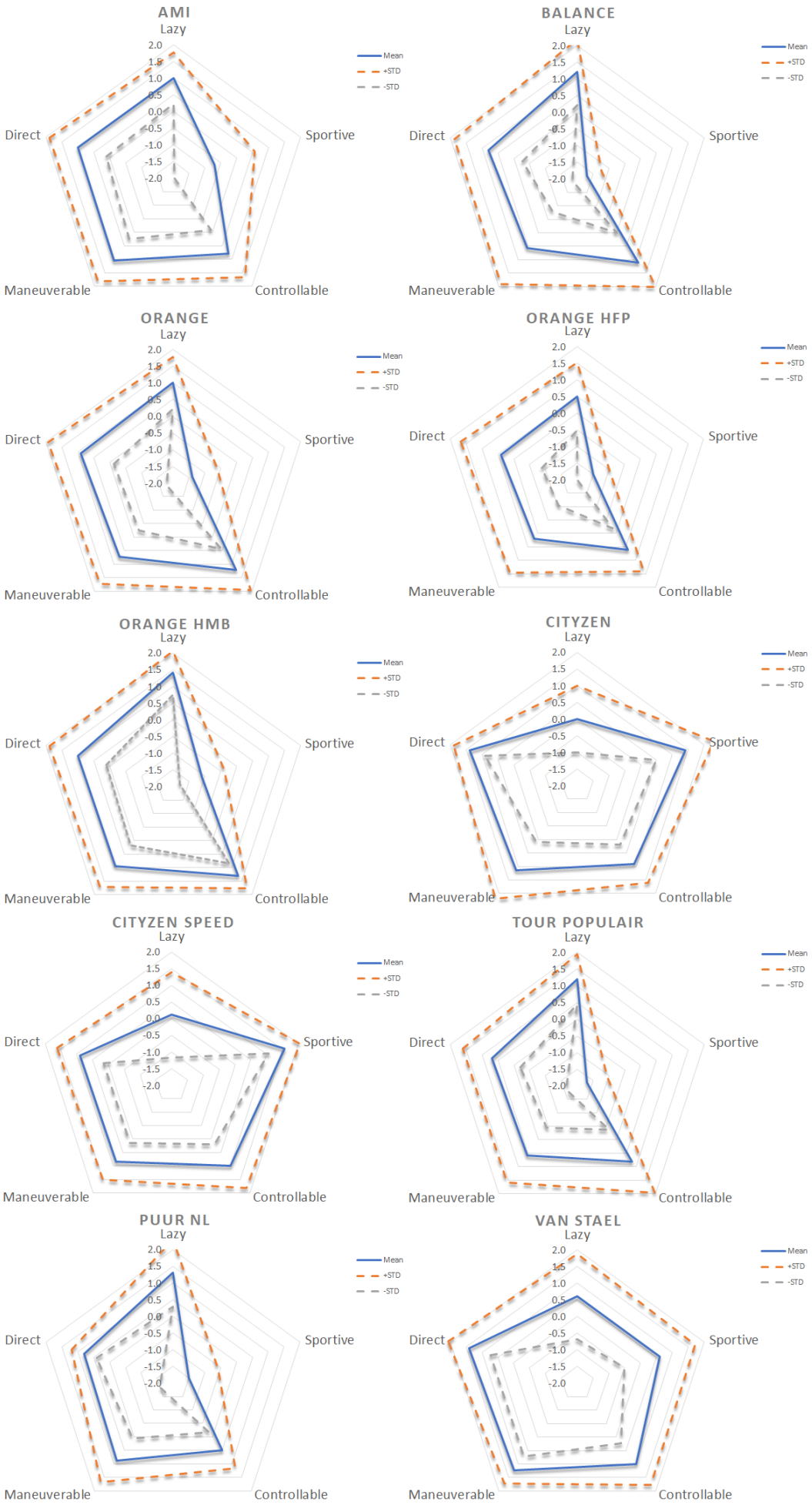

Figure 60: Handling quality profiles for all bicycles. Only the handling qualities with a correlation to an objective measure are included

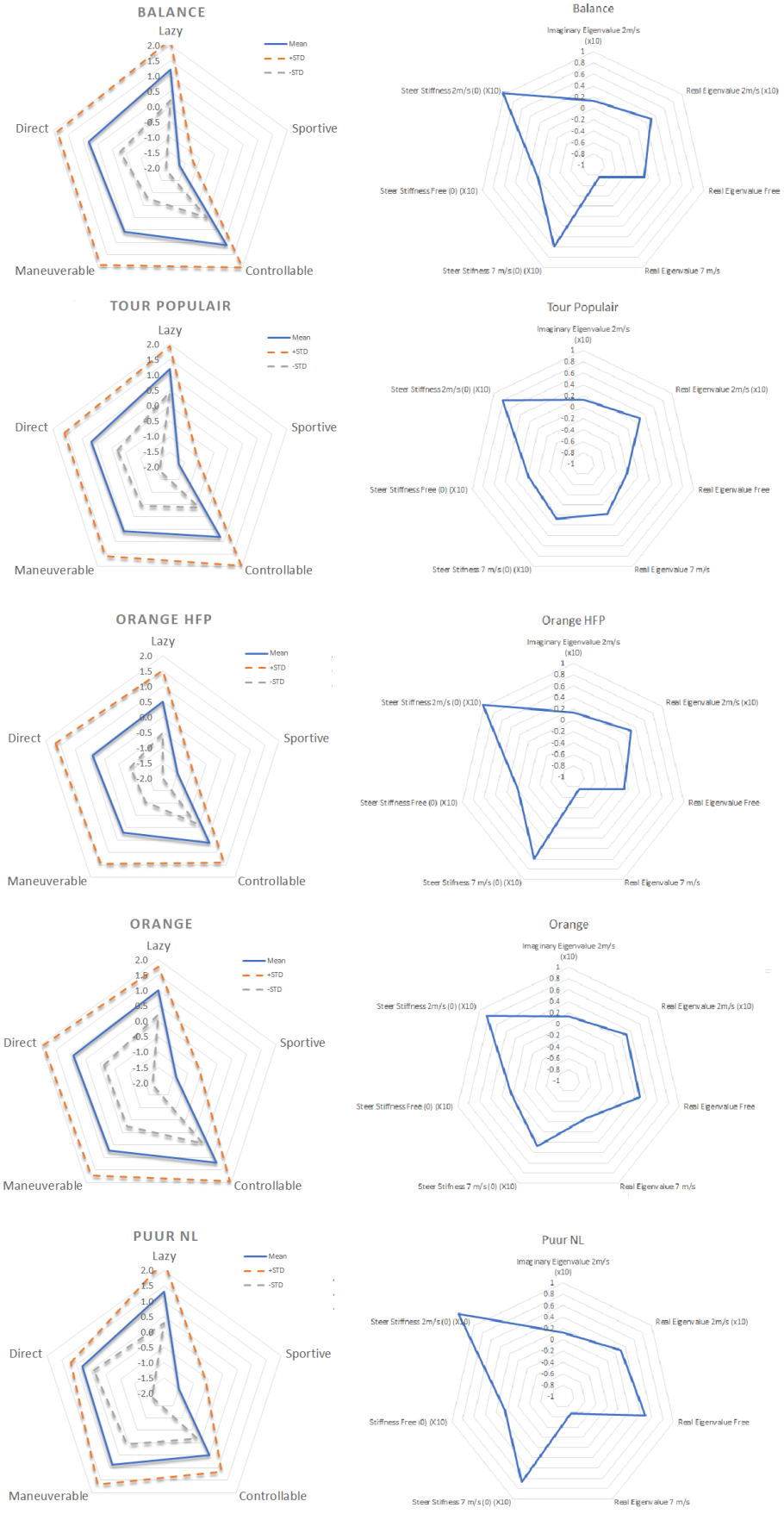

Figure 61: Handling quality profiles and objective measure profiles for category 1: Lazy bicycles

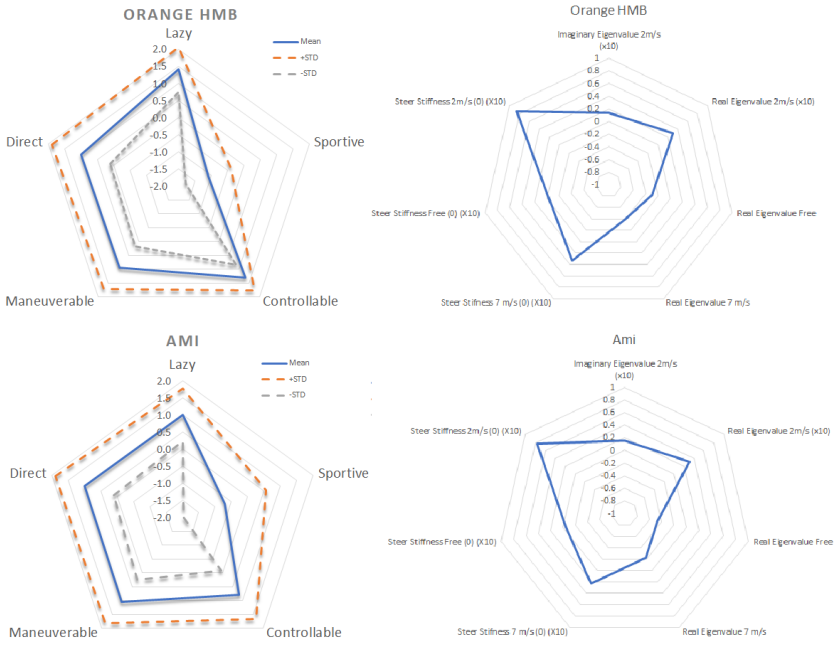

Figure 62: Handling quality profiles and objective measure profiles for category 2: Transition from lazy to sportive

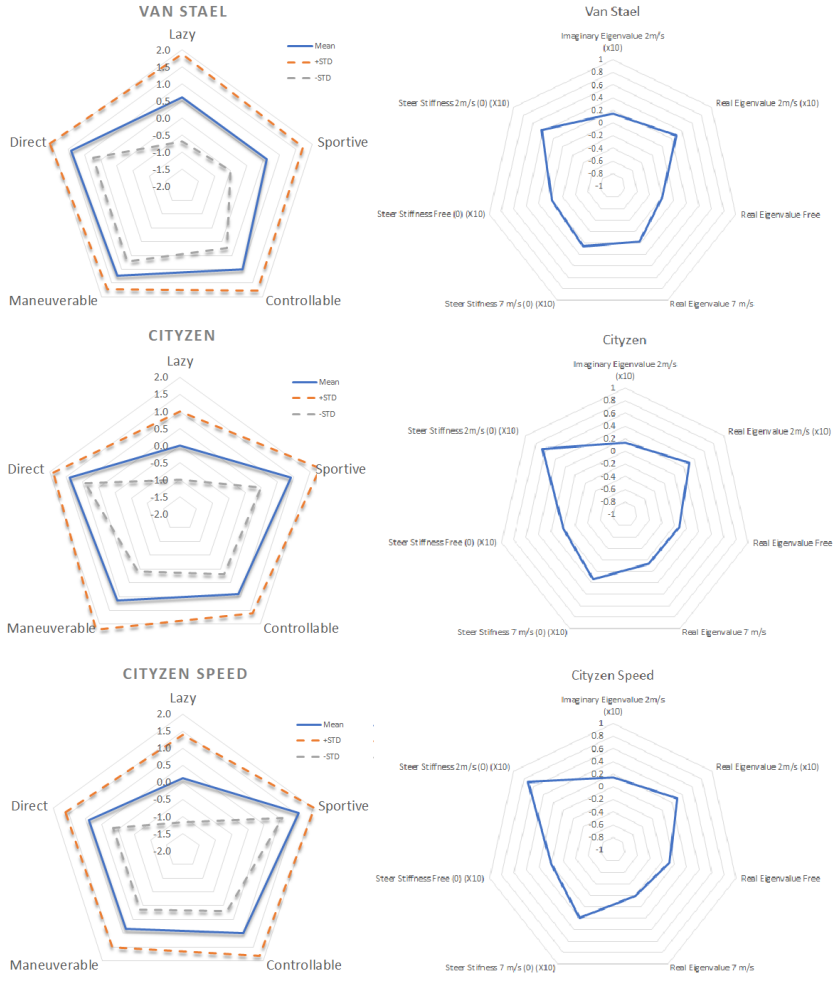

Figure 63: Handling quality profiles and objective measure profiles for category 3: Sportive bicycles

5.2. DISCUSSION

With both the subjective data and objective data from all the rider-bicycle combinations, it clear that only a few handling qualities can be correlated with the objective measures. This is just very rough, as the correlations are only moderate to weak.

The questions about following a straight line (8 and 9, corresponding with nervous) or tipping over (6, corresponding with stability at slow speed) appear to be difficult question to answer, since there are no correlations. The same conclusion was drawn at the section about the PSD and Cronbach's α; participants have difficulty with identifying their amount of steering and the actions they make. What stands out, is that question 7 shows a lot of correlations with the steer stiffness. This question asks for the same kind of steering behaviour as the question 6, 8 and 9, which show no correlations. Moreover, in the previous section about the PSD became clear that the participants have answered the question reversed to what the measured data showed. So the correlations that show up here are unreliable. They might be correct, but because of the small test group, the results on similar questions and the results from the PSD, these correlations seem too unreliable to use in further analyses. Therefore, when mentioning a correlation with *stable (capsize)*, it is classified as unreliable.

The correlations for lazy, controllable, maneuverable and direct are less strong than for sportive. At the beginning of the report was mentioned that Gazelle has two basic geometries: lazy and sportive. These are assumed to be opposites, but with a gradient from one to the other. When looking at the correlations, the same trend is visible. Where a lower steer stiffness increases 'sportive', a higher steer stiffness increases 'lazy' for both the free speed and 7 m/s at 0 Hz. The same shows for the real eigenvalue at 7 m/s. A higher real eigenvalue increases sportive, a lower real eigenvalue increases lazy. Although the correlations for sportive are stronger, it is the same trend as the Gazelle employees use. The correlations at lazy are just not yet strong enough to be significant. On the other hand, there are not as many correlations with lazy, what should be the opposite from sportive. This might be due to understanding of the terms lazy and sportive by the participants, there can be a mismatch in what the Gazelle employees mean and what the participants think it should be. When looking at the differences in rating on question 1 (lazy) between the Gazelle- and independent participants (Appendix D), there are more differences between the two groups than there are on sportive. Maybe, that when the handling quality was put into different words, the results might have been more of what was expected. That lazy is actually opposite to sportive. It already shows for a small number of objective measures, but not all are significant.

Starting from these two basic geometries, the other handling qualities seem to be subjected to sportive or lazy. Sportive shows a positive correlation at 2 m/s with the imaginary eigenvalue, just as controllable, maneuverable and direct, where the latter three have a weaker correlation. This might indicate that those three handling qualities are going along with a sportive handling quality. For example, a sportive bicycle is at low speeds controllable, maneuverable and direct. On the other hand, both lazy and maneuverable show a correlation with the steer stiffness at the free speed. This would then indicate a lazy bicycle at a self-chosen speed is maneuverable. However, this is all very bluntly said. It has to be taken into account that, except for sportive, all these correlations are very weak. They do not show a certainty, only a trend in the results. It also has to be taken into account that there was only a small group of participants, who were probably unable to identify all of their own steering behaviour. Therefore, these results are showing a trend, but are not conclusive.

Based on the correlations that are found, new handling quality profiles of the bicycles are set up, with just the handling qualities that have shown correlations and that are found to be reliable. These include:

- Lazy
- Sportive
- Controllable
- Maneuverable
- Direct

The ones that show no correlation and are left out include:

- Safe
- Forgiving
- Stable (weave)
- Stable (capsize)
- Nervous

This is done, because the qualities without correlation cannot be predicted based on the objective measures that are used. These qualities are of interest for the whole perception of the bicycle, but not for the purpose of this study; which handling qualities can be predicted by using corresponding modelled objective measures. The bicycles can now be compared for only the useful qualities. As the results did not provide an actual objective number to define a handling quality with, but more an indication of a higher or lower value, upcoming bicycles can be compared to the current bicycles. A new bicycle for a specific target group can be put into one of the three categories: lazy, lazy-to-sportive and sportive. The handling quality profile can then be fine-tuned to specific handling qualities and with the use of the correlations between the handling qualities and objective measures, the bicycle can be modelled with objective measures corresponding to the desired handling qualities. This will ultimately result in a bicycle that meets the desired handling qualities, as set by Gazelle.

5.3. SUMMARY

This chapter covered the correlations between the objective measures and the subjective handling qualities. The actual goal of this study. The results showed that there were only 24 correlations, with a strength of only weak to moderate. The most and strongest correlations were found for sportive, one of the qualities that describe the basic bicycle geometry. The other qualities seem subjected to sportive. The handling qualities that showed a significant correlation are lazy, sportive, maneuverable, direct and stable (capsize), where the latter is classified as unreliable. The handling qualities that did not show any correlation are safe, forgiving, stable (weave) and nervous. By altering the steer stiffness or eigenvalues, the handling qualities that correlate with those specific objective measures can be manipulated when designing a new bicycle. The new handling quality profiles can be used as a reference.

6

Discussion and Conclusion

6.1. Discussion

This study started with interviewing the Gazelle employees. Among them various ideas were in existence about the handling qualities of bicycles. These qualities were analysed, documented and put into a questionnaire. Because the questionnaire had to be shortened, some qualities were not completely clear or described properly, so in the future the questionnaire has to be reviewed and revised.

The questionnaire was used in the cycling experiment with 10 participants and 10 different bicycles. The results from the questionnaire pointed out that not all questions with the same handling quality are answered the same way. This confirmed the suggestion that the questions were open for different interpretations. In the end, these unreliable handling qualities are not used in further analysis. The protocol of the experiment was not followed precisely, but this gave no complications for the data. The data logging with the iPhones was in a few cases complicated by low batteries, resulting in 9 unusable data sets. Due to these unusable sets, the average of the Puur NL, Tour Populair and Orange HFP are affected. The overall results are a little less reliable due to a smaller amount of data. The remaining data from the experiment, 99 sets, were used in the comparison with the objective measures.

In finding the objective measures, the properties of the bicycle had to be defined. During this process, not all bicycles or bicycle parts were available. Due to these missing data, assumptions had to be made to fill all bicycle properties. The front and rear wheels of the Ami, Balance and Cityzen Speed were measured, as well as the front wheels from the Puur NL and Van Stael and both wheels from the Orange HFP and HMB were known. This data is used to scale and find the values for the other wheels. Also, the front assembly and the rear frame were partially measured and partially modelled. The front assembly of the Ami, Balance and Van Stael were measured for the moment of inertia and remodelled with the correct masses in Solid Works. The moment of inertia results from that were within the range of the actual measurement, so it was decided that those results were reliable enough to continue with. The rear frame was also remodelled with the correct masses in Solid Works, with the electrical motors and batteries as separate components, and the moments of inertia for the rear frame were retrieved from the model. While constructing the bicycle model, a lot of assumptions had to be made. All these assumptions are based on actual measurements and within the range of the actual measurements, However they are not fully reliable. There might be some errors in the data. Nevertheless, a complete uncontrolled rider-bicycle model could be set up.

This model is loaded into JBike6. The objective measures coming out of it are calculated numbers for the eigenvalues and steer stiffness for three different speeds and for two different frequencies of steering. Another used model was the HQM, but the gains that were required for the model were unstable. So, for the correlations, only the eigenvalues and the steer stiffness are used.

The objective values, the eigenvalues and steer stiffness are correlated with the subjective handling quality results from the questionnaire by a Spearman's ρ ranked correlation. Only 24 correlations were found to be significant and those were only moderate to weak correlations. This is probably due to a small number of participants. When searching for correlations, 90 data points from different 10 participants is not that much when dealing with subjective answers. There are always participants who think differently. That is already 10% of all the data points. The more participants, the more reliable the correlations get and the stronger the correlation gets. Or, it should point out that there is absolute no correlation at all. In these results, the

difference between significant and not-significant are really small. The answers of the participants are often scattered across the graph and combination is just significant. There are only a few correlations that are of moderate strength. A re-do of the experiment with more participants will result in stronger correlations, if there are actually correlations. Or it will show that these handling qualities cannot be defined by objective measurements.

One outstanding highlight is the basic geometry 'sportive' as defined by the Gazelle employees is showing up as 'leading' in the correlation. Sportive and lazy described the basic geometry of the bicycle with the possibility of fine tuning in between. The same shows in the correlations, where 'sportive' shows the most significant results. The other handling qualities seem to come along with sportive, as those do not have that strong and many correlations. Although lazy does not show up as leading, it is supposed to be the opposite of lazy according to the Gazelle employees. Though it may not be as distinct for the participants, the results for sportive are probably also of interest for the lazy type of bicycle within Gazelle. In addition, this distinction between lazy and sportive also showed up in the handling quality profiles. The bicycles could be grouped with matching profiles, for lazy, sportive and a transition from lazy to sportive. With this knowledge, a bicycle can be developed and fine-tuned with the handling qualities that are subjected to the two main geometries. With the handling quality profiles, the three distinct categories and the correlating objective measures, a bicycle can be modelled to a most optimal handling bicycle for a specific target group.

In the end, this study has found subjective handling qualities that correlate to objective modelled measures. The results can only be used as guidelines, as correlations are too weak to provide an actual objective value for each handling quality. It does not work to compare the bicycle parameters to the objective measure in search for a value. There is not one single parameter that can be altered to create a specific handling quality. Or a specific combination of parameters that is responsible for a handling quality. There is still a lot of freedom within designing the bicycle, because various parameter combinations make up the handling qualities of the bicycle. This study has searched for correlations between the objective values and handling qualities, and in addition it is found that multiple parameters are responsible for those correlations. This will be shown in the last part of this report, with a case study.

It remains trial and error within the model, until a there a configuration is found that gives rise to the desired handling qualities and to the demands of the looks of the bicycle. But, this does not have to be done by producing and testing a bicycle anymore. It can be done on forehand. Optimal handling of a bicycle can be looked into with more focus, or it can be checked for strange or unwanted values in a new bicycle design. The guidelines that are set up, by handling quality or by objective value, can be used together with the handling quality profiles of the tested bicycles to check new designs for their handling or to try and find new designs with specific handling qualities. But, it has to be kept in mind that this is only a first time study, with a small number of participants that were not able to feel every action while riding a bicycle, and with many assumptions in the rider-bicycle model. The results are not solid, there are uncertainties. However, it is a start from which further studies can build on. Also, when using these guidelines in evaluating bicycles, trial and error will point out if the results work for a new design, or not.

6.2. CONCLUSION

The aim of study was to find objective measures from a rider-bicycle model that correspond with subjectively defined handling qualities, as used at the Royal Dutch Gazelle. These objective measures could then be used as a scientific basis for the design process. In search for objective measures that can define subjective handling qualities, three sub-questions were defined and answered.

6.2.1. WHAT SUBJECTIVE HANDLING QUALITIES ARE USED AT THE ROYAL DUTCH GAZELLE?

To answer this question, 9 employees, engineers and marketeers, are interviewed. During the interviews, 9 bicycles selected by Gazelle were discussed on their purpose and handling qualities that came with it. After the interviews, one more bicycle was added to the list. During the interviews it became clear that there is no defined set of handling qualities, but there are ideas about the handling of the bicycle in their heads. They do hold them into account when developing a bicycling, but they are using specific setups to insert a handling quality into the bicycle. They have two main geometries from which they start a bicycle, lazy and sportive. Those to have some kind of values for the parameter that they know (by head), what type of bicycle it will be and from that point on they start with fine tuning. But they have not specific handling qualities that they put into a bicycle. While discussing the bicycle, they did came up with terms that they use while developing the

bicycles. These terms are evaluated, listed, and turned into a questionnaire. The list was shortened and some handling were qualities removed, which resulted in a final set of handling qualities that are used by Gazelle.

So, to answer the question *'What handling qualities are used at the Royal Dutch Gazelle?'*:

Dutch terminology	English terminology
Bicycle feeling	**Bicycle feeling**
'Lui'	Lazy
'Sportief'	Sportive
'Veilig'	Safe
Bicycle behaviour	**Bicycle behaviour**
'Stabiel'	Stable
Capsize	Capsize
Weave	Weave
'Gemoedelijk'	Forgiving
'Beheersbaar'	Controllable
'Wendbaar'	Maneuverable
'Nerveus'	Nervous
'Direct'	Direct

6.2.2. WHAT OBJECTIVE MEASURES CAN BE MODELLED AND USED AS BICYCLE HANDLING PARAMETER?

To find objective measures to correlate the handling qualities with, the program JBike6 is used. This program models an open-loop rider-bicycle system from which the eigenvalues of the system can be calculated as well as a steer stiffness while steering and while not steering. In order to complete this model, rider measures from a cycling experiment are used to come as close as possible to an actual rider model. The parameters used from the rider are the mass, moment of inertia and trunk angle while seated, the peak frequency of steering at three different speeds and the speeds at which they cycled. To define the bicycle model, general parameters from the geometry are used (wheelbase, steering axis angle, trial and wheel diameter). For each bicycle component, (steering assembly, rear frame and both wheels), the centre of mass, the mass and the moment of inertia around a principle axis are defines with the use of Solid Works files. These files are updates with actual measurements to come as close to the real bicycle properties as possible.

With these rider- and bicycle properties, different for each rider-bicycle combination, a rider-bicycle model is constructed in JBike6. The answer to *'What objective measures can be modelled and used as bicycle handling parameter?'*:

- Largest imaginary eigenvalue at 2 m/s.
- Largest real eigenvalue at 2 m/s.
- Largest real eigenvalue at a self-chosen speed.
- Largest real eigenvalue at 7 m/s.
- Steer stiffness with steering at 0 Hz at 2 m/s.
- Steer stiffness with steering at a peak frequency at 2 m/s.
- Steer stiffness with steering at 0 Hz at a self-chosen speed.
- Steer stiffness with steering at a peak frequency at a self-chosen speed.
- Steer stiffness with steering at 0 Hz at 7 m/s.
- Steer stiffness with steering at a peak frequency at 7 m/s.

These objective measures are modelled and used for further analysis. Besides the JBike6 model, an already existing handling quality measure (HQM) was used as an objective measure. However, during the process of defining bicycle properties, gains for the control system, it appeared that the gains that were found by the program did not met the requirement for a stable closed loop system. For that reason, the results are unreliable and not used as an objective measure to define bicycle handling qualities.

6.2.3. IS THERE A CORRELATION BETWEEN ANY OBJECTIVE MEASURE AND SUBJECTIVE HANDLING QUALITY?

The most important question was the question if there is a correlation between a subjective handling quality and one of the modelled objective measure. If so, that would mean that a handling quality from a newly designed bicycle can be evaluated before the bicycle goes in to production.

The subjective handling qualities are evaluated during a cycling experiment. 10 participants have cycled all 10 bicycles and scored them on the handling qualities with the use of a questionnaire about the handling qualities. The objective measures came from the rider-bicycle model in JBike6.

Each question is correlated to each objective measure with the data from all participants on all bicycles. This resulted in a total set of 90 data points for each combination of handling quality with objective measure. The analysis was conducted with a Spearman's ρ correlation coefficient and a $p-value$. Only with $p < 0.05$ the correlation was found to be significant. From the 140 possible correlations, only 24 were significant. Those who were significant had only a moderate to weak correlation.

So, to answer the last question: *'Is there a correlation between any objective measure and subjective handling quality?'*. Yes, there is. However, it has to be noted that these are only weak to moderate. The handling qualities that correlated with the objective measures are listed below.

- **Lazy** ; The bicycle gives the rider a lazy feeling, with a high *steer stiffness* at a self-chosen speed and at 7 m/s, and when the *real eigenvalue* is small at 7 m/s.
- **Sportive** ; The bicycle gives the rider a sportive feeling, with a low *steer stiffness* at all speeds, with a high *imaginary eigenvalue* at 2 m/s and a high *real eigenvalue* at 7 m/s.
- **Controllable** ; The bicycle is controllable with a low *imaginary eigenvalue* at 2 m/s.
- ***Stable (Capsize)*** *; The bicycle does not sway across the road at high speeds with a low* steer stiffness *at all speeds and a high* imaginary eigenvalue *at 2 m/s.* (Unreliable result)
- **Maneuverable** ; The bicycle is rated maneuverable with a high *real and imaginary eigenvalue* at 2 m/s and with a high *steer stiffness* at a self-chosen speed.
- **Direct** ; The bicycle is rated as direct with a high *real and imaginary eigenvalue* at 2 m/s and with a high *steer stiffness* at a self-chosen speed.

6.2.4. OVERALL CONCLUSION

During this study, handling qualities are defined and bicycles are evaluated on these qualities during a cycling experiment. In the cycling experiment, rider measures are recorded and used to create a rider-bicycle model that is as accurate as possible. All parameters on COM, mass, moment of inertia and principle axis of the bicycle components are modelled with references from actual measurements, as well as all the parameters that define the general geometry of the bicycle. These are put into a rider-bicycle model together with the rider measures to define objective measures. Those objective modelled measures are correlated with the handling qualities from the evaluated bicycles and 24 correlations appeared to be significant. These objective measures can be used to define or evaluate bicycle handling qualities of a bicycle. This can be done by playing with the different bicycle parameters to create values for the objective measures such that a bicycle is created with preferred handling qualities. Or, a bicycle can be designed and evaluated in which handling quality profile it fits with the current setup.

The subjective handling qualities 'lazy', 'sportive', 'controllable', 'maneuverable' and 'direct" can be predicted by the eigenvalues and steer stiffness at three different speeds as objective modelled measures. By altering the parameters of the bicycle, in different combinations, the objective measures will change and predict a handling quality that is included in the bicycle. There is no straight forward number to define a handling quality, a value for a specific parameter to create a specific handling quality. All parameters together give rise to a value for an objective measure that corresponds with a handling quality. This gives a lot of freedom when designing a new bicycle, multiple configurations can result in the same qualities. When new objective values are known, they can be compared to the values of the 10 researched bicycles from this study, and together with the existing handling quality profiles and the three categories, a new handling quality profile can be set up for the enhanced bicycle. The other way around, a desired handling quality profile can be put together. By comparing these with the other profiles and the corresponding objective measures, the bicycle can be modelled with trial and error until the desired objective measures are met.

In conclusion, there are correlations between objective measures and subjective handling qualities. However, they are not strong and do not provide solid numbers. They do provide guidelines to work with and future research is necessary to get more in-depth results.

6.3. RECOMMENDATIONS

At last I want to give some recommendations towards Gazelle, in terms of this study and of data organization to actually make use of this study.

I found out that there are various ideas about handling qualities among the employees. These ideas can have a different meaning for all the engineers. When it is really the goal to make use of handling qualities and this study, it is necessary to document every thought on handling qualities and discuss their meaning. This will prevent misunderstanding of handling qualities and improve communication to other departments. Solid definitions of handling qualities will form a bridge between a design concept from the marketing department to the actual design product from the engineer department. The marketeers will know how to describe a bicycle performance and the engineers know what to implement into the bicycle.

Secondly, when a bicycle needs to be modelled on forehand and dynamics have to be evaluated, mass properties have to be known. At the moment, the Solid Works files are not completely correct, and a data base of every part of the bicycle with at least the weight is not available. When modelling a bicycle, and even a simple model, the mass properties have to be known. Therefore, I recommend building the Solid Works files as accurate as possible, and not just as a render or general shape, but with correct mass properties included. This way, there is a complete model with moments of inertia and without much effort, a bicycle can be put into dynamic model. Or, when this is not an option, the masses of each part should be documented. It will take some more effort, but then a bicycle can be modelled as well to evaluate the dynamic properties. Without any knowledge on the properties of the bicycle, a bicycle cannot be modelled and the handling qualities cannot be evaluated as has been done in this study.

A third recommendation, on how to use this study. As mentioned before, the correlations from this study can only be used as guidelines. The bicycles that are research can be used as reference, and by altering the bicycle parameters the handling qualities will change. The correlations that are found are not strong, meaning that these correlations are not a solid prediction. It might happen that the correlation will be right for one bicycle, not right for the other or that the improving of the handling quality will only occur in a lesser amount. Use the correlations that are found as guidelines and go on from that. Further research is necessary to find stronger correlations and suitable parameter combinations for each type of bicycle for selected handling qualities.

Finally, this study had a limited amount of data and a very select test group. More data is required to get more solid results. The final goal for Gazelle seems to develop a bicycle that is pleasing for the consumer. At the moment these consumers do not provide solid feedback about their bicycle and there is no data about consumer experience up to a level of handling qualities. To gather this information, that can be used in further studies, the consumer can be questioned about their experience with the bicycle. The Experience Center in Amersfoort would be a perfect place to gather this data. Consumers come there to test out bicycles and when they fill in a questionnaire about their experience, the first step in gathering a large amount of data is made. It might even be possible to equip the bicycle at the Experience Center with a device that logs the steering actions and speed of the bicycle, just as in this study. Then all the data necessary can be collected at one place. Therefore, I would recommend gathering data about consumer experiences and cycling actions on the bicycles at the Gazelle Experience Center, so future studies can work with a larger data set and a non-biased test group, to increase the reliability of the results.

7

A Case Study: Balance

To show how this study can be used, a case study of a redesign of the balances is analysed. The Balance that was tested during the cycling experiment had a front wheel motor, and the new one the motor at the cranks. This is adapted in the Solid Works file from the Balance. The original Balance from the cycling experiment will be referred to as 'old' and the adapted Balance will be referred to as 'new'. The new and old properties of the bicycles are explained in the following sections. Finally, the changes and the consequences for the handling qualities are discussed.

7.1. Balance old

From the cycling experiment, a handling quality profile was set up for each bicycle. The handling quality profile from the old Balance is presented in figure 64. When evaluating the properties of the old Balance, the properties of the average rider are used as rider-model. Because the new Balance is not yet tested, the frequency of steering and preferred self-chosen speed are unknown. Therefore, the data for the average rider is used on both bicycles, such that the bicycle can be compared to each other with equal rider values. The properties of the rider and the old Balance are shown in figure 65 (Balance Old). The bicycle is analysed for its eigenvalues and steer stiffness in JBike6. The results are presented in figure 66 (Balance Old).

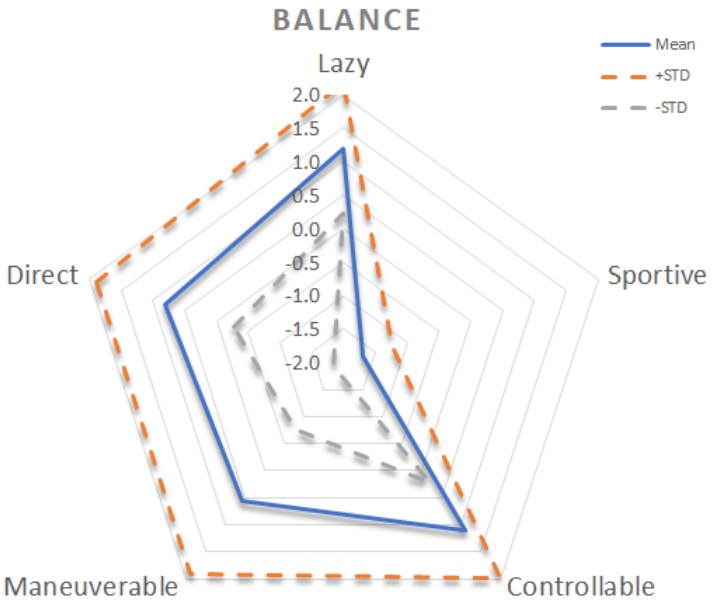

Figure 64: Handling quality profile for the old Balance

7.2. BALANCE NEW

The new Balance is slightly adapted from the old. Instead of a front wheel motor, the motor is now located at the cranks. This means that in the bicycle model a motor has to be added to the rear frame and that the front wheel has to be modelled without electrical support. Gazelle gave the information that the new motor is the same as the motor for the Ami. Therefore, the motor from the Ami Solid Works file is transferred to the Balance file. Because this frame is not designed for crank support, there is no actual room for the motor. In Solid Works the motor can just be put over the frame at a desired location, so the motor is located at the cranks, crossing the rear frame. This is different than would be in the actual new frame, but it resembles the new Balance close enough, since there are no files yet to work with. Its main point is that there is an extra weight at the bottom of the rear frame. From this adapted file, the new mass and inertia properties are retrieved that are used for the new JBike6 model. The properties of the new Balance are shown in figure 65 (Balance New).

Also the front wheel had to be changed, since the weight of the motor is removed. There are no measurements available for the new front wheel of the Balance, but the wheels of the Ami are most similar to those of the Balance. So, in order to model the front wheel properties of the Balance B, the wheels are scaled with the wheels of the Ami A by mass:

$$\frac{m_{Front,A}}{m_{Rear,A}} m_{Rear,B} = m_{Front,B}$$

The same is done for the moment of inertia:

$$\frac{I_{Front,A}}{I_{Rear,A}} I_{Rear,B} = I_{Front,B}$$

These new properties can be found in figure 65 (Balance New). The new Balance is put into JBike6 and the eigenvalues and steer stiffness's are calculated and presented in figure 66 (Balance New), with increase (>) or decrease (<) with respect to the old Balance. The eigenvalue-figures from JBike6 from both the Balances are added for a more clear picture of the differences (figure 67).

7.3. NEW HANDLING QUALITIES

7.3.1. MOTOR LOCATION

The two previous sections have shown the properties and objective values from the old and the new Balance, where the motor is relocated from the front wheel to the cranks. This section will compare the values and subject them to the correlations that are found, to predict new handling qualities. Figure 66 shows the eigenvalue and steer stiffness results from the new and old Balance, with a consequence of increased (>) or decreased (<) value for the new Balance compared to the old one. It shows that for each speed the steer stiffness is decreased (except for 7 m/s with the peak frequency). The real eigenvalues are increased for 2 m/s and 7 m/s, decreased for 5.5 m/s (the 'self-chosen speed') and the imaginary value at 2 m/s is also decreased. This is also visible from figure 67, with a changed stable region for the new Balance (green area). Those increased and decreased objective values can be translated to handling qualities with use of the correlations:

Balance Old

General		Wheels	Front	Rear
Head Angle [°]	66	Diameter [m]	0.609	0.609
Wheel base [m]	1.201	Mass [kg]	5.45	3.5
Trail [m]	0.075	$I_{xx\ \&\ Iyy}$ [kgm^2]	0.056	0.061
Fork Offset [m]	0.05	I_{zz} [kgm^2]	0.113	0.123

Components	Rear Frame	Front Frame
CoM X (U) [m]	0.303	0.019
CoM Y (V) [m]	0.523	0.818
Mass [kg]	14.930	3.670
I_{11} [kgm^2]	0.409	0.290
I_{22} [kgm^2]	1.882	0.050
I_{zz} [kgm^2]	2.246	0.333
Principle Angle [°]	12.035	23.780

Balance New

General		Wheels	Front	Rear
Head Angle [°]	66	Diameter [m]	0.609	0.609
Wheel base [m]	1.201	Mass [kg]	1.9	3.5
Trail [m]	0.075	$I_{xx\ \&\ Iyy}$ [kgm^2]	0.066	0.061
Fork Offset [m]	0.05	I_{zz} [kgm^2]	0.133	0.123

Components	Rear Frame	Front Frame
CoM X (U) [m]	0.343	0.019
CoM Y (V) [m]	0.483	0.818
Mass [kg]	17.909	3.670
I_{11} [kgm^2]	0.487	0.290
I_{22} [kgm^2]	2.102	0.050
I_{zz} [kgm^2]	2.538	0.333
Principle Angle [°]	-16.569	23.780

Rider

Speed [m/s]	Peak frequency [Hz]
2	1
5.5	1
7	1

Average Rider	
CoM X [m]	0.357
CoM Y [m]	1.092
Mass [kg]	82.200
I_{11} [kgm^2]	9.718
I_{22} [kgm^2]	1.993
I_{zz} [kgm^2]	9.122
Principle Angle [°]	-8.500

Figure 65: Bicycle properties for the old and new Balance with the average rider.

Bicycle	Balance - Old	Balance - New	New vs Old
Real Eigenvalue 2m/s	3.0823	3.3752	>
Imaginary Eigenvalue 2m/s	1.4234	1.3764	<
Real Eigenvalue 5.5 m/s	0.5871	0.1745	<
Real Eigenvalue 7 m/s	-0.7447	-0.4825	>
Steer Stiffness 2m/s	10.3539	9.0403	<
Steer Stiffness 2m/s (0)	10.3052	9.0129	<
Steer Stiffess 5.5 m/s (peak)	6.0382	5.1941	<
Steer Stiffness 5.5 m/s (0)	7.7329	5.8918	<
Steer Stiffness 7 m/s (Peak)	4.9507	7.2707	>
Steer Stifness 7 m/s (0)	5.8956	3.6624	<

Figure 66: Eigenvalue and steer stiffness results from the old and new Balance with average rider. An increase (>) or decrease (<) is provided for the new values compared to the old values

- > Real eigenvalue at 2 m/s: more maneuverable and more direct
- < Imaginary eigenvalue 2 m/s: less sportive, less controllable, less stable (unreliable),less maneuverable, less direct
- < Real eigenvalue at 5.5 m/s: X
- > Real eigenvalue at 7 m/s: less lazy, more sportive
- < Steer stiffness at 2 m/s with peak Hz: more sportive, more stable (unreliable)
- < Steer stiffness at 2 m/s with 0 Hz: more sportive, more stable (unreliable)
- < Steer stiffness at 5.5 m/s with peak Hz: more sportive, less maneuverable
- < Steer stiffness at 5.5 m/s with 0 Hz: less lazy, more sportive, more stable (unreliable)
- > Steer stiffness at 7 m/s with peak Hz: X
- < Steer stiffness at 7 m/s with 0 Hz: less lazy, more sportive, more stable (unreliable)

Overall, the results show that according to the correlations, the new Balance should be less lazy and more sportive. Only the imaginary eigenvalue at 2 m/s shows an opposite result. However, the correlation for the steer stiffness at 2 m/s is stronger, and more objective values show an increase in the handling quality sportive. Therefore, it is more likely that the bicycle is more sportive, instead of less sportive. The same trend shows for stable. But, because the correlations and results for the capsize stability were classified as unreliable, those will not be considered with a new handling quality profile.

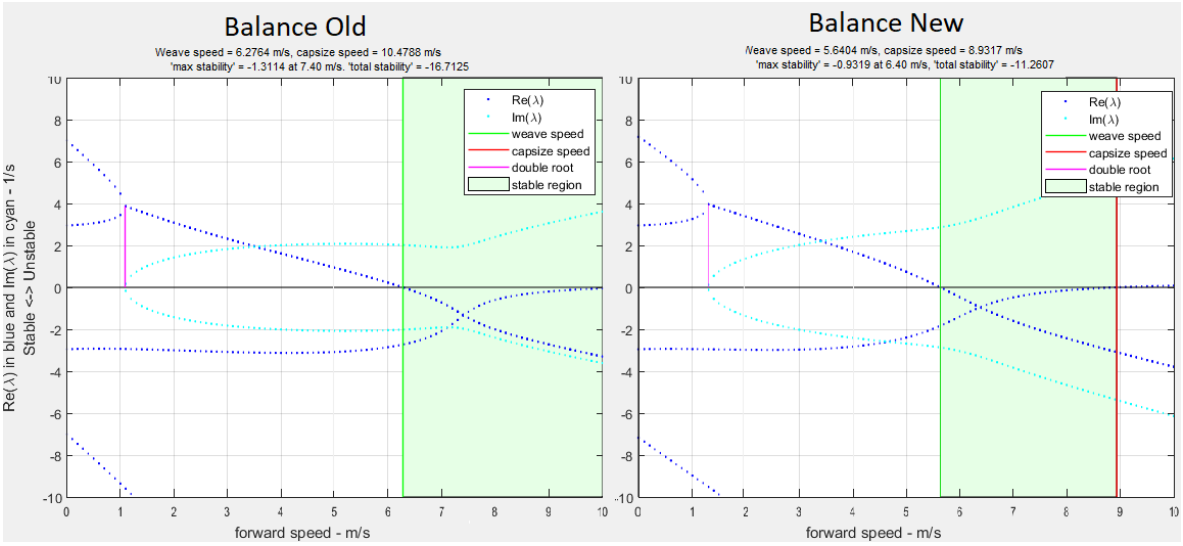

Figure 67: Eigenvalue 'stability plots' from the old (left) and new Balance (right). The green area shows the open-loop self-stable region of the bicycle

The other handling qualities are less clear than sportive. A decrease in lazy as handling quality is mentioned 3 times in combination with an increase of sportive. This follows the general trend that sportive is the opposite of lazy. This also increases the likeliness that the bicycle has become more sportive, and that the imaginary value is not conclusive for the sportiness of the bicycle. It remains unclear if the imaginary eigenvalue is satisfying for the other handling qualities. Controllable is only mentioned one time, direct is also mentioned as increased, while maneuverable has another increase and decrease as handling quality. Because of this inconclusive result, and the trend that lazy and sportive are general handling qualities with the other are more for fine tuning, probably direct and controllable are not changed that much, and the maneuverability might only be decreased for a very small amount.

When looking at the actual values as well and comparing them with the values of the other bicycles with the average rider (figure 50 in chapter 4), a handling quality profile can be set up for the new Balance. The consequences of changed objective values are roughly estimated, but the amount of increase or decrease of the value can only be estimated by using reference bicycles.

After comparing the values, it appears that the new Balance has the highest real eigenvalue at 2 m/s of all other bicycles, which would point towards more maneuverable and more direct. On the other hand, the imaginary eigenvalue at 2 m/s shows the position of the new Balance lower than the Ami, the old Balance, Orange, Orange HMB, Cityzen Speed and the Van Stael, but higher than the Orange HFP, Tour Populair and Puur NL and equal to the Cityzen. This shows that a decrease in the imaginary eigenvalue is not altering the handling qualities for a large amount, but it might just be a little, like a fine tuning within the general qualities. All the other values, the real eigenvalue at 7 m/s and all the steer stiffness's show the same. There is an increase or decrease in the value, but it is not that large that it reaches the range of the Van Stael for example, a completely different bicycle. The values are changed to a range between the Oranges and the Puur NL. So, the new handling qualities for the improved Balance should probably lie between the profiles of the Puur NL and the Oranges.

Based on the findings of an increase or decrease in specific handling qualities and a range in where these new qualities should lie based on the other reference bicycles, a new handling quality profile is set up (figure 68)

The values for direct and controllable are not changed, due to inconclusive results. Maneuverable is decreased only a little, because with the imaginary eigenvalue included, maneuverable has one point more on 'less maneuverable'. This is only a guess and the decrease in the quality is only minor. Lazy is decreased while sportive is increased within the range of the handling quality values of the Oranges and the Puur NL. This all together shows that the change in relocating the motor does not have a huge effect on the handling quality profile, but shows the largest effect for sportive and lazy. This is similar to the previous conclusions, where sportive and lazy are determined to be opposite and the general handling qualities.

This new profile is based on the correlations that are found in the research and it was said that these are

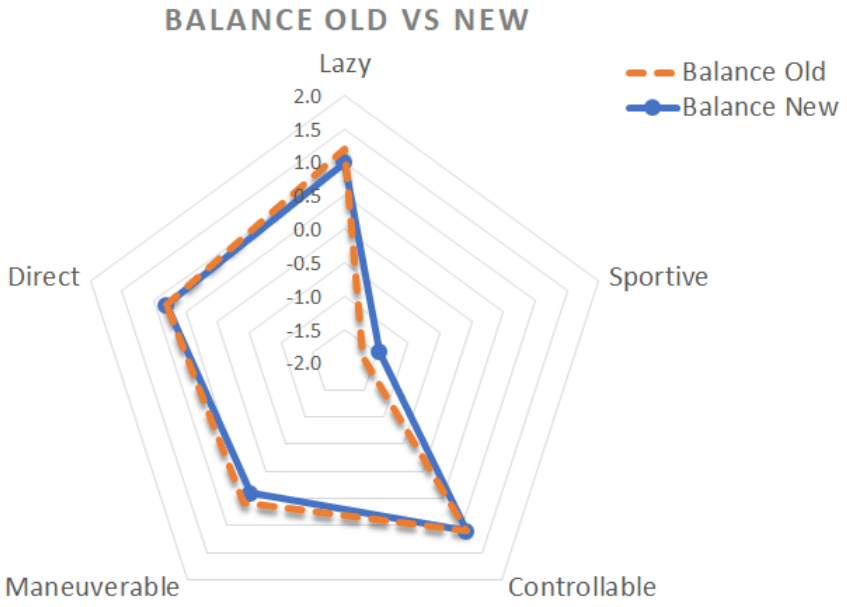

Figure 68: Handling quality profile for the old and the new Balance

not to be considered as 'the truth', but as guidelines to work with. This new handling quality profile is an estimation based on reference bicycles and weak correlations. Moreover, there might be differences that are not picked up with these correlations. It provides only an indication of the new qualities.

7.3.2. PARAMETER CHANGES

With just relocating the motor, the handling qualities do not change a great amount. As described in the report, the objective values can be manipulated by altering the parameters in different combinations. To provide an example, how the Balance can be improved even more, the head angle and the trail of the Balance, with the motor located at the cranks, are changed. The head angle (and with it the principle angle of the moment of inertia of the steer) are changed with + and - 10°and the trail to 0.05 m and 0.1 m in all possible configurations (figure 69). The original configuration, with 66°head angle and 0.075 m trail, is also included as Balance-66-75. The new Balance with the 9 possible configurations of the head angle and trail are analysed by the JBike6 model. This resulted in different objective values for the eigenvalues and steer stiffness, provided in figure 69.

With these new objective measures, new handling quality profiles can be estimated for each of the different configurations. This is done the same way as for the original new Balance. The values are compared to the old Balance, to see if there is an increase or decrease. Then, the values are compared to the values of the other bicycles, to see were the bicycles would score on the handling qualities. Based on these subjective scores, a new handling quality profile is estimated. These new profiles are shown in figure 70.

These handling quality profiles are all estimations. The correlations are not perfect, so the objective values are not always in line with the subjective values. Therefore, it was difficult to assign a subjective score to a new configuration. The old Balance was leading, and the other bicycles are used to estimate the score. This means that with a higher objective value, the subjective score is not always higher. The overall minimum and maximum score of the other bicycles are used as well to rate the new Balances.

Just as with the old and new Balance in the previous part, the values for direct are inconclusive due to the real and imaginary eigenvalue at 2 m/s. These show opposite results. Maneuverable shows only a small change, since there is one more correlation that add to changing handling qualities than for direct. Maneuverable was very difficult to estimate, because the correlations with this quality were not strong and the objective values and score do not always match. So, the assigned scores are questionable for maneuverable. Only Balance new 4 shows an overall improvement with respect to the old Balance and is more reliable.

The results for lazy and sportive are more conclusive. It shows that Balance-56-75, -66-100 and -56-100 are most lazy of them all. These have a head angle of 56°and 66°. Balance-76-75, -66-50 and 76-50 are most sportive, with head angles of 76°and also 66°. However, Balance-76-100 also has a head angle of 76°and is far

more lazy than Balance-76-75 and -76-50, and with a head angle of 66°the bicycle can be lazy or sportive. With different head angles, 0.05 m trail gives rise to more a more sportive bicycle and 0.1 m trail to lazy bicycles. On the other hand, a trail of 0.075 m provides both lazy as sportive handling. This shows that it is not just one parameter that provides a specific handling quality, but there are multiple configurations than cause an objective value to increase or decrease. There are more parameters to change, like the wheelbase, the wheel diameter, but also the masses and the distribution. So, to improve the Balance, more parameters than just a new location of the motor have to be changed to really improve specific handling qualities of the current Balance. To change the handling qualities of the Balance more than just with the new location of the motor and within the demands of supporting elderly cyclists, a configuration with head angle 66°and a trail of 0.1 m would be a good solution. With these parameter values, the Balance is more maneuverable, only slightly less controllable, really lazy and not sportive at all. This will improve the Balance more towards desirable handling qualities for elderly people who have difficulties with cycling.

Despite that the correlations are not strong, and the new estimated profiles might show some deviation from the actual bicycles, this case study shows the possibilities of this research. A bicycle can be improved by changing different parameters in different combinations and the handling qualities can be estimated with the use of handling quality profiles.

Bicycle	Head Angle [°]	Trail [m]	Imaginary Eigenvalue 2m/s	Real Eigenvalue 2m/s	Real Eigenvalue 5.5 m/s	Real Eigenvalue 7 m/s	Steer Stiffness 2 m/s (0)	Steer Stiffness 5.5 m/s (0)	Steer Stifness 7 m/s (0)
Balance-66-75	66	0.075	1.3764	3.3752	0.1745	-0.4825	9.0129	5.8918	3.6624
Balance-76-75	76	0.075	1.5104	2.5821	-0.6025	-0.2376	5.2631	3.4808	2.2077
Balance-56-75	56	0.075	0.8925	3.9217	0.8364	-0.9025	11.9443	7.8898	4.9937
Balance-66-50	66	0.050	1.4447	3.1056	-0.4935	-0.0910	6.3269	3.0843	0.7682
Balance-66-100	66	0.100	1.3090	3.5247	0.5536	-0.9587	11.6047	8.6056	6.4634
Balance-76-50	76	0.050	1.4932	2.4304	-0.4874	-0.0383	3.6756	1.7548	0.3827
Balance-56-50	56	0.050	1.1660	3.5692	0.2171	-0.2197	8.5246	4.3711	1.4043
Balance-76-100	76	0.100	1.5012	2.6435	-0.1776	-0.4633	6.7346	5.0915	3.9178
Balance-56-100	56	0.100	0.5494	4.1495	1.1897	-0.5232	15.2940	11.3391	8.5141

Figure 69: Objective measures of the different configurations of the new Balance

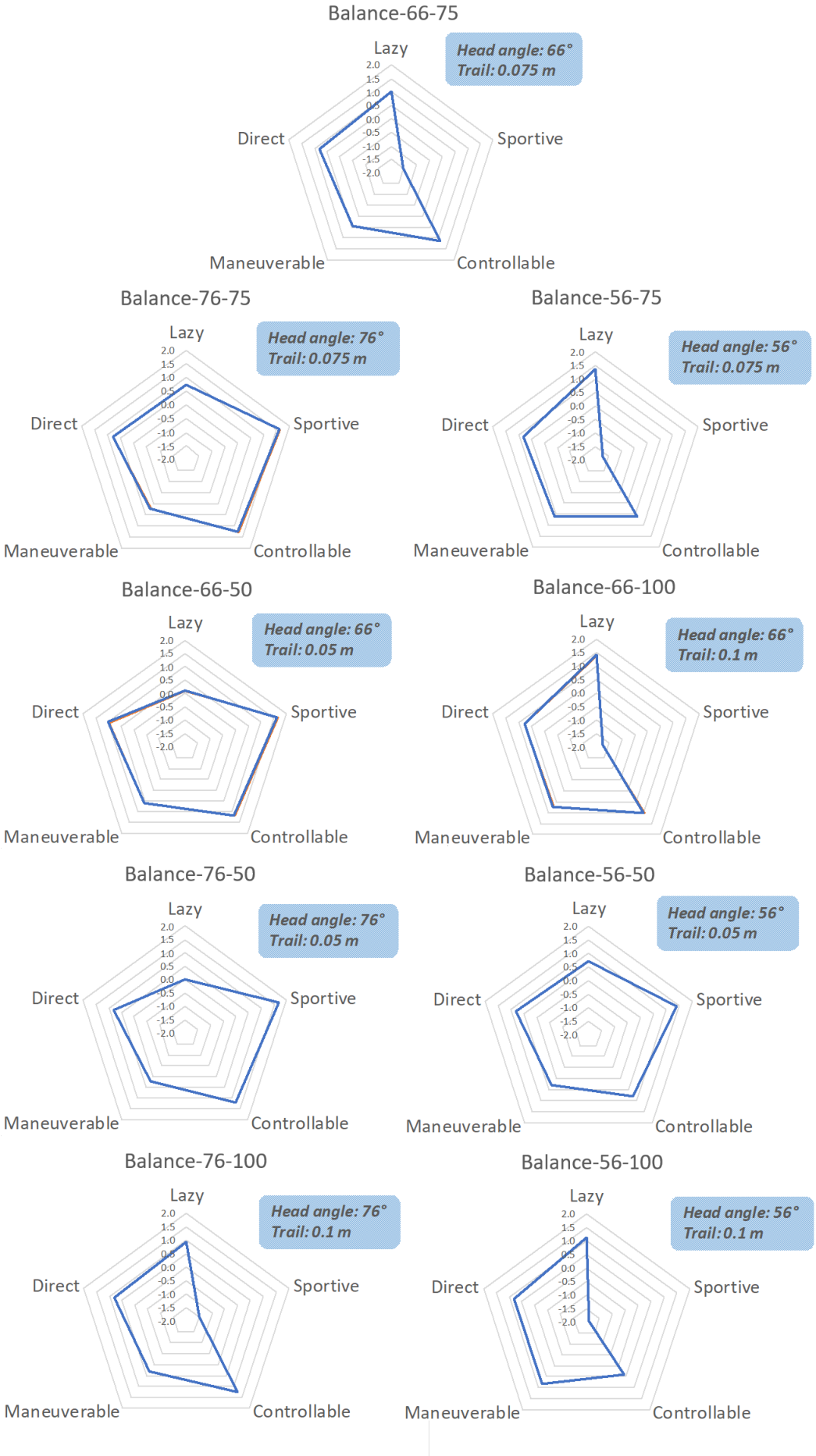

Figure 70: Handling quality profiles for each head angle and trail configuration of the new Balance

8

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A

HANDLING QUALITIES PER BICYCLE

BALANCE

1. What is the vision behind the bicycle?

This bicycle was an odd one to start with. The rear part of the bicycle, from seat tube to the rear wheel were already designed by another company and the Gazelle engineers had to start from there. The idea for this bicycle was a bicycle for elderly who do not dare to cycle anymore. Safety is the main property of the bicycle, the cyclist has to be able to touch the ground with their feet at all time and the bicycle has to be stable. The cyclist has to feel secure and feel safe to cycle again. This bicycle is approached from a different point of view than usual. Safety and security came first, not the 'perfect cycling experience'. The looks of the bicycle did not matter at all.

2. How is this vision incorporated in the bicycle?

The rear part has the main feature in the bicycle, but that was already designed when the Gazelle engineers started with the further development. An extreme seat tube angle of 50°, with adjusted seat post, makes sure the cyclist can reach the ground. This also ensures the cyclist has a safe feeling when mounting and dismounting. The front part of the bicycle has a head tube angle (steering axis angle) of 66° and a large fork offset. This causes the front wheel to be further in front and creates a large wheelbase, which would increase the stability of riding in a straight line. There is no high oscillation of the front wheel (also known as shimmy). This adds to the safe and secure feeling the cyclist should have. The frame has a high stiffness, so les torsion, what also adds to the stability. The bicycle is equipped with a telescopic fork, to transfer the force from the leg to the pedal as efficiently as possible, with the least amount of losses. Cyclists who will ride this bicycle often have decreased muscle power in their legs, so the less losses the better. On the other hand, the Balance bicycle does have a front wheel motor, what makes the steering more difficult.

3. Which handling qualities are assigned to this bicycle?

- 'Veilig'
  - Safe
- 'Stabiel'
  - Stable
- 'Moeilijk de hoek om'
  - Difficulties with cornering
- 'Gemoedelijk stuurgedrag'

  - Forgiving steering behaviour
- 'Comfortabel'
  - Comfortable
- 'Weinig vertraging van stuur input naar output, maar niet zo snel dat er geen controle is'
  - Few delay from steering input to output, but not too fast that there is no control
- 'Zekerheid'
  - Security
- 'Beheersbaarheid'
  - Controllability
- 'Voorspelbaar'
  - Predictable
- 'Niet direct'
  - Not direct

4. Can you explain these handling qualities?

- 'Veilig': more stable, more controllable, more predictable
- 'Stabiel': Easy in riding straight
- 'Voorspelbaar': not sensitive for perturbations, a pebble will almost not be felt
- 'Gemoedelijk stuurgedrag': Cornering with a secure feeling
- 'Comfortabel': an ergonomically designed bicycle
- 'Zekerheid': creating the feeling that the rider can intervene at any time
- 'Niet direct': there is a delay, there is force absorption

5. Which part of the bicycle gives rise to which handling quality?

The further the front wheel lies to the front, the easier the bicycle is following a straight path. This can be realized by a small head tube angle and a large fork offset. Better steering behavior can be realized by using a crank-motor instead of a front wheel motor, and by not having a front reach mounted to the steering assembly. Also a fixed fork with inner-tube-springs ensures better steering behavior. A telescopic fork loses force. The frame of the Balance bicycle is not stiff, so therefore the bicycle is not direct in steering. This is also due to the location of the center of mass, low and further to the rear of the bicycle. A lower center of mass has effect on the roll angle of the bicycle and therefore the way a corner can be initiated.

AMI

1. What is the vision behind the bicycle?

The Ami is a reaction on bicycles from the other bicycle companies in the Netherlands. It is based on an Orange (the benchmark from the Royal Dutch Gazelle), but more focused on a target group of elderly cyclists. Also, this bicycle has to give a secure and safe feeling, but is not as extreme as the Balance.

2. How is this vision incorporated in the bicycle?

Because this bicycle is a reaction to opposing companies, they have also investigated bicycle from other companies. The Ami has a wide and low entry for the bicycle, which reduces the time standing on one leg when mounting and dismounting the bicycle. The Ami also has smaller wheel diameters. This makes the bicycle easier to handle when walking with the bicycle, but also stabilizes the bicycle while riding it. Another feature has increases the stability of the bicycle is the location of the support motor, around the cranks instead of in the front wheel. This reduces the possibility of slip while riding over gravel. The bicycle is based on a so called '70°geometry'. It has a head tube of 70°, but a smaller seat tube angle to address to the older target group. Therefore, it is a stable, straight-up-sitting bicycle. However, the steer is straight (a small angle for the handlebars), which causes the bicycle to behave a bit more sportive feeling.

3. Which handling qualities are assigned to this bicycle?

- 'Veilig'
  - Safe
- 'Stabiel rechtuit'
  - Stable riding straight
- 'Goed stuurgedrag'
  - Good steering behaviour
- 'Comfortabel'
  - Comfortable
- 'Weinig vertraging van stuur input naar output, maar niet zo snel dat er geen controle is'
  - Few delay from steering input to output, but not too fast that there is no control
- 'Zekerheid'
  - Security
- 'Direct'
  - Direct

4. Can you explain these handling qualities?

- 'Goed stuurgedrag': Having a secure feeling when cornering
- 'Stabiel': Easy in riding straight
- 'Stabiel rechtuit': Easy following a straight path and no oscillation
- 'Direct': Less delay

5. Which part of the bicycle gives rise to which handling quality?

The straight steer causes a direct steering behavior. The small head tube angle increases the stability when following a straight path. The steering behavior is improved by moving the motor to the cranks and not in the front wheel. The Ami is the improved version of the Balance. It is better looking, but the feet cannot always touch the ground.

ORANGE

The Orange is the benchmark of the 'comfort bicycle'. 1 in 7 bicycles in the Netherlands is an Orange. Bicycle from other companies are also based on the Orange from the Royal Dutch Gazelle.

1. What is the vision behind the bicycle?

The Orange is a modern, comfortable bicycle, which is designed for people between 35 and 60 years old. It is meant for everyday use and is branched as sportive city bicycle. The bicycle is less lazy compared to the Balance. It is a typical ladies bicycle. A lot of elderly men ride the lady-version, from the moment they cannot lift their leg over the saddle. The Orange is the benchmark bicycle, it fulfills all needs of the consumer. It is important that the bicycle instantly feels nice: the saddle, the handlebars, shifting gears, everything has to feel right for the consumer.

2. How is this vision incorporated in the bicycle?

This bicycle originated from a racing bicycle and for that has a more sportive geometry. The head tube angle is adjusted to create more space for the steer and the rider. It is a robust, stable bicycle, which is caused by the stiffness of the frame. The posture of the rider on this bicycle is straight up, what puts more pressure on the lower back, instead of the shoulders and wrists. But because of the straight up posture, the rider has a better overview on the surroundings, without moving the neck up or down. Because of the stability, cycling in a straight path is easy and can be executed with a low velocity. Steering into a corner will result in a fluent line, but correcting while cornering is more difficult. The bicycle has a relative low entry, which is common in a comfort bicycle. Because of the robustness, low entry and complete finish with accessories, the bicycle is quite heavy. The finish touch of the Orange is adaptable, the frame remains the same but the colors and different types of steering, forks, saddles and handlebars, make the bicycle fit and comfortable for every individual.

3. Which handling qualities are assigned to this bicycle?

- 'Veilig'
  - Safe
- 'Stabiel'
  - Stable
- 'Sportief'
  - Sportive
- 'Vloeiend de bocht in'
  - Fluently in the corners
- 'Comfortabel'
  - Comfortable
- 'Voorspelbaar'
  - Predictable
- 'Direct stuurgedrag'
  - Direct steering behaviour

4. Can you explain these handling qualities?

- 'Comfortabel': an ergonomically designed bicycle

- ‘Stabiel’: Few capsize and weave. Capable of riding with low velocity, without oscillating across the road or tipping over.
- ‘Veilig’: Creates a feeling of trust and is not sensitive to perturbations
- ‘Gemoedelijk stuurgedrag’: Cornering with a secure feeling
- ‘Direct stuurgedrag’: Because of the surroundings (a city environment), direct steering behavior is necessary. Direct steering behavior does not have a surprise element and thus is predictable. There is no delay in input and output.

5. Which part of the bicycle gives rise to which handling quality?

Also in this bicycle the fork offset and angles are important for the stability and steering behavior of the bicycle, as described in the previous bicycles. Lots of Orange owners tilt the handlebars even further forward. This gives a more chopper-like style and creates a ‘no hurry’ feeling and provides a wider overview. A nice remark about the Orange bicycle: with the right tuning of fork, steer and saddle, the Orange can be transformed in a Cityzen (will be discussed next). With the different tuning, the frame tilts, altering the angles with respect to the horizontal and also alter the handling qualities of the bicycle. The bicycle can be made more sportive, or more lazy with different assembly mounted to the same frame.

CITYZEN

1. What is the vision behind the bicycle?

This bicycle is designed to bring people from A to B in a faster manner, especially with the electrical version (supported up to 45 km/h). The bicycle is more sportive and motivates for speed. Cycling at a lower velocity with this bicycle is more challenging. This bicycle is also lighter than others.

2. How is this vision incorporated in the bicycle?

The frame is more straight up, because of the lager angles for the seat- and head tube. The posture of the rider is more bend over. It is equipped with a short and straight steer and in combination with the posture, more pressure is put on the hands. The position of the rider is also above the crank axis, instead of behind the crank axis as in the other bicycles. The tires on the bicycle are also smaller than other, more race like. The bicycle has a more direct steering behavior, more nervous and is fast in the corners.

3. Which handling qualities are assigned to this bicycle?

- ’Minder stabiel’
  - Less stable
- ’Nerveus’
  - Nervous
- ’Wendbaar’
  - Maneuverable
- ’Direct stuurgedrag’
  - Direct steering behaviour

4. Can you explain these handling qualities?

- 'Direct stuurgedrag': There is no delay between input and output
- 'Nerveus': Despite the sportive geometry, the bicycle is not very nervous. But more than the Orange. Nervous is also associated with maneuverable
- The bicycle is uncomfortable, the road surface can be felt trough the rear frame, because there is little damping in the frame.

5. Which part of the bicycle gives rise to which handling quality?

The center of mass is located higher and more to the front. This makes the bicycle fast in the corners. Because of the low weight of the bicycle, it is less stable. For this bicycle, the rules for a sportive geometry accounts, as described in figure 5. The Cityzen is a typical men's bicycle, just as the Orange is a lady's bicycle. The consumer associates the Cityzen with speed, because of the shape of the bicycle, but also because of coloring choices. The feeling of the bicycle is also influences by the looks of it, it biases the consumer.

TOUR POPULAIR

1. What is the vision behind the bicycle?

The Tour Populair is the original Gazelle bicycle, a classical model that has not been changed for the last 80 to 100 years. This bicycle is classified as extremely lazy.

2. How is this vision incorporated in the bicycle?

The classic model has a very lazy geometry, that makes the rider lean back on top of the bicycle. The rider is seated with an upright back.

3. Which handling qualities are assigned to this bicycle?

- 'Stabiel'
  - Stable
- 'Lui'
  - Lazy
- 'Comfortabel'
  - Comfortable
- 'Niet direct'
  - Not direct

4. Can you explain these handling qualities?

- 'Stabiel': The bicycle does not tip over at low velocities and keeps riding in a straight line. Almost does not want to go into a corner

5. Which part of the bicycle gives rise to which handling quality?

Because the greater torsion in the frame, the bicycle has larger absorption qualities. This makes the bicycle comfortable to ride on, it is more comfortable than the Orange. The large fork offset is part of the classic configuration and makes it easy to follow a straight path. In Germany this bicycle is commonly known as the 'Holland Rad'. Over there it is accepted that the steer is colliding with body parts, due to the large angle of the handle bars, and that the posture is all the way backwards leaning and that the bicycle feeling is not perfect. It is a typical classic bicycle, from which the current bicycles are evolved.

PUUR NL

1. What is the vision behind the bicycle?

The Puur NL is the modern version of the Tour Populair. Also in this bicycle, the handling qualities are inferior to the looks of the bicycle. The front rack is very important for the looks of the bicycle and addresses the demands of the consumer. This bicycle focusses on a younger target group.

2. How is this vision incorporated in the bicycle?

The frame is a little bit more straight than the Tour Populair (66.5°over 65°), but maintains the lazy geometry with an extreme straight up posture for the rider. When the front rack is loaded, it induces oscillation in the steering behavior and also steering in the corners is not optimal because of the rack.

3. Which handling qualities are assigned to this bicycle?

- 'Stabiel'
  - Stable
- 'Lui'
  - Lazy
- 'Zwaar stuurgedrag'
  - Heavy steering behaviour
- 'Onverwoestbaar'
  - Indestructable

4. Can you explain these handling qualities?

- 'Stabiel': Easy to ride with low velocity, without falling over
- 'Onverwoestbaar': The bicycle feels robust, like a tank
- 'Zwaar stuurgedag': It rides like a tank, easy straight through, but cornering is a disaster. Intervening in an unpredicted situation is easier.

5. Which part of the bicycle gives rise to which handling quality?

The large fork offset and small angles are responsible for the lazy qualities: easy straight through but difficult cornering. Because of the weight on the front wheel by the front rack, the steering behavior drastically decreases. But, because this bicycle is designed and used by young adults, that does not matter. Young adults are flexible, can easily intervene and do not have a problem with riding with 6 next to each other and the possibility of collisions. Therefore, it is no problem that this bicycle has worse steering behavior due to the front rack.

B

QUESTIONNAIRES

FIRST ENGLISH VERSION

Figure B.1.

The first column shows the corresponding handling quality, the second column shows the questions followed by the rating. The last two columns show the corresponding terminology from the Cooper-Harper scale and the other reviews studies[10]–[13].

FIRST DUTCH VERSION

Figure B.2.

The first column shows the corresponding handling quality, the second column shows the questions followed by the rating. The last two columns show the corresponding terminology from the Cooper-Harper scale and the other reviews studies[10]–[13].

FINAL DUTCH VERSION

Figure B.3.

The first column shows the corresponding handling quality, the second column shows the questions followed by the rating. The last two columns show the corresponding terminology from the Cooper-Harper scale and the other reviews studies[10]–[13]. The questionnaire used in the experiment would only contain the columns with the statements and ratings.

Handling Qualities	**Statements**	**Strongly disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly agree**	*Cooper-Harper terminology*	*Other used terminology*
		-2	-1	0	+1	+2		
Lazy	1. The bicycle gives me a relaxed feeling							
Sportive	2. The bicycle gives me a sportive feeling							
Safe	3. I feel safe at all times riding the bicycle							
Safe	4. I am not afraid of falling							
Secure	5. I am self-secure when riding this bicycle							
Secure	6. I can control this bicycle at any time						*controllability*	
Comfortable (Ergonomic)	7. The bicycle gives a comfortable posture							
Comfortable (Ergonomic)	8. I can keep this seated posture the entire day							
Comfortable (Road surface)	9. The bicycle does not vibrate when I ride a bumpy road							vehicle response
Stable (Weave)	10. I have the feeling of tipping over when I ride **slowly**						*controllability*	centering
Stable (Capsize)	11. I have the feeling the bicycle starts swaying across the road at **high** speeds						*controllability*	centering
Stable (Capsize) / Nerveus	12. The bicycle easily holds a straight line						*rider compensation*	centering
Forgiving (own interpretation)	13. The bicycle is forgiving							
Controllable	14. I can intervene at any time if I want to						*controllability*	
Controllable	15. The bicyle is under control when dismounting						*controllability*	
Controllable	16. The bicycle is under control when mounting						*controllability*	
Controllable	17. The bicycle is under control when I take a corner						*controllability*	cornering / steering response
Manoeuvrable	18. The bicycle easily steers into a corner						*effort*	effort / smoothness / cornering
Manoeuvrable	19. The bicycle easily steers around an obstacle						*effort*	effort / smoothness / steering precision
Manoeuvrable	20. I do not have to put in effort to turn the steer						*effort*	effort / smoothness
Nervous	21. I have to make steering corrections to follow a straight line						*rider compensation*	nervousness / steering precision / centering
Nervous	22. I have to make steering corrections in a corner						*rider compensation*	cornering / nervousness / steering precision
Direct	23. The bicycle immediately turns into a corner when I steer							cornernig / steering response
Direct / Manoeuvrable	24. I does not take much effort to change the heading of the bicycle						*effort*	effort
Predictable	25. I know how far the bicycle will turn when I make a steering action							cornering / vehicle response / steering precision
Predictable	26. I know how the bicycle reacts when I make a steering action							vehicle response

Figure B1: First version of the questionnaire on bicycle handling qualities. Translated from Dutch to English

Rij-eigenschappen	**Stellingen**	**Sterk mee oneens**	**Mee oneens**	**Neutraal**	**Mee eens**	**Sterk mee eens**	*Cooper-Harper termen*	*Bekende termen*
		-2	**-1**	**0**	**+1**	**+2**		
Lui	1. De fiets geeft mij een ontspannen gevoel.							
Sportief	2. De fiets geeft mij een sportief gevoel.							
Veilig	3. Ik voel mij ten alle tijden veilig op de fiets.							
Veilig	4. Ik ben niet bang om te vallen.							
Zeker	5. Ik ben zeker van mijzelf als ik op deze fiets rijdt.							
Zeker	6. Ik kan deze fiets ten alle tijden onder controle houden.						*controllability*	
Comfortabel (Ergonomisch)	7. De fiets zit comfortabel							
Comfortabel (Ergonomisch)	8. Deze zit-houding kan ik de hele dag volhouden.							
Comfortabel (Weggevoel)	9. De fiets trilt niet als ik over een hobbelige weg fiets.							vehicle response
Stabiel (Weave)	10. Als ik **langzaam** rijd heb ik het gevoel dat ik omval.						*controllability*	centering
Stabiel (Capsize)	11. Als ik **hard** rijdt heb ik het gevoel dat de fiets gaat zwabberen over de weg.						*controllability*	centering
Stabiel (Capsize) / Nerveus	12. De fiets blijft gemakkelijk rechtuit rijden.						*rider compensation*	centering
Gemoedelijk (eigen interpretatie)	13. De fiets stuurt gemoedelijk.							
Beheersbaar	14. Ik kan op ieder moment ingrijpen als ik dat wil.						*control*	
Beheersbaar	15. De fiets is onder controle bij het afstappen.						*controllability*	
Beheersbaar	16. De fiets is onder controle tijdens het opstappen.						*controllability*	
Beheersbaar	17. De fiets is onder controle als ik een bocht neem.						*controllability*	cornering / steering response
Wendbaar	18. De fiets stuurt makkelijk de bocht in.						*effort*	effort / smoothness / cornering
Wendbaar	19. De fiets stuurt makkelijk om obstakels heen.						*effort*	effort / smoothness / steering precision
Wendbaar	20. Ik hoeft geen moeite te doen om het stuur te draaien						*effort*	effort / smoothness
Nerveus	21. Ik moet stuurcorrecties maken om de fiets rechtdoor te laten gaan.						*rider compensation*	nervousness / steering precision / centering
Nerveus	22. Ik moet stuurcorrecties maken in een bocht.						*rider compensation*	cornering / nervousness / steering precision
Direct	23. De fiets gaat meteen de bocht in als ik aan het stuur draai.							cornernig / steering response
Direct / Wendbaar	24. Het kost mij weinig moeite om de fiets van richting te laten veranderen.						*effort*	effort
Voorspelbaar	25. Ik weet hoever de fiets de bocht in draait als ik een stuurbeweging maak.							cornering / vehicle response / steering precision
Voorspelbaar	26. Ik weet hoe de fiets reageert als ik een stuurbeweging maak.							vehicle response

Figure B2: First version of the questionnaire on bicycle handling qualities. Original Dutch version

Handling Qualities	**Eigen gevoel op de fiets**	**Sterk mee oneens**	**Mee oneens**	**Neutraal**	**Mee eens**	**Sterk mee eens**	*Cooper-Harper termen*	*Bekende termen*
		-2	**-1**	**0**	**+1**	**+2**		
Lui	1. De fiets geeft mij een ontspannen gevoel.							
Sportief	2. De fiets geeft mij een sportief gevoel.							
Veilig	3. Ik voel mij ten alle tijden veilig op de fiets.							
Zeker / Beheersbaar	4. Ik kan deze fiets ten alle tijden onder controle houden.						*controlability*	
Gemoedelijk	5. De fiets stuurt gemoedelijk.							
	Rechtdoor rijden	**Sterk mee oneens**	**Mee oneens**	**Neutraal**	**Mee eens**	**Sterk mee eens**	*Cooper-Harper termen*	*Bekende termen*
		-2	**-1**	**0**	**+1**	**+2**		
Stabiel (Weave)	6. Als ik **langzaam** rijd heb ik het gevoel dat ik omval.						*controlability*	centering
Stabiel (Capsize)	7. Als ik **hard** rijd heb ik het gevoel dat de fiets gaat zwabberen over de weg.						*controlability*	centering
Stabiel / Nerveus	8. De fiets blijft gemakkelijk rechtuit rijden.						*rider compensation*	centering
Nerveus	9. Ik moet stuurcorrecties maken om de fiets rechtdoor te laten gaan.						*rider compensation*	nervousness / steering precision / centering
Beheersbaar	10. De fiets is onder controle bij het wegrijden vanuit stilstand en bij stoppen.						*controlability*	
	Sturen	**Sterk mee oneens**	**Mee oneens**	**Neutraal**	**Mee eens**	**Sterk mee eens**	*Cooper-Harper termen*	*Bekende termen*
		-2	**-1**	**0**	**+1**	**+2**		
Wendbaar	11. De fiets stuurt makkelijk om obstakels heen.						*effort*	effort / smoothness / steering precision
Wendbaar	12. De fiets gaat gemakkelijk de bocht in.							effort / smoothness / cornering
Wendbaar	13. Ik hoeft geen moeite te doen om het stuur te draaien						*effort*	effort / smoothness
Direct / Wendbaar	14. Het kost mij weinig moeite om de fiets van richting te laten veranderen.						*effort*	effort

Figure B3: Final version of the questionnaire on bicycle handling qualities. Original Dutch version

C

Pilot Study Matlab

```
%%%%%%%%%%%%%%%%%%%%%
% Data_Reader_Pilot %
%%%%%%%%%%%%%%%%%%%%%

clear all
close all

%% Load Data
data(:,:) = xlsread...
    ('C:\Users\carli\Documents\Afstudeer Project\Project\Test Dag\Pilot_Carlijn.csv');

%% Time
FS = 100;
samples = length(data(:,1));                        %amount of samples

Total_Seconds = samples/FS;                         %time in seconds
Total_time = Total_Seconds/60;                      %time in minutes
Time_sample = Total_Seconds/samples;                %time per sample
Time_line = linspace(0,Total_Seconds,samples);      %timeline in seconds

Fast_Riding = repmat(7,1,samples);
Slow_Riding = repmat(2,1,samples);

%% GPS
Lattitude = data(:,6);
Longitude = data(:,7);

%% Position and Velocity
%Distance from GPS
    %distance between 2 points
    %arc conversion to meters on Earth
for i = 1:samples-1;
    [arclen(i), az] = distance(Lattitude(i), Longitude(i), Lattitude(i+1), Longitude(i+1));
    distOut(i) = (arclen(i)/360)*(2*pi)*6371000;
    i = i+1;
end

%Solve problem with discrete distOut values
    %find and remove indices of zeros in data and remove
index = find(distOut == 0);
distOut_new = removerows(distOut','ind',index);
Time_new = removerows(Time_line','ind', index);
Lattitude_new = removerows(Lattitude,'ind', index);
Longitude_new = removerows(Longitude,'ind', index);

distOut_new = [0;distOut_new];
Distance(1) = 0;
Velocity(1) = 0;
```

```
Time_new = [0;Time_new];

%Travelled distance with corresponding velocity profile
    %travelled distance over time it took --> time is not continuous
for i = 1:length(distOut_new)-1;
    Distance(i+1) = distOut_new(i)+Distance(i);
    Velocity(i+1) = smooth(Distance(i+1)-Distance(i))/(Time_new(i+1)-Time_new(i));
end

%Equal length as time
Distance(end+1) = Distance(end);
Velocity(end+1) = 0;

 %% Motions
Yaw = data(:,29);                   %[rad]
Roll = data(:,30);                  %[rad]
Pitch = data(:,31);                 %[rad]

Yaw_deg = radtodeg(Yaw(:));         %[degree]
Roll_deg = radtodeg(Roll(:));       %[degree]
Pitch_deg = radtodeg(Pitch(:));     %[degree]

Gyro_X = data(:,25);                %angular velocity pitch [rad/s]
Gyro_Y = data(:,26);                %angular velocity roll [rad/s]
Gyro_Z = data(:,27);                %angular velocity [rad/s]

Gyro_X_deg = radtodeg(Gyro_X(:));   %angular velocity pitch [deg/s]
Gyro_Y_deg = radtodeg(Gyro_Y(:));   %angular velocity roll [deg/s]
Gyro_Z_deg = radtodeg(Gyro_Z(:));   %angular velocity yaw [deg/s]

%% Figures and Filters
%Route
Figure_Route_Pilot( Longitude, Lattitude)

%Filter Velocity
CutOff = 15;                            %cutoff frequency at 15 Hz to remove noise
[B,A] = butter(4,CutOff/(FS/2),'low');  %--> 10 Hz is the limit of the human
Velocity_Filter = filtfilt(B,A,Velocity); %filter velocity to remove peaks

%Filter Gyro
CutOff = 15;
[B,A] = butter(4,CutOff/(FS/2),'low');
Gyro_Y_Filter = filtfilt(B,A,Gyro_Y_deg);
Gyro_Z_Filter = filtfilt(B,A,Gyro_Z_deg);
Roll_deg_filter = filtfilt(B,A,Roll_deg);
Yaw_deg_filter = filtfilt(B,A,Yaw_deg);

%Distance and Velocity Figure
Figure_Dis_Vel_Pilot(Time_new, Distance, Velocity_Filter);

%Motion and Motion Rate Figure
Figure_Gyro_Pilot(Time_line, Gyro_Y_Filter, Roll_deg_filter, Gyro_Z_Filter, Yaw_deg_filter)

%Distance, Velocity and Motion Rate Figure
Figure_All_Pilot( Time_new, Time_line, Distance, Velocity_Filter, Gyro_Y_Filter,...
    Gyro_Z_Filter)

%Power Spectral Density
[Surface_Yaw_Free, Freq_max_Yaw_Free, Freq_Yaw_Free, Power_Yaw_Free] = PSD(Gyro_Z_Filter);
figure(5)
plot(Freq_Yaw_Free, Power_Yaw_Free)
title('PSD Yaw Pilot')
path = 'C:\Users\carli\Documents\Afstudeer Project\Project\Test Dag\Pilot';
filename = ('Pilot - Gyro_Yaw_Free.png');
saveas(figure(5),fullfile(path,filename))
%%%
```

```
%Save Figure
path = 'C:\Users\carli\Documents\Afstudeer Project\Project\Test Dag\Pilot';
filename = ('Pilot - GPS.png');
saveas(figure(1),fullfile(path,filename));
end
%%%
```

```
plot(Time_new, Velocity, Time_new, Fast_Riding,'r', Time_new, Slow_Riding, 'k')
ylabel('Velocity [m/s]')
xlabel('Time [s]')
subplot(4,1,3)
plot(Time_line, Gyro_Y)
xlabel('Time [s]')
ylabel('Roll angular velocity [deg/s]')
xlabel('Time[s])')
subplot(4,1,4)
plot(Time_line, Gyro_Z)
xlabel('Time [s]')
ylabel('Yaw angular velocity [deg/s]')

%Save Figure
path = 'C:\Users\carli\Documents\Afstudeer Project\Project\Test Dag\Pilot';
filename = ('Pilot - All.png');
saveas(figure(4),fullfile(path,filename));
end
%%%
```

D

Cycling Experiment

Matlab Files for Analysis

```
%%%%%%%%%%%%%%%
% Data_Reader %
%%%%%%%%%%%%%%%

clear all
close all

%% Load Data
location = ...
 ['C:\Users\carli\Documents\Afstudeer Project\Project\Test Dag\...Gazelle test dag 24 april\'];
bicycles = ["Ami"; "Cityzen"; "Orange"; "Orange HMB"; "Orange HFP"; "Tour Populair"; ...
    "Puur NL"; "Balance"; "Van Stael";"Cityzen Speed"];
participants = [" - P1"; " - P2"; " - P3"; " - P4"; " - P5"; ...
    " - P6"; " - P7"; " - P8"; " - P9"; " - P10"];
addition = [" - Sample rate 10"; " - Sample rate 20"];
extension = [".csv"];

%Create Empty Variables
data = 0;
arclen = 0;
distOut = 0;
Time_new = 0;
Distance = 0;
Velocity = 0;

for k = 6                   %Bicycle loop
    for l = 9               %Participant loopt within the bicycle loop
         clear data arclen distOut Time_new Distance Velocity   %Clear data for new bicycle

         Bicycle_current = bicycles(k);                                          %Assing bicycle
         Participant_current = participants(l);                                  %Assign Participant

        %% Find Data with different sample rate (determined by name)
        if (Bicycle_current == 'Orange HFP') &&  (Participant_current == ' - P7' ...
                || Participant_current == ' - P8')
                FS = 10;
                data(:,:) = xlsread(strcat(location, bicycles(k), participants(l),...
                    addition(1),extension));
        elseif (Bicycle_current == 'Tour Populair') &&  (Participant_current == ' - P7' ...
                || Participant_current == ' - P8')
                FS = 20;
                data(:,:) = xlsread(strcat(location, bicycles(k), participants(l),...
                    addition(2),extension));
        elseif Bicycle_current == 'Puur NL' && Participant_current == ' - P8'
                FS = 20;
                data(:,:) = xlsread(strcat(location, bicycles(k), participants(l),...
```

```
            addition(2), extension));
elseif Bicycle_current == 'Cityzen Speed' && Participant_current == ' - P10'
          %Cityzen Speed and P10 are in last position in the Bicycle and Participant
                    %vectors for this reason
        return
else
    FS = 100;
     data(:,:) = xlsread(strcat(location, bicycles(k), participants(l), extension));
end

%% Time
samples = length(data(:,1));                              %amount of samples

Total_Seconds = samples/FS;                               %total amount of time in seconds
Total_time = Total_Seconds/60;                            %total armound of time in minutes
Time_sample = Total_Seconds/samples;                      %time per sample
Time_line = linspace(0,Total_Seconds,samples);            %creating a time line in seconds

Fast_Riding = repmat(7,1,samples);
Slow_Riding = repmat(2,1,samples);

%% GPS
Lattitude = data(:,6);
Longitude = data(:,7);

%% Position and Velocity
%Distance from GPS
    %distance between 2 points
    %arc length conversion to meters on Earth
for i = 1:samples-1;
  [arclen(i), az] = distance(Lattitude(i), Longitude(i), Lattitude(i+1), Longitude(i+1));
  distOut(i) = (arclen(i)/360)*(2*pi)*6371000;
  i = i+1;
end

%Solve problem with discrete distOut values
index = find(distOut == 0);                               %find indices of zeros in data

distOut_new = removerows(distOut','ind',index);           %remove all zeros by using indices
Time_new = removerows(Time_line','ind', index);           %Match distance, remove zeros
Lattitude_new = removerows(Lattitude,'ind', index);       %Match distance, remove zeros
Longitude_new = removerows(Longitude,'ind', index);       %Match distance, remove zeros

distOut_new = [0;distOut_new];                            %add zero starting position
Distance(1) = 0;                                          %add zero start in travelled distance
Velocity(1) = 0;                                          %add zero start at velocity profile
Time_new = [0;Time_new];                                  %add starting time in timeline

%Travelled distance with corresponding velocity profile
    %travelled distance over time it took--> time is not continuous!
for i = 1:length(distOut_new)-1;
    Distance(i+1) = distOut_new(i)+Distance(i);
    Velocity(i+1) = smooth(Distance(i+1)-Distance(i))/(Time_new(i+1)-Time_new(i));
end

%Equal length as time
Distance(end+1) = Distance(end);                  %add endpoint
Velocity(end+1) = 0;

%% Motions
Yaw = data(:,29);                                 %[rad]
Roll = data(:,30);                                %[rad]
Pitch = data(:,31);                               %[rad]

Yaw_deg = radtodeg(Yaw(:));                       %[degree]
Roll_deg = radtodeg(Roll(:));                     %[degree]
Pitch_deg = radtodeg(Pitch(:));                   %[degree]

Gyro_X = data(:,25);                              %angular velocity pitch [rad/s]
Gyro_Y = data(:,26);                              %angular velocity roll [rad/s]
Gyro_Z = data(:,27);                              %angular velocity [rad/s]
```

```
Gyro_X_deg = radtodeg(Gyro_X(:));              %angular velocity pitch [deg/s]
Gyro_Y_deg = radtodeg(Gyro_Y(:));              %angular velocity roll [deg/s]
Gyro_Z_deg = radtodeg(Gyro_Z(:));              %angular velocity yaw [deg/s]

%% Figures and Filters

%Route
 Figure_Route( Longitude, Lattitude, bicycles(k), participants(l) )

if FS > 50 && samples > 500                        %skip data that cannot be filtered
    %Filter Velocity
    CutOff = 15;                                   %cutoff frequency at 15 Hz
    [B,A] = butter(4,CutOff/(FS/2),'low');             %10 Hz is the limit of the human,
    Velocity_Filter = filtfilt(B,A,Velocity);      %filter velocity to remove peaks

    %Filter Gyro
    CutOff = 20;                                   %cutoff frequency at 20 Hz
    [B,A] = butter(4,CutOff/(FS/2),'low');             %No data losses
    Gyro_Y_Filter = filtfilt(B,A,Gyro_Y_deg);
    Gyro_Z_Filter = filtfilt(B,A,Gyro_Z_deg);
    Roll_deg_filter = filtfilt(B,A,Roll_deg);
    Yaw_deg_filter = filtfilt(B,A,Yaw_deg);

    %Distance and Velocity Figure
     Figure_Dis_Vel(Time_new, Distance, Velocity_Filter, bicycles(k), participants(l));

    %Motion and Motion Rate Figure
     Figure_Gyro(Time_line, Gyro_Y_Filter, Roll_deg_filter, Gyro_Z_Filter,...
         Yaw_deg_filter, bicycles(k), participants(l))

    %Distance, Velocity and Motion Rate Figure
     Figure_All( Time_new, Time_line, Distance, Velocity_Filter, Gyro_Y_Filter, ...
         Gyro_Z_Filter, bicycles(k), participants(l) )

    %% Defining Segments for the motions
    if (Bicycle_current == 'Tour Populair')&& (Participant_current == ' - P4' ...
            || Participant_current == ' - P2')
        disp('No Data Available for Tour Populair P4 and P2')
            Velocity_Free = 0; Velocity_7 = 0; Velocity_25 = 0;
            Surface_Yaw_Free = 0;Surface_Roll_Free = 0; Surface_Yaw_7 = 0;
            Surface_Roll_7 = 0; Surface_Yaw_25 = 0;Surface_Roll_25 = 0;
            Freq_max_Yaw_Free = 0; Freq_max_Roll_Free = 0; Freq_max_Yaw_7 = 0;
            Freq_max_Roll_7 = 0; Freq_max_Yaw_25 = 0; Freq_max_Roll_25 = 0;

    elseif(Bicycle_current == 'Puur NL')&& (Participant_current == ' - P9')
        disp('No Data Available for Puur NL - P9')
            Velocity_Free = 0; Velocity_7 = 0; Velocity_25 = 0;
            Surface_Yaw_Free = 0; Surface_Roll_Free = 0; Surface_Yaw_7 = 0;
            Surface_Roll_7 = 0; Surface_Yaw_25 = 0; Surface_Roll_25 = 0;
            Freq_max_Yaw_Free = 0;  Freq_max_Roll_Free = 0; Freq_max_Yaw_7 = 0;
            Freq_max_Roll_7 = 0; Freq_max_Yaw_25 = 0; Freq_max_Roll_25 = 0;

    else

        %Start and Endpoints for segments
        if Bicycle_current == 'Orange' && Participant_current == ' - P10'
            Start_Free = find(abs(Longitude - 6.1099) < 10^-3 &...
                abs(Lattitude - 52.0469)< 10^-3);
            Start_Free = Start_Free(1500);
        elseif(Bicycle_current == 'Orange HMB' && Participant_current == ' - P10')
            Start_Free = find(abs(Longitude - 6.1098) < 10^-3 &...
                abs(Lattitude - 52.0469)< 10^-3);
            Start_Free = Start_Free(1500);
        else

            Start_Free = find(abs(Longitude - 6.1094) < 10^-3 &...
                abs(Lattitude - 52.0441) < 10^-3);
            Start_Free = Start_Free(1500);
        end
```

```
End_Free = find(abs(Longitude - 6.1040) < 10^-3 &...
    abs(Lattitude - 52.0508)< 10^-3);
End_Free = End_Free(end-1500);

Start_7 = find(abs(Longitude - 6.1025) < 10^-3 &...
    abs(Lattitude - 52.0483)< 10^-3);
Start_7 = Start_7(1500);

if Bicycle_current == 'Tour Populair' && Participant_current == ' - P9'
    End_7 = find(abs(Longitude - 6.1037) < 10^-3 &...
        abs(Lattitude - 52.0470)< 10^-3);
    End_7 = End_7(end-500);
else
    End_7 = find(abs(Longitude - 6.1037) < 10^-3 &...
        abs(Lattitude - 52.0470)< 10^-3);
    End_7 = End_7(end-1500);
end

Start_25 = find(abs(Longitude - 6.0999) < 10^-3 &...
    abs(Lattitude - 52.0495) < 10^-3);
Start_25 = Start_25(1500);
End_25 = find(abs(Longitude - 6.0961) < 10^-3 &...
    abs(Lattitude - 52.0505)< 10^-3);
End_25 = End_25(end-1500);

%Cutting the segments
Gyro_Yaw_Free = Gyro_Z_Filter(Start_Free:End_Free);
Gyro_Roll_Free = Gyro_Y_Filter(Start_Free:End_Free);

Gyro_Yaw_7 = Gyro_Z_Filter(Start_7:End_7);
Gyro_Roll_7 = Gyro_Y_Filter(Start_7:End_7);

Gyro_Yaw_25 = Gyro_Z_Filter(Start_25:End_25);
Gyro_Roll_25 = Gyro_Y_Filter(Start_25:End_25);

Long_Free = Longitude(Start_Free:End_Free);
Lat_Free = Lattitude(Start_Free:End_Free);
Long_7 = Longitude(Start_7:End_7);
Lat_7 = Lattitude(Start_7:End_7);
Long_25 = Longitude(Start_25:End_25);
Lat_25 = Lattitude(Start_25:End_25);

figure(3)
plot(Long_Free,Lat_Free,Long_7,Lat_7,Long_25,Lat_25);

%% Defining Segments for Velocity (different length)
%Start and Endpoints for segements
if (Bicycle_current == 'Orange' || Bicycle_current == 'Orange HMB') && ...
        (Participant_current == ' - P10')
    Start_Free_Vel = find(abs(Longitude_new - 6.1098) < 10^-3 & ...
        abs(Lattitude_new - 52.0469)< 10^-3);
    Start_Free_Vel = Start_Free_Vel(1);
else
    Start_Free_Vel = find(abs(Longitude_new - 6.1094) < 10^-3 & ...
        abs(Lattitude_new - 52.0441)< 10^-3);
    Start_Free_Vel = Start_Free_Vel(1);
end

End_Free_Vel = find(abs(Longitude_new - 6.1040) < 10^-3 & ...
    abs(Lattitude_new - 52.0508)< 10^-3);
End_Free_Vel = End_Free_Vel(end);

Start_7_Vel = find(abs(Longitude_new - 6.1025) < 10^-3 & ...
    abs(Lattitude_new - 52.0483)< 10^-3);
Start_7_Vel = Start_7_Vel(1);
End_7_Vel = find(abs(Longitude_new - 6.1037) < 10^-3 & ...
    abs(Lattitude_new - 52.0470)< 10^-3);
End_7_Vel = End_7_Vel(end-50);

Start_25_Vel = find(abs(Longitude_new - 6.0999) < 10^-3 & ...
    abs(Lattitude_new - 52.0495) < 10^-3);
```

```
            Start_25_Vel = Start_25_Vel(1);
            End_25_Vel = find(abs(Longitude_new - 6.0961) < 10^-3 & ...
                abs(Lattitude_new - 52.0505)< 10^-3);
            End_25_Vel = End_25_Vel(end);

            %Mean Velocity for segements
            Velocity_Free = mean(Velocity(Start_Free_Vel:End_Free_Vel));
            Velocity_7 = mean(Velocity(Start_7_Vel:End_7_Vel));
            Velocity_25 = mean(Velocity(Start_25_Vel:End_25_Vel));

            %Power Spectral Density
            [Surface_Yaw_Free, Freq_max_Yaw_Free, Freq_Yaw_Free, Power_Yaw_Free] = ...
                PSD(Gyro_Yaw_Free);
                    figure(5)
                    plot(Freq_Yaw_Free, Power_Yaw_Free)
                    title('PSD Yaw Free')
                    path = 'C:\Users\carli\Documents\Afstudeer Project\Project\Test Dag...';
                    filename = char(strcat(Bicycle_current, Participant_current,...
                        ' - Gyro_Yaw_Free.png'));
                    saveas(figure(5),fullfile(path,filename));

            [Surface_Roll_Free, Freq_max_Roll_Free, Freq_Roll_Free, Power_Roll_Free] = ...
                PSD(Gyro_Roll_Free);

            [Surface_Yaw_7, Freq_max_Yaw_7, Freq_Yaw_7, Power_Yaw_7] = PSD(Gyro_Yaw_7);
                    figure(6)
                    plot(Freq_Yaw_7, Power_Yaw_7)
                    title('PSD Yaw 7')
                    path = 'C:\Users\carli\Documents\Afstudeer Project\Project\Test Dag...';
                    filename = char(strcat(Bicycle_current, Participant_current, ...
                        ' - Gyro_Yaw_7.png'));
                    saveas(figure(6),fullfile(path,filename));

            [Surface_Roll_7, Freq_max_Roll_7, Freq_Roll_7, Power_Roll_7] = PSD(Gyro_Roll_7);

            [Surface_Yaw_25, Freq_max_Yaw_25, Freq_Yaw_25, Power_Yaw_25] = PSD(Gyro_Yaw_25);
                    figure(7)
                    plot(Freq_Yaw_25, Power_Yaw_25)
                    title('PSD Yaw 25')
                    path = 'C:\Users\carli\Documents\Afstudeer Project\Project\Test Dag...';
                    filename = char(strcat(Bicycle_current, Participant_current, ...
                        ' - Gyro_Yaw_25.png'));
                    saveas(figure(7),fullfile(path,filename));

             [Surface_Roll_25, Freq_max_Roll_25, Freq_Roll_25, Power_Roll_25] =...
                 PSD(Gyro_Roll_25);

        end

    else
        %Distance and Velocity Figure
        Figure_Dis_Vel(Time_new, Distance, Velocity, bicycles(k), participants(l));

        %Motion and Motion Rate Figure
        Figure_Gyro(Time_line, Gyro_Y, Roll_deg, Gyro_Z, Yaw_deg, bicycles(k), participants(l))

        %Distance, Velocity and Motion Rate Figure
        Figure_All( Time_new, Time_line, Distance, Velocity, Gyro_Y, Gyro_Z, bicycles(k),...
            participants(l) )

                Velocity_Free = 0; Velocity_7 = 0; Velocity_25 = 0;
                Surface_Yaw_Free = 0; Surface_Roll_Free = 0; Surface_Yaw_7 = 0;
                Surface_Roll_7 = 0; Surface_Yaw_25 = 0; Surface_Roll_25 = 0;
                Freq_max_Yaw_Free = 0;  Freq_max_Roll_Free = 0; Freq_max_Yaw_7 = 0;
                Freq_max_Roll_7 = 0; Freq_max_Yaw_25 = 0; Freq_max_Roll_25 = 0;
    end

    All_data(1,:) = ["Bicycle" "Participant" "Velocity Free" "Velocity 7km/h (2m/s)" ...
        "Velocity 25km/h (7m/s)" "Surface Yaw Free" "Surface Roll Free" ...
        "Surface Yaw 7km/h (2m/s)" "Surface Roll 7km/h (2m/s)"  "Surface Yaw 25km/h (7m/s)" ...
        "Surface Roll Free 25km/h (7m/s)" "Freq_max_Yaw_Free" "Freq_max_Roll_Free" ...
```

```
            "Freq_max_Yaw_7" "Freq_max_Roll_7" "Freq_max_Yaw_25" "Freq_max_Roll_25"];
        All_data(l+1,:)  = [Bicycle_current Participant_current Velocity_Free Velocity_7...
            Velocity_25 Surface_Yaw_Free Surface_Roll_Free Surface_Yaw_7 Surface_Roll_7 ...
            Surface_Yaw_25 Surface_Roll_25 Freq_max_Yaw_Free Freq_max_Roll_Free Freq_max_Yaw_7 ...
            Freq_max_Roll_7 Freq_max_Yaw_25 Freq_max_Roll_25];

    end
            path = 'C:\Users\carli\Documents\Afstudeer Project\Project\Test Dag...';
            filename = char(strcat(Bicycle_current, ' - Data File.xls'));
            xlswrite(fullfile(path,filename), All_data);
end


%%%%%%%%%%%%%%%%
% Figure_Route %
%%%%%%%%%%%%%%%%

function [  ] = Figure_Route( Longitude, Lattitude, Bicycle, Participant )
%Creates and saves a figure of the selected data

        figure(1);
        plot(Longitude, Lattitude)
        hold on
        plot(6.109437290584770, 52.044108677703900, 'bo', 6.103978743782360,...
            52.050834903542000, 'bo', 6.102531356742700, 52.048359517987800, 'r*', ...
            6.103796521207410, 52.047074111226900, 'r*', 6.099947383632970, 52.049549873966700,...
            'k+', 6.096133701508950, 52.050579171676200, 'k+');
        hold off
        legend('Route', 'Free Speed', ' ', '7 km/h', ' ', '25 km/h', ' ')

        %Save Figure
        path = 'C:\Users\carli\Documents\Afstudeer Project\Project\Test Dag...';
        filename = char(strcat(Bicycle, Participant, ' - GPS.png'));
        saveas(figure(1),fullfile(path,filename));
end


%%%%%%%%%%%%%%%%%%
% Figure_Dis_Vel %
%%%%%%%%%%%%%%%%%%

function [  ] = Figure_Dis_Vel( Time, Distance, Velocity, Bicycle, Participant )
%Creates and saves a figure of the selected data

            Fast_Riding = repmat(7,1,length(Velocity));  %create line at 7 m/s
            Slow_Riding = repmat(2,1,length(Velocity));  %create line at 2 m/s

            figure(2);
            subplot(2,1,1)
            plot(Time, Distance);
            ylabel('Travelled distance [m]');
            xlabel('Time [s]');
            axis tight;
            subplot(2,1,2);
            plot(Time, Velocity, Time, Fast_Riding,'r', Time, Slow_Riding, 'k');
            ylabel('Velocity [m/s]');
            xlabel('Time[s])');
            axis tight;

            %Save Figure
            path = 'C:\Users\carli\Documents\Afstudeer Project\Project\Test Dag...';
            filename = char(strcat(Bicycle, Participant, ' - Distance-Velocity.png'));
            saveas(figure(2),fullfile(path,filename));
end


%%%%%%%%%%%%%%%%
% Figure_Gyro %
%%%%%%%%%%%%%%%%
```

```
function [  ] = Figure_Gyro( Time, Gyro_Y, Roll_deg, Gyro_Z, Yaw_deg, ...
    Bicycle, Participant )
%Creates and saves a figure of the selected data
                figure(3);
                subplot(2,2,1)
                plot(Time, Gyro_Y)
                xlabel('Time [s]')
                ylabel('Roll angular velocity [deg/s]')
                axis tight
                subplot(2,2,2)
                plot(Time, Roll_deg)
                xlabel('Time [s]')
                ylabel('Roll angle [deg]')
                axis tight
                subplot(2,2,3)
                plot(Time, Gyro_Z)
                xlabel('Time [s]')
                ylabel('Yaw angular velocity [deg/s]')
                axis tight
                subplot(2,2,4)
                plot(Time, Yaw_deg)
                xlabel('Time [s]')
                ylabel('Yaw angle [deg]')
                axis tight

                %Save Figure
                path = 'C:\Users\carli\Documents\Afstudeer Project\Project\Test Dag...';
                filename = char(strcat(Bicycle, Participant, ' - Gyro.png'));
                saveas(figure(3),fullfile(path,filename));
end


%%%%%%%%%%%%%%
% Figure_All %
%%%%%%%%%%%%%%

function [  ] = Figure_All(Time_new, Time_line, Distance, Velocity, Gyro_Y, Gyro_Z, ...
    Bicycle, Participant )

                Fast_Riding = repmat(7,1,length(Velocity));     %create line at 7 m/s
                Slow_Riding = repmat(2,1,length(Velocity));     %create line at 2 m/s

                figure(4);
                subplot(4,1,1)
                plot(Time_new, Distance)
                ylabel('Travlled distance [m]')
                xlabel('Time [s]')
                subplot(4,1,2)
                plot(Time_new, Velocity, Time_new, Fast_Riding,'r', Time_new, Slow_Riding, 'k')
                ylabel('Velocity [m/s]')
                xlabel('Time [s]')
                subplot(4,1,3)
                plot(Time_line, Gyro_Y)
                xlabel('Time [s]')
                ylabel('Roll angular velocity [deg/s]')
                xlabel('Time[s])')
                subplot(4,1,4)
                plot(Time_line, Gyro_Z)
                xlabel('Time [s]')
                ylabel('Yaw angular velocity [deg/s]')

                %Save Figure
                path = 'C:\Users\carli\Documents\Afstudeer Project\Project\Test Dag...';
                filename = char(strcat(Bicycle, Participant, ' - All.png'));
                saveas(figure(4),fullfile(path,filename));
end


%%%%%%%
% PSD %
```

```
%%%%%%%
function [Surface, Freq_Max, Freq, Power_Filter] = PSD( Motion )
    FS = 100;
    FFT  = fft(Motion);
    P2 = abs(FFT/length(FFT));
    P1 = P2(1:length(FFT)/2+1);
    P1(2:end-1) = 2*P1(2:end-1);
    f = FS*(0:(length(FFT)/2))/length(FFT);
    f_end = find(f>=10);        %minimal freq
    f_start = find(f>=0.5);     %maximal freq

    Freq = f(f_start:f_end);
    Power = P1(f_start:f_end);

    Surface = trapz(Freq,Power);

            CutOff = 10;                                %cutoff frequency at 15 Hz
            [B,A] = butter(4,CutOff/(FS/2),'low');
            Power_Filter = filtfilt(B,A,Power);
            plot(Freq,Power_Filter)

            Power_Max = find(Power_Filter == max(Power_Filter));
            Freq_Max = Freq(Power_Max);
end
```

ALL RESULTS

Figure D.1.

Measures from the iPhone sensors and subjective opinions on the bicycles, for each participant on each bicycle. The lines marked in red are the data sets that could not be used due to a wrong sample rate.

GAZELLE PARTICIPANTS

Figure D.2.

Subjective scores on the bicycle from only the Gazelle-participants.

INDEPENDENT PARTICIPANTS

Figure D.3.

Subjective scores on the bicycle from only the independent-participants.

DIFFERENCES GAZELLE-INDEPENDENT

Figure D.4.

Differences between the subjective scores of the Gazelle- and the independent-participants.

Figure D1: All analysed data from the cycling experiment, objective measures and subjective score. The red marked data is unusable data

Bicycle	Participant	Rider COM X	Rider COM Y	Rider mass	Rider Angle	Velocity Free	Velocity 2	Velocity 7	Peak Freq Free	Peak Freq 2	Peak Freq 7	Surface Yaw Free	Surface Roll Free	Surface Yaw 2	Surface Roll 2	Surface Yaw 7	Surface Roll 7	Question 1	Question 2	Question 3	Question 4	Question 5	Question 6	Question 7	Question 8	Question 9	Question 10	Question 11	Question 12	Question 13	Question 14
Ami	Mathieu	0.3985	1.034	70	-16	6.9001	3.5565	6.9924	1.0779	0.50349	1.1688	2.8411	2.1799	5.4914	1.8267	3.5288	2.3625	1	-1	-1	0	0	-1	-1	0	1	1	1	1	-1	-1
Ami	Eddy	0.335	1.0261	80	-7	6.8294	2.9957	6.5484	1.1524	0.62487	1.1308	2.6699	2.0709	5.8743	1.5893	4.1492	2.5896	1	2	2	2	1	-1	-2	1	1	2	2	2	2	2
Ami	Lex	0.361	1.0686	96	-7	6.471	3.2514	6.5041	1.3235	0.87677	1.3254	2.3032	1.7412	3.0116	1.0889	3.0504	2.0829	1	-1	1	1	1	-1	-1	0	1	1	1	1	1	1
Ami	Sierd	0.3124	1.0909	70	-11	6.9167	3.3641	6.7268	1.2495	0.83569	1.6376	3.7817	2.5912	5.9745	1.8458	4.3038	2.706	1	-2	1	1	1	2	-2	1	-1	0	2	1	1	2
Ami	Wolf	0.3584	1.0511	68	-13	6.2418	2.7181	6.9463	1.0945	0.50447	1.0033	3.1425	1.9114	7.0739	1.7618	5.1341	3.3835	2	0	1	2	-1	-2	-2	1	0	1	1	2	2	1
Ami	Ingmar	0.2831	1.0877	75	-11	6.4656	2.907	6.3525	1.2996	1.529	1.2979	3.9947	3.9349	6.8172	2.4809	3.9916	4.3234	-1	-1	-1	-1	1	-1	0	1	0	-1	-1	0	0	1
Ami	Hans	0.327	1.0544	95	-8	5.7023	2.7546	6.4243	1.0953	0.71328	1.1586	2.3682	3.2529	2.9608	1.0374	2.9651	3.6191	1	1	2	2	0	0	-1	2	-1	2	1	2	2	2
Ami	Wouter	0.3855	1.0596	91	-13	6.3522	3.2921	6.7153	1.0969	0.50044	0.98765	2.737	3.1561	4.3648	1.9426	3.8428	4.3762	1	-1	1	1	1	-1	-1	1	-1	1	1	1	1	1
Ami	Martin	0.3324	1.0435	110	-8	6.0147	3.615	6.5864	1.0544	0.63839	1.3619	1.9981	1.5323	3.5606	1.3325	3.9274	2.5371	1	-2	1	1	-1	0	1	1	1	1	1	-1	1	1
Ami	Andre	0.3284	1.0891	67	-15	5.6493	3.0349	6.4686	0.71462	1.011	1.1269	2.4333	1.3844	3.5721	1.0708	3.8662	2.104	2	-2	1	2	1	0	1	2	0	0	1	1	0	1
Balance	Mathieu	0.3809	1.0675	70	-6	7.301	4.1586	7.0103	1.1399	0.88709	1.1463	2.6997	2.2633	3.8909	3.0336	3.2958	2.4171	2	-1	2	2	2	-1	-2	2	-1	2	1	1	2	1
Balance	Eddy	0.371	1.0738	80	-2	6.5433	2.9536	6.2911	0.68798	1.2653	0.50007	2.3144	2.329	5.8952	3.6574	2.8424	2.9349	2	-2	2	2	2	-2	-1	-1	-1	2	2	1	-1	-1
Balance	Lex	0.3443	1.1246	96	-4	6.7247	2.9449	6.3384	1.3221	0.68729	1.2662	2.5343	2.0737	2.2925	2.495	3.0557	2.8184	-1	-2	-1	0	-1	-1	-1	0	1	-1	0	1	1	1
Balance	Sierd	0.3712	1.1134	70	-5	6.1735	3.512	6.2707	1.1686	0.72633	1.2355	3.2952	2.901	5.0321	5.324	4.0232	3.265	1	-2	1	1	1	1	-2	1	-1	0	1	1	1	2
Balance	Wolf	0.3522	1.0791	68	-10	6.5425	2.808	6.4461	0.68959	0.82187	0.79828	5.7266	3.3737	4.7852	2.8932	5.0996	3.2633	2	-2	2	2	0	0	-1	2	-1	1	-2	-2	-2	-1
Balance	Ingmar	0.2735	1.127	75	-11	6.0043	2.8363	6.4391	0.76806	0.5527	1.3071	3.1185	2.2546	10.2592	6.2691	3.971	2.918	1	-2	1	1	1	-1	1	0	-1	1	-2	0	-2	0
Balance	Hans	0.3953	1.065	95	-9	5.8216	2.919	6.5237	1.118	0.64119	1.1214	2.555	1.8934	3.7918	2.0078	3.4852	2.457	2	-2	2	2	1	0	-1	1	-2	2	1	2	2	2
Balance	Wouter	0.3979	1.0707	91	-14	6.7164	3.3332	6.1413	1.134	0.77835	1.1416	2.4776	2.2407	3.7918	2.0021	3.2437	2.3865	1	-1	1	1	1	0	-1	-1	-1	0	1	1	1	1
Balance	Martin	0.3215	1.0959	110	-10	5.3166	3.0051	6.2372	1.0942	0.7116	1.1106	1.8339	1.6213	3.2923	2.3359	3.5967	3.1141	0	-2	1	0	-1	0	1	1	0	1	1	0	1	1
Balance	Andre	0.3646	1.1014	67	-14	5.8645	3.2347	6.8638	1.0717	0.50635	1.1386	1.9646	2.1584	2.272	3.1834	2.8348	3.1448	2	-2	-1	1	1	2	-2	-2	2	-2	2	2	2	2
Orange	Mathieu	0.3639	1.1367	70	-11	5.5702	3.6237	6.292	0.91988	0.55822	1.0591	2.6096	1.637	4.9473	2.2018	4.2749	2.5457	1	0	2	2	1	1	-1	1	-2	2	1	1	1	2
Orange	Eddy	0.3174	1.1286	80	-5	5.3464	2.5416	5.8288	0.81696	1.1365	0.78405	2.6423	1.8905	6.4925	3.8413	4.5162	3.4704	1	-1	1	1	1	0	-1	-2	2	1	1	-1	1	-1
Orange	Lex	0.3525	1.1326	96	-4	5.0488	3.3982	4.8962	1.1423	1.2011	1.0826	2.1546	1.585	3.5432	2.3783	3.8161	2.7135	-1	-1	1	1	0	-1	-1	1	1	0	1	1	1	1
Orange	Sierd	0.2969	1.1365	70	-10	5.7413	3.4874	6.0942	1.237	1.3464	1.4823	2.6101	1.7987	3.9501	2.5292	5.1024	3.4467	1	-2	1	1	1	0	-2	1	0	1	1	1	1	1
Orange	Wolf	0.3535	1.1285	68	-16	4.9014	2.4818	6.1026	0.55399	0.53639	1.2545	2.9516	2.1265	4.2285	2.6426	5.5288	4.0911	2	-2	2	2	2	-1	-1	2	-2	2	0	0	1	1
Orange	Ingmar	0.2863	1.1735	75	-14	4.866	2.6598	5.8407	0.60583	0.58768	1.4487	2.7904	1.809	4.3211	2.6352	4.2279	3.2425	1	-2	1	1	1	0	-1	1	-1	0	-1	-1	-1	-1
Orange	Hans	0.3462	1.0959	95	-4	4.7879	2.9438	5.853	1.0832	0.5005	1.1792	1.6514	1.2071	2.7494	1.721	4.6993	3.3072	2	-2	2	2	2	0	-1	2	-2	2	2	2	2	2
Orange	Wouter	0.36	1.1329	91	-17	5.0954	3.3629	5.5511	0.93779	0.50639	1.2744	2.5278	1.8077	4.5573	2.7052	4.6637	3.4685	1	-2	1	0	1	1	-1	1	1	1	-1	-1	1	1
Orange	Martin	0.32	1.1658	110	-7	5.4666	4.331	5.5806	1.0994	0.98957	1.1327	2.4092	1.8999	3.4793	2.6103	4.4042	3.1314	1	-2	1	1	2	-1	0	1	-1	1	1	1	1	1
Orange	Andre	0.3561	1.12	67	-16	4.2624	2.9628	5.9338	0.50042	0.51	0.50546	7.2483	9.6999	2.1062	2.1518	2.9234	2.8497	1	0	2	2	2	-2	-2	2	-2	2	2	2	2	2
Orange HFP	Mathieu	0.3439	1.095	70	-10	7.0356	3.7914	8.1298	1.2051	0.69525	1.2099	3.0536	2.2406	3.9964	2.4064	2.957	2.3129	0	-1	-1	-1	-1	-1	-1	-1	-1	0	1	-1	-1	1
Orange HFP	Eddy	0.2777	1.1326	80	0	6.6055	3.0477	10.9066	0.54281	0.77258	0.86719	2.4888	1.824	6.1415	5.5283	5.7814	3.493	1	-1	0	2	-2	0	-2	0	-2	1	1	1	1	1
Orange HFP	Lex	0.2622	1.1358	96	-7	6.7352	4.1167	6.7312	1.1886	0.5901	1.2127	2.0014	1.7058	3.3858	2.0018	2.6024	2.0501	-1	-2	-2	1	2	1	-2	0	0	1	1	1	1	1
Orange HFP	Sierd	0.2969	1.1365	70	-10	6.3752	3.5601	6.5188	0.81265	0.64876	1.3938	2.7676	2.0414	6.2912	3.6957	4.0731	2.8144	0	-2	1	1	0	0	-2	1	0	1	0	0	1	0
Orange HFP	Wolf	0.2651	1.1361	68	-12	7.2011	2.7886	6.6305	1.0768	0.50237	1.3829	4.3507	3.4331	5.3829	3.3805	9.1217	6.025	0	-2	-2	-1	-1	-2	-2	1	0	-1	0	-2	-2	-2
Orange HFP	Ingmar	0.252	1.1381	75	-5	5.8049	3.347	5.923	0.60631	0.99454	0.50223	2.0751	1.6871	4.5321	2.6328	4.2479	2.7293	1	-1	1	1	1	0	-1	1	-1	1	-1	0	0	1
Orange HFP	Hans	0.3258	1.1302	95	-17	0	0	0	0	0	0	0	0	0	0	0	0	2	-2	2	2	1	1	-2	2	-2	1	1	2	2	2
Orange HFP	Wouter	0.3397	1.0964	91	-11	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	1	0	-1	1	-1	1	-1	-1	-1	-1	0	-1
Orange HFP	Martin	0.2507	1.1508	110	-2	5.4349	3.4823	5.8338	1.0157	0.69292	0.69018	2.1408	1.5579	2.9168	1.8389	3.3894	2.4453	-1	-1	-1	0	-2	-1	0	1	0	0	0	-1	-1	-1
Orange HFP	Andre	0.2642	1.1292	67	-12	0	0	0	0	0	0	0	0	0	0	0	0	2	-2	0	0	2	-2	-2	1	-2	2	2	2	2	2
Orange HMB	Mathieu	0.3496	1.1241	70	-11	6.7796	2.9468	6.654	1.1	0.73831	0.95764	3.8672	2.3053	4.1313	1.7916	3.6006	2.468	2	0	1	1	1	-1	-1	1	-2	2	1	1	1	2
Orange HMB	Eddy	0.2988	1.1231	80	-1	6.394	3.3429	6.1023	0.52819	0.96074	0.81066	2.6281	1.4866	5.5518	2.2427	4.3362	2.638	1	-2	-1	-1	-1	1	1	-2	-2	1	1	1	1	1
Orange HMB	Lex	0.357	1.171	96	-2	6.4237	2.9978	6.4037	1.2374	0.72121	1.2357	3.3311	2.007	4.2904	1.916	3.7291	2.2357	0	-1	0	1	1	-1	1	-1	1	1	1	1	1	1
Orange HMB	Sierd	0.2977	1.134	70	-12	6.909	4.4156	6.7537	1.2736	0.75485	1.2526	5.6014	2.9597	4.7319	2.2307	3.3175	2.2093	1	-1	1	2	2	1	-2	1	0	1	1	1	1	1
Orange HMB	Wolf	0.2973	1.1135	68	-13	6.3942	3.3124	6.1357	1.279	0.57074	1.2522	3.5451	2.0189	5.7974	2.7211	6.7256	3.548	2	0	2	1	2	0	-1	-2	-2	2	0	1	1	0
Orange HMB	Ingmar	0.2504	1.1294	75	-13	5.123	3.1998	6.7093	0.62231	0.5	0.51054	1.876	1.0162	3.7018	1.6045	4.1947	2.7166	1	-1	1	1	1	-1	-1	1	0	1	-1	-1	0	-1
Orange HMB	Hans	0.3459	1.0957	95	-12	5.6658	2.9234	5.9674	1.184	0.6959	1.2096	2.0623	1.3295	3.0076	1.3217	3.2407	2.0245	2	-2	2	2	2	0	-1	2	-2	2	2	2	2	2
Orange HMB	Wouter	0.3797	1.1125	91	-14	5.0599	3.394	6.5644	0.93612	0.56779	1.0824	2.5805	1.2561	4.1233	1.8398	4.2511	2.3935	2	-1	1	1	1	1	-1	1	1	1	0	1	1	1
Orange HMB	Martin	0.2604	1.1284	110	-5	6.7634	3.575	6.624	1.2097	0.56111	1.2449	2.8092	1.815	4.9628	2.3439	3.8539	2.564	1	-1	1	1	2	-1	1	0	1	1	1	0	1	1
Orange HMB	Andre	0.321	1.1385	67	-16	6.1823	2.9366	6.2093	1.211	0.67544	1.027	2.9756	1.7366	2.4532	1.1707	2.9549	1.7559	2	-2	2	2	2	-2	-2	2	-2	1	2	2	2	2
Cityzen	Mathieu	0.4216	1.1064	70	-25	6.8271	5.1371	6.7767	2.147	1.2436	2.1126	3.2459	1.8512	4.0549	1.5935	5.5381	2.9328	2	2	2	2	2	1	-1	-1	1	-1	1	1	2	2
Cityzen	Eddy	0.366	1.1105	80	-20	6.4603	3.3148	6.4432	1.0853	0.83857	1.2145	3.6704	1.8922	5.2174	1.2981	6.6042	3.2032	-1	2	2	2	2	-1	-1	-2	2	-2	2	2	2	2
Cityzen	Lex	0.3673	1.1153	96	-19	5.4085	3.3678	6.2172	1.1957	1.1177	1.2628	2.7109	1.2729	4.0155	1.2593	5.2561	2.6801	0	1	0	0	0	1	-1	1	1	0	1	1	1	1
Cityzen	Sierd	0.363	1.1122	70	-29	7.1652	4.0602	6.6972	1.3737	0.85311	1.5395	3.8713	1.9895	5.3875	1.7739	5.3569	2.9022	0	2	2	2	1	0	-2	2	-2	1	2	1	1	1
Cityzen	Wolf	0.4	1.1164	68	-28	6.788	2.8119	6.7064	1.4594	0.87735	1.3657	4.5057	2.5663	5.3539	1.1058	6.4822	3.5944	-1	2	2	0	1	-1	-2	-2	0	0	2	2	2	2
Cityzen	Ingmar	0.3948	1.1322	75	-29	5.6397	3.0676	6.7288	1.1172	0.50145	0.51202	2.9848	1.3137	5.6756	1.1084	4.3416	2.2841	1	2	2	2	0	0	-2	1	-1	0	2	1	1	1
Cityzen	Hans	0.4288	1.1193	95	-27	6.4046	3.7725	6.6928	1.1923	0.50704	1.3249	2.3959	1.453	3.2652	1.0355	4.9086	2.857	-1	-1	2	2	-1	-1	-1	2	-1	1	1	1	2	2
Cityzen	Wouter	0.432	1.1197	91	-32	5.6671	3.4433	6.0103	1.0556	0.505	2.3852	2.3318	1.317	2.4073	0.8964	4.3269	2.372	-1	1	0	-1	-2	-1	-1	1	1	0	-1	-2	1	1
Cityzen	Martin	0.3993	1.164	110	-22	5.2766	3.6857	5.8257	1.1556	0.50511	1.4238	2.655	1.3406	5.1809	1.4845	4.6393	2.7503	1	1	1	1	1	0	-2	1	-1	1	2	2	1	1
Cityzen	Andre	0.383	1.1122	67	-27	5.1376	4.5307	6.1161	0.94086	0.67998	1.2155	2.6393	1.0113	3.8845	1.2789	5.2738	2.185	0	2	2	1	1	-1	-2	0	-1	0	1	1	1	1
Cityzen Speed	Mathieu	0.4331	1.1257	70	-26	8.631	5.2973	7.8289	1.3527	1.2171	1.1097	3.1567	2.1848	3.7505	1.8292	3.7197	2.3984	-1	2	-1	0	1	-1	-2	1	-1	1	0	1	1	0
Cityzen Speed	Eddy	0.3771	1.1462	80	-22	7.8109	3.428	6.0869	1.259	0.5599	0.75499	3.0454	1.7262	6.2225	1.9079	6.205	2.758	-2	2	0	2	1	-1	-2	-1	1	-1	2	2	2	2
Cityzen Speed	Lex	0.4115	1.1664	96	-24	8.4258	4.1425	7.3466	1.4059	0.66614	1.1665	3.6556	2.0868	4.1366	1.6928	4.4521	2.4626	-1	1	-1	1	1	-1	-1	1	1	1	1	1	1	1
Cityzen Speed	Sierd	0.363	1.1122	70	-29	8.1586	3.4386	6.5133	1.2601	0.70073	1.2755	3.7179	1.886	3.5828	1.3901	4.0423	2.0683	1	2	2	1	1	1	-2	1	-2	2	0	-1	1	0
Cityzen Speed	Wolf	0.3924	1.152	68	-26	7.5421	2.9182	7.3877	0.81315	0.76196	0.804	4.8054	2.5159	6.0208	2.308	10.1075	5.7726	2	2	2	2	2	-1	0	1	-1	2	1	1	0	0
Cityzen Speed	Ingmar	0.324	1.1585	75	-24	8.6582	3.2162	6.3387	1.6741	0.5087	1.1575	3.5511	2.0523	4.5031	1.5698	3.1502	1.6241	1	1	1	1	0	1	-2	1	-1	1	1	1	1	1
Cityzen Speed	Hans	0.3839	1.105	95	-22	7.8263	3.3998	7.0106	1.3175	0.90844	1.0313	3.2077	1.7108	3.7253	1.3186	4.4358	2.6062	1	2	-2	2	-1	2	-2	2	-2	1	1	1	1	2
Cityzen Speed	Wouter	0.4608	1.0751	91	-29	7.6789	2.5308	6.4643	1.2066	0.63535	1.0429	2.6553	1.4565	4.0735	1.3332	2.693	1.5145	0	1	1	1	1	0	-1	1	-1	1	1	1	1	1
Cityzen Speed	Martin	0.3648	1.1503	110	-18	6.2631	3.9369	6.6197	0.98087	0.65602	1.1713	2.7763	1.4839	4.0302	1.5821	3.3677	2.0251	-1	1	0	0	1	-1	-1	1	-1	1	-1	1	1	1
Tour Populair	Mathieu	0.3032	1.1159	70	-3	5.4893	3.7521	6.5629	0.92521	0.51234	1.0821	2.3599	1.5876	4.1155	2.3811	3.8014	2.5847	1	0	1	2	2	-2	-2	2	-1	1	1	1	2	1
Tour Populair	Eddy	0.2829	1.1327	80	-4	0	0	0	0	0	0	0	0	0	0	0	0	2	-1	2	2	2	-2	-2	2	-2	2	-1	1	2	1
Tour Populair	Lex	0.2525	1.1367	96	0	4.6155	3.3556	5.9939	0.87345	0.77803	1.2892	1.6561	1.1555	3.2631	2.0619	3.9026	2.8375	1	-2	1	1	1	-1	-1	1	0	0	1	1	1	1
Tour Populair	Sierd	0.2275	1.1189	70	-4	0	0	0	0	0	0	0	0	0	0	0	0	2	-2	2	2	2	-2	-2	2	-2	2	2	2	2	2
Tour Populair	Wolf	0.2533	1.1134	68	-7	5.0763	2.3796	6.2406	1.1739	0.51118	1.3578	2.4313	1.6672	5.0862	3.2075	5.1879	3.4302	0	-2	0	1	-1	0	1	1	0	-2	-1	-1	-1	-1
Tour Populair	Ingmar	0.2225	1.1533	75	-9	5.2746	4.5247	5.8943	1.0549	1.2822	1.3564	2.7341	1.9016	1.8106	1.201	4.4398	3.0634	0	-2	-2	-1	1	-1	0	-1	-1	1	0	0	-1	0
Tour Populair	Hans	0.2943	1.1085	95	-6	0	0	0	0	0	0	0	0	0	0	0	0	2	-2	2	2	2	1	1	1	-1	2	1	1	2	2
Tour Populair	Wouter	0.319	1.0995	91	-6	0	0	0	0	0	0	0	0	0	0	0	0	2	-2	0	0	1	1	1	1	1	1	0	-1	0	1
Tour Populair	Martin	0.2136	1.1389	110	-2	5.5223	0	6.148	1.2221	0	1.2115	1.7993	1.0751	0	0	5.1197	3.0702	1	-2	1	1	1	-1	-1	1	0	1	1	1	1	1
Tour Populair	Andre	0.2681	1.1444	67	-10	5.3805	3.1689	6.1403	0.50817	0.50545	0.76003	2.113	1.5029	3.1301	1.8119	4.4206	3.136	1	-2	0	1	2	-1	0	0	-1	1	1	0	1	1
Puur NL	Mathieu	0.3217	1.1284	70	-4	6.2891	4.6964	6.5026	1.0204	1.0481	1.0525	2.2925	1.8578	4.2512	2.5711	4.3565	2.9141	1	1	1	2	2	2	-1	-1	1	1	1	2	2	1
Puur NL	Eddy	0.2557	1.1062	80	6	5.4504	3.1236	6.1379	0.72848	1.1937	0.66111	2.2983	1.6661	4.7374	2.8134	4.3225	2.897	2	-2	1	2	2	-2	-2	2	-1	2	2	1	2	1
Puur NL	Lex	0.3067	1.0948	96	1	4.9997	3.4904	6.3836	1.3833	0.8643	0.98086	2.1657	1.5013	3.8544	2.44	4.5633	3.1304	2	-2	2	1	1	1	-1	-1	1	-1	0	1	1	1
Puur NL	Sierd	0.2275	1.1189	70	4	5.7416	4.0078	5.9904	1.438	0.50438	0.92089	2.5257	1.9475	4.8544	3.16	4.4577	3.3506	2	-2	2	2	2	-2	-2	0	-2	1	1	1	1	1
Puur NL	Wolf	0.2409	1.1218	68	-2	5.129	2.8495	6.3564	0.65422	0.50412	1.018	2.8391	1.9743	5.0634	3.1661	5.6035	4.1034	2	-1	1	1	1	-1	-1	1	-1	0	1	1	1	1
Puur NL	Ingmar	0.2694	1.117	75	4	6.1058	3.2431	6.4859	0.84918	0.83623	1.368	2.5904	1.8542	5.4534	2.8929	3.6906	2.7606	2	-1	1	2	0	1	-1	1	-1	0	0	0	-1	0
Puur NL	Hans	0.2614	1.1126	95	-5	5.2881	3.2867	5.9166	1.0204	1.0692	1.0848	1.9642	1.5272	3.4245	1.9054	4.4918	3.172	1	-2	1	1	1	-2	0	0	1	0	1	1	1	1
Puur NL	Wouter	0.305	1.1085	91	-8	0	0	0	0	0	0	0	0	0	0	0	0	-1	-2	0	0	-1	0	1	-1	1	0	-1	-1	0	0
Puur NL	Martin	0.2693	1.1325	110	-5	0	0	0	0	0	0	0	0	0	0	0	0	2	-2	2	1	-1	0	-1	1	-1	1	1	1	1	1
Puur NL	Andre	0.3233	1.1118	67	-9	5.2223	2.9817	6.1568	0.50073	0.51455	0.5601	2.0813	1.5455	1.7535	0.87148	2.9941	2.2207	0	-2	1	1	2	-2	0	-1	0	0	1	1	1	1
Van Stael	Mathieu	0.3885	1.078	70	-25	7.0368	4.7878	7.0537	2.3377	0.85812	1.3456	3.3204	1.9267	4.6386	1.868	5.2855	2.9674	2	2	2	2	1	-2	-2	1	-1	1	2	2	2	2
Van Stael	Eddy	0.3487	1.0822	80	-19	5.5329	2.8601	6.3756	1.1852	1.035	1.2754	2.4685	1.4803	5.9797	1.9562	3.8895	2.3467	-1	1	1	2	-1	-1	-1	1	-1	2	1	2	2	2
Van Stael	Lex	0.3527	1.1208	96	-17	6.1696	3.6782	6.4625	1.1992	0.98064	1.3976	2.8693	1.7894	3.8916	1.7023	5.5827	3.3445	1	2	1	1	1	-1	-1	1	0	1	1	1	1	1
Van Stael	Sierd	0.343	1.1211

Gazelle Participants

Bicycle	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14
Ami	1.0	-0.5	0.8	1.0	0.8	-0.3	-1.5	0.8	0.3	1.0	1.5	1.3	0.8	1.0
STD	0.0	1.5	1.1	0.7	0.4	1.3	0.5	0.4	0.8	0.7	0.5	0.4	1.1	1.2
Balance	1.0	-1.8	1.0	1.3	1.0	-0.8	-1.5	0.5	-0.5	0.8	1.0	1.0	0.8	0.8
STD	1.2	0.4	1.2	0.8	1.2	1.1	0.5	1.1	0.9	1.3	0.7	0.0	1.1	1.1
Orange	0.5	-1.0	1.3	1.3	0.8	0.0	-1.3	0.3	0.3	1.0	1.0	0.5	1.0	0.8
STD	0.9	0.7	0.4	0.4	0.4	0.7	0.4	1.3	1.5	0.7	0.0	0.9	0.0	1.1
Orange HFP	0.0	-1.5	-0.5	0.0	0.5	0.5	-1.8	0.0	-0.8	0.8	0.8	0.3	0.5	0.8
STD	0.7	0.5	1.1	1.0	1.1	1.1	0.4	0.7	0.8	0.4	0.4	0.8	0.9	0.4
Orange HMB	1.0	-1.0	0.3	0.8	0.8	0.0	-0.3	-0.3	-0.5	1.3	1.0	1.0	1.0	1.3
STD	0.7	0.7	0.8	1.1	1.1	1.0	1.3	1.3	1.1	0.4	0.0	0.0	0.0	0.4
Cityzen	0.3	1.8	1.5	1.5	0.5	-0.8	-1.5	1.5	-1.0	1.0	1.5	1.5	1.5	1.5
STD	1.1	0.4	0.9	0.9	0.9	0.4	0.5	0.5	1.2	0.7	0.5	0.5	0.5	0.5
Cityzen Speed	-0.8	1.8	-0.3	1.0	0.5	-0.5	-1.3	0.5	-0.3	0.8	0.5	0.8	1.3	0.8
STD	1.1	0.4	0.8	0.7	0.9	0.9	1.3	0.9	1.3	1.1	0.5	1.1	0.4	0.8
Tour Populair	1.5	-1.3	1.5	1.8	1.8	-1.5	-1.8	1.8	-1.3	1.3	0.8	1.3	1.3	1.0
STD	0.5	0.8	0.5	0.4	0.4	0.5	0.4	0.4	0.8	0.8	1.1	0.4	0.8	0.0
Puur NL	1.8	-1.3	1.5	1.8	1.8	-1.5	-1.0	1.5	-0.8	1.0	1.5	1.3	1.3	1.0
STD	0.4	1.3	0.5	0.4	0.4	0.5	0.7	0.5	1.1	0.7	0.5	0.4	0.4	0.0
Van Stael	1.0	1.3	1.5	1.8	0.8	-1.3	-1.5	1.3	-0.3	1.5	1.3	1.5	1.8	1.8
STD	1.2	0.8	0.5	0.4	1.1	0.4	0.5	0.4	0.8	0.5	0.4	0.5	0.4	0.4

Figure D2: Mean score for each bicycle with STD, by the Gazelle-participants

Independent Participants

Bicycle	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14
Ami	1.0	-0.8	0.8	1.5	-0.2	-0.5	-0.2	1.2	-0.3	0.7	0.8	0.8	1.2	1.0
STD	1.0	1.1	0.9	0.5	0.9	0.8	1.2	0.7	0.7	0.9	0.4	1.1	0.7	0.6
Balance	1.3	-1.7	1.3	1.2	0.7	-0.5	-0.5	0.8	-1.2	1.2	0.2	0.5	0.3	0.8
STD	0.7	0.5	0.5	0.7	0.9	0.8	1.1	1.1	0.7	0.7	1.6	1.4	1.7	1.1
Orange	1.3	-1.7	1.5	1.3	1.7	-0.5	-1.0	1.3	-1.2	1.3	0.5	0.5	1.0	1.0
STD	0.5	0.7	0.5	0.7	0.5	1.0	0.6	0.5	1.1	0.7	1.3	1.3	1.0	1.0
Orange HFP	1.0	-1.4	0.4	0.6	0.2	-0.6	-1.2	1.2	-1.2	0.6	0.2	0.4	0.6	0.6
STD	1.1	0.5	1.0	0.8	1.5	1.0	0.7	0.4	0.7	1.0	1.2	1.4	1.2	1.4
Orange HMB	1.7	-1.2	1.5	1.3	1.7	-0.5	-0.8	1.3	-0.7	1.3	0.7	0.8	1.2	0.8
STD	0.5	0.7	0.5	0.5	0.5	1.0	0.9	0.7	1.4	0.5	1.1	1.1	0.7	1.1
Cityzen	-0.2	1.2	1.0	1.0	-0.3	-0.8	-1.7	0.8	-0.5	0.8	1.2	0.8	0.7	1.3
STD	0.9	1.1	0.8	1.0	1.1	0.7	0.5	0.7	0.8	0.7	1.1	1.3	1.2	0.5
Cityzen Speed	0.8	1.5	1.0	1.0	0.5	0.5	-1.3	1.2	-1.0	1.3	0.5	0.5	0.8	0.8
STD	0.9	0.5	0.6	0.6	1.0	1.1	0.7	0.4	1.0	0.5	0.8	0.8	0.4	0.7
Tour Populair	1.0	-2.0	0.3	1.0	0.7	0.0	0.5	-0.2	0.2	0.5	0.2	-0.2	0.5	0.5
STD	0.8	0.0	0.9	0.6	1.2	0.8	0.8	0.9	0.9	1.3	0.7	0.9	1.0	1.1
Puur NL	1.0	-1.7	0.8	0.7	0.5	-0.8	0.0	-0.2	0.2	0.2	0.5	0.5	0.5	0.7
STD	1.2	0.5	0.4	0.9	1.0	1.1	0.8	0.9	0.9	0.4	0.8	0.8	0.8	0.5
Van Stael	0.3	0.2	1.0	1.2	0.2	-1.2	-0.8	0.7	-0.7	0.7	1.0	1.2	1.3	1.2
STD	1.2	1.1	0.6	0.7	1.3	1.1	1.1	0.9	0.7	0.7	0.6	0.4	0.5	0.7

Figure D3: Mean score for each bicycle with STD, by the independent-participants

Differences Gazelle - Independent

Bicycle	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14
Ami	0.0	0.3	0.1	0.5	0.9	0.3	1.3	0.4	0.6	0.3	0.7	0.4	0.4	0.0
STD	1.0	0.4	0.2	0.2	0.5	0.5	0.7	0.3	0.1	0.2	0.1	0.6	0.4	0.6
Balance	0.3	0.1	0.3	0.1	0.3	0.3	1.0	0.3	0.7	0.4	0.8	0.5	0.4	0.1
STD	0.5	0.0	0.8	0.1	0.3	0.3	0.6	0.1	0.2	0.6	0.9	1.4	0.6	0.0
Orange	0.8	0.7	0.3	0.1	0.9	0.5	0.3	1.1	1.4	0.3	0.5	0.0	0.0	0.3
STD	0.4	0.0	0.1	0.3	0.0	0.3	0.1	0.8	0.4	0.0	1.3	0.4	1.0	0.1
Orange HFP	1.0	0.1	0.9	0.6	0.3	1.1	0.6	1.2	0.5	0.2	0.6	0.2	0.1	0.2
STD	0.4	0.0	0.1	0.2	0.4	0.1	0.3	0.3	0.1	0.6	0.7	0.5	0.3	0.9
Orange HMB	0.7	0.2	1.3	0.6	0.9	0.5	0.6	1.6	0.2	0.1	0.3	0.2	0.2	0.4
STD	0.2	0.0	0.3	0.6	0.6	0.0	0.4	0.6	0.3	0.0	1.1	1.1	0.7	0.6
Cityzen	0.4	0.6	0.5	0.5	0.8	0.1	0.2	0.7	0.5	0.2	0.3	0.7	0.8	0.2
STD	0.2	0.6	0.0	0.1	0.2	0.3	0.0	0.2	0.5	0.0	0.6	0.8	0.7	0.0
Cityzen Speed	1.6	0.3	1.3	0.0	0.0	1.0	0.1	0.7	0.8	0.6	0.0	0.3	0.4	0.1
STD	0.2	0.1	0.3	0.1	0.1	0.3	0.6	0.5	0.3	0.6	0.3	0.3	0.1	0.1
Tour Populair	0.5	0.8	1.2	0.8	1.1	1.5	2.3	1.9	1.4	0.8	0.6	1.4	0.8	0.5
STD	0.3	0.8	0.4	0.1	0.8	0.3	0.3	0.5	0.1	0.4	0.4	0.5	0.1	1.1
Puur NL	0.8	0.4	0.7	1.1	1.3	0.7	1.0	1.7	0.9	0.8	1.0	0.8	0.8	0.3
STD	0.7	0.8	0.1	0.5	0.5	0.6	0.1	0.4	0.2	0.3	0.3	0.3	0.3	0.5
Van Stael	0.7	1.1	0.5	0.6	0.6	0.1	0.7	0.6	0.4	0.8	0.3	0.3	0.4	0.6
STD	0.0	0.2	0.1	0.3	0.3	0.6	0.6	0.5	0.1	0.2	0.1	0.1	0.0	0.3

Figure D4: Differences between the scores for each bicycle between the Gazelle- and the independent-participants

E

Rider-Bicycle Model

Geometry File

Figure E.1.
Geometry file of the Puur NL, frame size 54

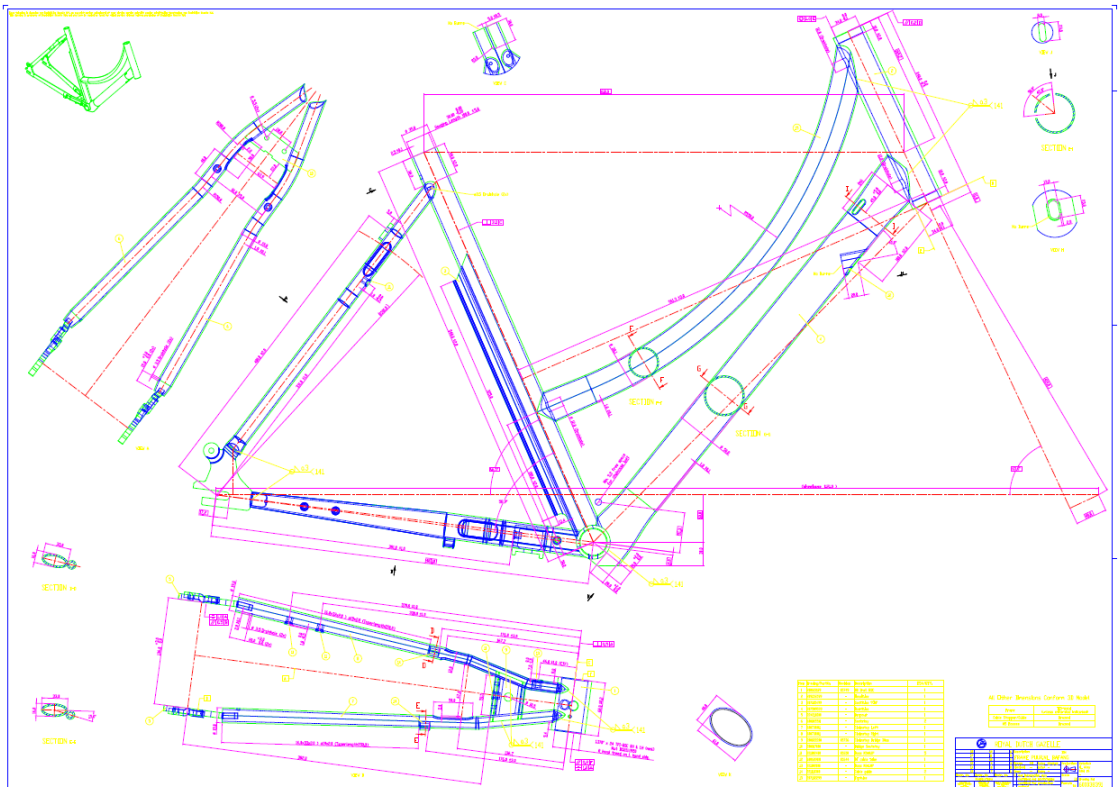


Figure E1: Geometry document of the Puur NL D54

WHEELS

Not all wheels are measured. Therefore the other wheels are scaled with the known wheels for their mass and moment of inertia. The Ami, Balance, Orange HFP, Orange HMB and Cityzen Speed are fully known. The front wheels of the Puur NL and Van Stael are also known. From the Tour Populair only the weight of the front wheel is known. The wheels of the Orange, Cityzen, Tour Populair and the rear wheels of the Puur NL and Van Stael have to be scaled. This is done with the use of pictures and a list of information about the wheels (figure E.2.). Figure E.3. shows the end result of which wheels are used for the scaling.

Fiets	Diameter	Naaf Voor	Naaf achter	Overige
Cityzen Speed		28standard + schijfrem	cassette + sch	Hoge velg
Cityzen		28standard + schijfrem	nexus + sch of cassette +sch	hoge velg
Puur NL		28dynamo	nexus	
Orange		28dynamo	nexus	
Orange HFP		28panasonic motor	nexus	
Orange HMB		28standard	nexus	
Tour Poplulair		28standard roller brake	sturmey archey	1 wandig old
Van Stael		28standard	nexus	hoog
Balance		24panasonic motor	nexus	
Ami		26standard	nexus	

Figure E2: Information about the naves of the wheels and possible extra options (in Dutch)

Actual wheels		Measured wheels used for scaling
Ami		
	Front	Ami Front
	Rear	Ami Rear
Balance		
	Front	Balance Front
	Rear	Balance Rear
Orange		
	Front	Cityzen Speed Front
	Rear	Orange HMB Rear
Orange HFP		
	Front	Orange HFP Front
	Rear	Orange HFP Rear
Orange HMB		
	Front	Orange HMB Front
	Rear	Orange HMB Rear
Cityzen		
	Front	Cityzen Speed Front
	Rear	Cityzen Speed Rear
Cityzen Speed		
	Front	Cityzen Speed Front
	Rear	Cityzen Speed Rear
Tour Populair		
	Front	Cityzen Speed Front
	Rear	Cityzen Speed Rear
Puur NL		
	Front	Puur NL Front
	Rear	Cityzen Speed Front / Oeange HMB Rear (mass comparison)
Van Stael		
	Front	Van Stael Front
	Rear	Orange HMB Front / Orange HFP Rear (mass comparison)

Figure E3: The first column shows the actual wheels, the second column shown the wheels with which the actual wheels are scaled.

ORANGE

Figure E.4. and E.5.

The front wheel of the Orange has a dynamo, where the Orange HMB has a standard front wheel. The front wheel of the Orange includes more mass. The Cityzen Speed with disk brakes has almost the same weight as the Puur NL with dynamo, but the Puur NL has larger tiers (so more weight); 2.25 kg voor te Cityzen Speed versus 2.55 kg for the Puur NL. Because the Orange has a dynamo as well, and the Puur NL is comparable with the Cityzen except for the weight, the front wheel of the Orange will be scaled with the Cityzen Speed front wheel. Besides the 'addition' to the wheel, the wheels only differ 4 mm in diameter, which is less than with the Puur NL. The wheel is scaled on diameter:

$$\text{Moment of Inertia}_O = \frac{d_O}{d_{CS}} \qquad \text{Moment of Inertia}_{CS}$$

The rear wheel of the Orange is the same as the rear wheel of the HBM. This is copied 1 on 1.

Cityzen

Figure E.6. and E.7.

The wheels of the Cityzen Speed and Cityzen speed are equal. The values for both wheels are equal.

Tour Populair

Figure E.8. and E.9.

Because the Tour Populair has completely different wheels than all the others (old type of bicycle), it is difficult to compare the wheels to other wheels. Just as with the Cityzen Speed, the Tour Populair has extra attributes within the wheel (see figures). Because of that and because there is no alternative, the wheels of the Tour Populair are scaled with the wheels of the Cityzen Speed with differences in diameter and mass ratio between the front and rear wheel.

$$ratio_{f/r} = \frac{m_{front,CS}}{m_{rear,CS}}$$

$$m_{rear,TP} = m_{front,TP} * ratio_{f/r}$$

The same is done for the moment of inertia for the front and rear wheel, where both diameter and mass are taken into account.

$$I_{TP} = I_{CS} \frac{m_{TP}}{m_{CS}} \frac{d_{TP}}{d_{CS}}$$

Puur NL

Figure E.10. and E.11.

To scale for the rear wheel of the Puur NL, the front wheel should also be matched. The Puur NL can only be matched with the Orange or the Cityzen Speed, since those are the only bicycles with a different nave in regular wheels. The wheels of the Orange are scaled with the Cityzen Speed and Orange HMB and thus difficult to compare with the Puur NL. But, because those are most similar based on looks and nave, the Puur NL wheels are scaled with the Orange, and thus with the front wheel of the Cityzen Speed and the rear wheel of the Orange HMB.

The ratio between the weight of the front wheel of the Cityzen Speed and the rear wheel of the Orange HMB is applied to the wheels of the Puur NL to find the rear wheel mass. After that there is scaled for the moment of inertia.

$$m_{rear,PNL} = m_{front,PNL} \frac{m_{rear,HMB}}{m_{front,CS}}$$

$$I_{rear,PNL} = I_{front,PNL} \frac{m_{rear,PNL}}{m_{front,PNL}}$$

Van Stael

Figure E.12. and E.13.

The same case as for the Puur NL accounts for the Van Stael, there are 2 bicycles used to scale for the wheels of the Van Stael. The front wheel of the Orange HMB has a standard nave at a 28 inch wheel as well, so this one is used to match the front wheel of the Van Stael. As the Orange HFP has the most simplistic rear wheel of all bicycles, based on looks and nave, this one is matched with the rear wheel of the Van Stael, which has also not additions to the wheel. Exactly the same calculations are used for the Van Stael as for the Puur NL.

$$m_{rear,VS} = m_{front,VS} \frac{m_{rear,HFP}}{m_{front,HMB}}$$

$$I_{rear,VS} = I_{front,VS} \frac{m_{rear,VS}}{m_{front,VS}}$$

Rear Rack

Figure E.14. and E.15.

The Solid Works files of the Balance and the Tour Populair appeared to be incomplete. The other bicycles are compared to the two to find a matching rear rack. The Ami matched the Balance and the Puur NL matched the Tour Populair best.

Figure E4: Front wheels. Left: Cityzen Speed. Right: Orange

Figure E5: Rear wheels. Left: Orange HMB. Right: Orange

Figure E6: Front wheels. Left: Cityzen Speed. Right: Cityzen

Figure E7: Rear wheels. Left: Cityzen Speed. Right: Cityzen

Figure E8: Front wheels. Left: Tour Populair. Right: Cityzen Speed

Figure E9: Rear wheels. Left: Tour Populair. Right: Cityzen Speed

Figure E10: Front wheels. Left: Puur NL. Right: Cityzen Speed

Figure E11: Rear wheels. Left: Puur NL. Right: Orange HMB

Figure E12: Front wheels. Left: Van Stael. Right: Orange HMB

Figure E13: Rear wheels. Left: Van Stael. Right: Orange HFP

Figure E14: Rear rack. Left: Balance. Right: Ami

Figure E15: Rear rack. Left: Tour Populair. Right: Puur NL

JBIK6 MATLAB

```
%%%%%%%%%%%%%%
% JB7Carlijn %
%%%%%%%%%%%%%%
clear all
close all

[values, text, raw] = xlsread('JBike 6 File');
Bicycle = text(2:end,1); Participant = text(2:end,2); Head_Angle = values(:,1);
Wheel_base = values(:,2); Trail = values(:,3); FW_diameter = values(:,4);
FW_mass = values(:,5); FW_Ixx_Iyy = values(:,6); FW_Izz = values(:,7);
RW_diameter = values(:,8); RW_mass = values(:,9); RW_Ixx_Iyy = values(:,10);
RW_Izz = values(:,11); Frame_COM_X = values(:,12); Frame_COM_Y = values(:,13);
Frame_mass = values(:,14); Frame_I11 = values(:,15); Frame_I22 = values(:,16);
Frame_Izz = values(:,17); Frame_Angle = values(:,18); Rear_Rack_COM_X = values(:,19);
Rear_Rack_COM_Y = values(:,20); Rear_Rack_mass = values(:,21); Rear_Rack_I11 = values(:,22);
Rear_Rack_I22 = values(:,23); Rear_Rack_Izz = values(:,24); Rear_Rack_Angle = values(:,25);
Steer_COM_X = values(:,26); Steer_COM_Y = values(:,27); Steer_mass = values(:,28);
Steer_I11 = values(:,29); Steer_I22 = values(:,30); Steer_Izz = values(:,31);
Steer_Angle = values(:,32); Basket_COM_X = values(:,33); Basket_COM_Y = values(:,34);
Basket_mass = values(:,35); Basket_I11 = values(:,36); Basket_I22 = values(:,37);
Basket_Izz = values(:,38); Basket_Angle = values(:,39); Rider_COM_X = values(:,40);
Rider_COM_Y = values(:,41); Rider_mass = values(:,42); Rider_I11 = values(:,43);
Rider_I22 = values(:,44); Rider_Izz = values(:,45); Rider_Angle = values(:,46);

Velocity_Free = values(:,48);
Freq_Free = values(:,49);
Freq_2 = values(:,50);
Freq_7 = values(:,51);

for counter = 1:99

% set the bicycle parameters
[name, wheelbase, head_angle, trail,Drearwheel, mrearwheel, Irearwheel, ...
    alphaIrearwheel, Dfrontwheel, mfrontwheel, Ifrontwheel, alphaIfrontwheel, ...
    mframe, xcmframe, ycmframe, Iframe, alphaIframe, mfork, ucmfork, vcmfork, ...
    Ifork, alphaIfork,mbasket, ucmbasket, vcmbasket, Ibasket, alphaIbasket, ...
    mrack, xcmrack, ycmrack, Irack, alphaIrack,mrider, xcmrider, ycmrider, ...
    Irider, alphaIrider,app_name ,app_version ,min_eig_val_stable_thresh, ...
    save_settings,gravity ,min_vel ,max_vel ,vel_steps ,angle_units,...
    draw_coord_axes,draw_axis_lines ,draw_grid_lines ,draw_additional_plots,...
    use_styles_in_plot4,draw_root_lines ,draw_weave_speed ,draw_capsize_speed, ...
    shade_stable_region ,draw_imaginary_parts,draw_legend,XY_UV ,min_uvcm_mag, ...
    work_dir,double_root_method,run_verbose ,real_eigen_color ,imag_eigen_color, ...
    weave_speed_color ,capsize_speed_color ,double_root_speed_color, ...
    stable_region_shade_color ,axis_color,plot_background_color ,real_eigen_symbol, ...
    imag_eigen_symbol ,weave_speed_line_type ,capsize_speed_line_type, ...
    double_root_speeds_line_type ,real_eigen_size ,imag_eigen_size, ...
    weave_speed_size ,capsize_speed_size ,double_root_speeds_size] = ...
    JB7ini_Carlijn(Bicycle(counter), Participant(counter), Head_Angle(counter), ...
    Wheel_base(counter), Trail(counter), FW_diameter(counter), FW_mass(counter), ...
    FW_Ixx_Iyy(counter), FW_Izz(counter) ,RW_diameter(counter),RW_mass(counter), ...
    RW_Ixx_Iyy(counter) ,RW_Izz(counter) ,Frame_COM_X(counter) ,Frame_COM_Y(counter), ...
    Frame_mass(counter),Frame_I11(counter),Frame_I22(counter) ,Frame_Izz(counter),...
    Frame_Angle(counter) ,Rear_Rack_COM_X(counter) ,Rear_Rack_COM_Y(counter) ,...
    Rear_Rack_mass(counter) ,Rear_Rack_I11(counter) ,Rear_Rack_I22(counter),...
    Rear_Rack_Izz(counter) ,Rear_Rack_Angle(counter),Steer_COM_X(counter),...
    Steer_COM_Y(counter),Steer_mass(counter),Steer_I11(counter) ,Steer_I22(counter), ...
    Steer_Izz(counter) ,Steer_Angle(counter) ,Basket_COM_X(counter),...
    Basket_COM_Y(counter),Basket_mass(counter),Basket_I11(counter),...
    Basket_I22(counter),Basket_Izz(counter) ,Basket_Angle(counter),...
    Rider_COM_X(counter),Rider_COM_Y(counter),Rider_mass(counter),...
    Rider_I11(counter),Rider_I22(counter),Rider_Izz(counter), Rider_Angle(counter));
% calculate the linearized equations of motion
JBmck

%% draw the bike and eigenvalue plot
% you can skip this whole part or not
```

```
skip = 0;
if not(skip)
  JBfig
  % calculate the weave and capsize speed
  JBvcrit
  % calculate double root speed(s)
  if double_root_method == 0 % 0 = analytically
    JBdoubleroots; % analytical (uses Symbolic tool box)
  end
  % calculate the igenvalues and eigenvectors for a speed range
  JBeig
  % calculate double root speed(s)
  if double_root_method == 1 % 1 = interpolate from eigenvalues
    JBroots;
  end
  % plot only the Real part of the eigenvalues
  figure
  JBrev
end

%% determine eigenvalues for three forward speeds
vnomArray = [2 7 Velocity_Free(counter)];
EigenVals = [];
SteerStiffness = [];
for k = 1:length(vnomArray)
  vnom = vnomArray(k);
  M = M0;
  C = vnom.*C1;
  K = K0+vnom^2.*K2;
  E = polyeig(K,C,M);
  % sort the eigenvalues:real parts from large (unstable) to small (stable)
  [val,ind] = sort(real(E),'descend');
  EigenVals(k,:) = E(ind).';
  % determine steerstiffnes at steer frequency fsteer, use fsteer = 0 or
      % fsteer(k) = [ ... ] (also change saving option!)
  fsteer = 0*sqrt(-1);  %[Freq_2 Freq_7 Freq_Free]%
  A = fsteer^2.*M + fsteer.*C + K;  %fsteer(k)
  % response to a unit steer torque
  q = A\[0;1];
  % steerstiffnes is abs(1/q(2)), phase is angle(1/q(2))
  SteerStiffness(k) = abs(1/q(2));

end


vnomArray
EigenVals
SteerStiffness

EigenImag = imag(EigenVals);
EigenReal = real(EigenVals);

Eigenvalues_2 = [EigenReal(1,1) EigenImag(1,1) EigenReal(1,2) EigenImag(1,2) ...
    EigenReal(1,3) EigenImag(1,3) EigenReal(1,4) EigenImag(1,4)];
Eigenvalues_7 = [EigenReal(2,1) EigenImag(2,1) EigenReal(1,2) EigenImag(2,2)...
    EigenReal(2,3) EigenImag(2,3) EigenReal(2,4) EigenImag(2,4)];
Eigenvalues_5_5 = [EigenReal(3,1) EigenImag(3,1) EigenReal(3,2) EigenImag(3,2)...
    EigenReal(3,3) EigenImag(3,3) EigenReal(3,4) EigenImag(3,4)];

EigenValues(counter,:) = [Eigenvalues_2 Eigenvalues_7 Eigenvalues_5_5];
Stiffness(counter,:) = [Bicycle(counter) Participant(counter) SteerStiffness(1)...
    SteerStiffness(2) SteerStiffness(3)];

path = 'C:\Users\carli\Documents\Afstudeer Project\Project\Jbike6\JBike 6 Data';
filename = char(strcat(Bicycle(counter),' - ',  Participant(counter),...
    ' - Bicycle with Rider figure.png'));
saveas(figure(1), fullfile(path,filename));
filename = char(strcat(Bicycle(counter),' - ',  Participant(counter),...
    ' - Stability figure.png'));
saveas(figure(2), fullfile(path,filename));
```

```
filename = char(strcat(Bicycle(counter),' - ',  Participant(counter),...
    ' - JBike 6 vnomArray.xls'));
xlswrite(fullfile(path,filename), vnomArray);
filename = char(strcat(Bicycle(counter),' - ',  Participant(counter),...
    ' - JBike 6 EigenVals.xls'));
xlswrite(fullfile(path,filename), EigenVals);
filename = char(strcat(Bicycle(counter),' - ',  Participant(counter),...
    ' - JBike 6 SteerStiffness.xls'));
xlswrite(fullfile(path,filename), SteerStiffness);
filename = char(strcat(Bicycle(counter),' - ',  Participant(counter),...
    ' - JBike 6 MCK.xls'));
xlswrite(fullfile(path,filename), [M C K]);

clearvars -except counter Bicycle Participant Head_Angle Wheel_base Trail FW_diameter ...
    FW_mass FW_Ixx_Iyy FW_Izz RW_diameter RW_mass RW_Ixx_Iyy RW_Izz Frame_COM_X ...
    Frame_COM_Y Frame_mass Frame_I11 Frame_I22 Frame_Izz Frame_Angle Rear_Rack_COM_X ...
    Rear_Rack_COM_Y Rear_Rack_mass Rear_Rack_I11 Rear_Rack_I22 Rear_Rack_Izz ...
    Rear_Rack_Angle Steer_COM_X Steer_COM_Y Steer_mass Steer_I11 Steer_I22 Steer_Izz ...
    Steer_Angle Basket_COM_X Basket_COM_Y Basket_mass Basket_I11 Basket_I22 Basket_Izz ...
    Basket_Angle Rider_COM_X Rider_COM_Y Rider_mass Rider_I11 Rider_I22 Rider_Izz ...
    Rider_Angle Velocity_Free Freq_Free Freq_2 Freq_7 Stiffness EigenValues path
close all
end

filename = 'SteerStiffnes 2-7-Free freq 0 GOED' ; %freq x
path = 'C:\Users\carli\Documents\Afstudeer Project\Project\Jbike6\JBike 6 Data';
xlswrite(fullfile(path,filename), Stiffness)

filename = 'Eigenvalues 2-7-5_5'
xlswrite(fullfile(path,filename), EigenValues)



%%%%%%%%%%%%%%%%%%
% JB7ini_Carlijn %
%%%%%%%%%%%%%%%%%%
function [name, wheelbase, head_angle, trail,Drearwheel, mrearwheel, Irearwheel,...
    alphaIrearwheel, Dfrontwheel, mfrontwheel, Ifrontwheel, alphaIfrontwheel, ...
    mframe, xcmframe, ycmframe, Iframe, alphaIframe, mfork, ucmfork, vcmfork,...
    Ifork, alphaIfork,mbasket, ucmbasket, vcmbasket, Ibasket, alphaIbasket,...
    mrack, xcmrack, ycmrack, Irack, alphaIrack,mrider, xcmrider, ycmrider, ...
    Irider, alphaIrider, app_name ,app_version ,min_eig_val_stable_thresh ,...
    save_settings,gravity ,min_vel ,max_vel ,vel_steps ,angle_units,...
    draw_coord_axes,draw_axis_lines ,draw_grid_lines ,draw_additional_plots,...
    use_styles_in_plot4,draw_root_lines ,draw_weave_speed ,draw_capsize_speed,...
    shade_stable_region ,draw_imaginary_parts,draw_legend,XY_UV ,min_uvcm_mag,...
    work_dir,double_root_method,run_verbose ,real_eigen_color ,imag_eigen_color , ...
    weave_speed_color ,capsize_speed_color ,double_root_speed_color ,...
    stable_region_shade_color ,axis_color,plot_background_color,real_eigen_symbol,...
    imag_eigen_symbol ,weave_speed_line_type ,capsize_speed_line_type ,...
    double_root_speeds_line_type ,real_eigen_size ,imag_eigen_size ,...
    weave_speed_size ,capsize_speed_size ,double_root_speeds_size] = ...
    JB7ini_Carlijn(Bicycle, Participant, Head_Angle, Wheel_base, Trail, ...
    FW_diameter, FW_mass, FW_Ixx_Iyy, FW_Izz ,RW_diameter,RW_mass ,RW_Ixx_Iyy,...
    RW_Izz ,Frame_COM_X ,Frame_COM_Y,Frame_mass,Frame_I11,Frame_I22 ,Frame_Izz ,...
    Frame_Angle ,Rear_Rack_COM_X ,Rear_Rack_COM_Y ,Rear_Rack_mass ,Rear_Rack_I11 ,...
    Rear_Rack_I22,Rear_Rack_Izz ,Rear_Rack_Angle,Steer_COM_X ,Steer_COM_Y,...
    Steer_mass,Steer_I11 ,Steer_I22 ,Steer_Izz ,Steer_Angle ,Basket_COM_X,...
    Basket_COM_Y,Basket_mass,Basket_I11,Basket_I22,Basket_Izz ,Basket_Angle,...
    Rider_COM_X,Rider_COM_Y,Rider_mass,Rider_I11,Rider_I22,Rider_Izz, Rider_Angle)

% Created by Arend L. Schwab and Jim Papadopoulos, 18-Jun-2003
% Copyright ? 2003-2015 Schwab, Papadopoulos, Ruina, & Dressel
% Delft University of Technology & Cornell University

% Modification History
% 11/01/05 AED - new setting draw_root_lines
%              - New user parameter: vel_steps
% 11/03/05 AED - New user parameter: min_vel
% 11/06/05 AED - New constants XY_UV and min_uvcm_mag
%              - Change Swinn to Schwinn
```

```
% 11/08/05 AED - New bike configuration subdirectory
% 11/09/05 AED - Define plot colors here
%               - toggle between double root finding methods
% 11/10/05 AED - Define more colors and dot sizes
%               - Switch color designations to RGB
%               - keep name and version in single place: JBini.m', ...
%               - setting to save user settings, or not
% 11/11/05 AED - Define more colors, sizes, and types
%               - Option to use styles in plot4 window
% 11/15/05 AED - Option to display legend or not
%               - option to run in 'verbose' mode or not
% 10/11/06 AED - Option to shade stable region and pick color
%               - Set minimum eigenvalue for stability threshold
% 09/09/12 AED - Update version number
% 16/05/17 ALS - command line verion for carlijn with seperate
%                bicyce and rider files strat with JB6....
%-----------------------------------------------------------------------
% constants
%-----------------------------------------------------------------------

app_name = 'JBike6';
app_version ='February 8, 2015';

min_eig_val_stable_thresh = -1e-15;
%-----------------------------------------------------------------------
% user modifiabale settings
%-----------------------------------------------------------------------
save_settings = 0;            % 1 = save user settings to configuration file

gravity = 9.81;            % gravity (meters/second/second)

min_vel = 0.0;
max_vel = 10.0;               % default maximum velocity to investigate
vel_steps = 101;

angle_units = 2;              % 1 = radians, 2 = degrees
draw_coord_axes = 1;          % 1 = yes, 0 = no
draw_axis_lines = 1;          % 1 = yes, 0 = no
draw_grid_lines = 1;          % 1 = yes, 0 = no
draw_additional_plots = 0;    % 1 = yes, 0 = no
use_styles_in_plot4 = 1;      % 1 = yes, 0 = no
draw_root_lines = 0;          % 1 = yes, 0 = no
draw_weave_speed = 1;         % 1 = yes, 0 = no
draw_capsize_speed = 1;       % 1 = yes, 0 = no
shade_stable_region = 1;      % 1 = yes, 0 = no
draw_imaginary_parts = 0;     % 1 = yes, 0 = no
draw_legend = 1;              % 1 = yes, 0 = no
XY_UV = 1;                    % 1 = UV, 0 = XY
min_uvcm_mag = 1e-6;          % minimum u or v of cm magnitude
work_dir = 'JBini_files';     % where all the bike configuration files are kept
double_root_method = 1;       % 1 = interpolate from eigenvalues, 0 = analytically
run_verbose = 0;              % 1 = yes, 0 = no

%-----------------------------------------------------------------------
% styles
%-----------------------------------------------------------------------

% options are:
%
%    [0 0 1]  blue          .  point              -     solid
%    [0 1 0]  green         o  circle             :     dotted
%    [1 0 0]  red           x  x-mark             -.    dashdot
%    [0 1 1]  cyan          +  plus               --    dashed
%    [1 0 1]  magenta       *  star             (none)  no line
%    [1 1 0]  yellow        s  square
%    [0 0 0]  black         d  diamond
%    [1 1 1]  white         v  triangle (down)
%                           ^  triangle (up)
%                           <  triangle (left)
%                           >  triangle (right)
%                           p  pentagram
```

```
%                           h  hexagram

real_eigen_color = [0 0 1]; % blue
imag_eigen_color = [0 1 1]; % cyan
weave_speed_color = [0 1 0]; % green
capsize_speed_color = [1 0 0]; % red
double_root_speed_color = [1 0 1]; % magenta
stable_region_shade_color = [.9 1 .9]; %light green
axis_color = [0 0 0];              % black
plot_background_color = [1 1 1];   % white

real_eigen_symbol = '.';
imag_eigen_symbol = '.';
weave_speed_line_type = '-';
capsize_speed_line_type = '-';
double_root_speeds_line_type = '-';

real_eigen_size = 5;
imag_eigen_size = 5;
weave_speed_size = 1;
capsize_speed_size = 1;
double_root_speeds_size = 1;

%----------------------------------------------------------------------
% Bike parameters
%----------------------------------------------------------------------
%leave this in so user can still run just JBike6.m without user interface
%these values get overwritten when JBini_*.m is called from JBike6GUI.m

%You may change values, but do not remove nor change variable names.
%Unused variables (front basket, for example) must be set to zero.
%All units are meters, kilograms, and radians

%Read the help file (JBhelp.htm) for more details about parameters and
%their limitations, sign conventions, units, and illustrations.

    %----------------------------------------------------------------------
    % Schwinn Crown
    %----------------------------------------------------------------------
% get the Bicycle data
[name, wheelbase, head_angle, trail,Drearwheel, mrearwheel, Irearwheel, ...
    alphaIrearwheel, Dfrontwheel, mfrontwheel, Ifrontwheel, alphaIfrontwheel,...
    mframe, xcmframe, ycmframe, Iframe, alphaIframe, mfork, ucmfork, vcmfork, ...
    Ifork, alphaIfork,mbasket, ucmbasket, vcmbasket, Ibasket, alphaIbasket, ...
    mrack, xcmrack, ycmrack, Irack, alphaIrack,mrider, xcmrider, ycmrider, ...
    Irider, alphaIrider] = JB7BicyclePlusRider(Bicycle, Participant, Head_Angle, ...
    Wheel_base, Trail, FW_diameter, FW_mass, FW_Ixx_Iyy, FW_Izz ,RW_diameter,...
    RW_mass ,RW_Ixx_Iyy ,RW_Izz ,Frame_COM_X ,Frame_COM_Y,Frame_mass,Frame_I11,...
    Frame_I22 ,Frame_Izz ,Frame_Angle ,Rear_Rack_COM_X ,Rear_Rack_COM_Y ,Rear_Rack_mass ,...
    Rear_Rack_I11 ,Rear_Rack_I22,Rear_Rack_Izz ,Rear_Rack_Angle,Steer_COM_X ,Steer_COM_Y,...
    Steer_mass,Steer_I11 ,Steer_I22 ,Steer_Izz ,Steer_Angle ,Basket_COM_X,Basket_COM_Y,...
    Basket_mass,Basket_I11,Basket_I22,Basket_Izz ,Basket_Angle,Rider_COM_X,Rider_COM_Y,...
    Rider_mass,Rider_I11,Rider_I22,Rider_Izz, Rider_Angle);



%%%%%%%%%%%%%%%%%%%%%%%%
% JB7BicyclePlusRider %
%%%%%%%%%%%%%%%%%%%%%%%%
function [name, wheelbase, head_angle, trail,Drearwheel, mrearwheel, Irearwheel,...
    alphaIrearwheel, Dfrontwheel, mfrontwheel, Ifrontwheel, alphaIfrontwheel,...
    mframe, xcmframe, ycmframe, Iframe, alphaIframe, mfork, ucmfork, vcmfork,...
    Ifork, alphaIfork,mbasket, ucmbasket, vcmbasket, Ibasket, alphaIbasket, ...
    mrack, xcmrack, ycmrack, Irack, alphaIrack,mrider, xcmrider, ycmrider, ...
    Irider, alphaIrider] = JB7BicyclePlusRider(Bicycle, Participant, Head_Angle,...
    Wheel_base, Trail, FW_diameter, FW_mass, FW_Ixx_Iyy, FW_Izz ,...
    RW_diameter,RW_mass ,RW_Ixx_Iyy ,RW_Izz ,Frame_COM_X ,Frame_COM_Y,Frame_mass,...
    Frame_I11,Frame_I22 ,Frame_Izz ,Frame_Angle ,Rear_Rack_COM_X,Rear_Rack_COM_Y,...
    Rear_Rack_mass ,Rear_Rack_I11 ,Rear_Rack_I22,Rear_Rack_Izz ,Rear_Rack_Angle,...
    Steer_COM_X ,Steer_COM_Y,Steer_mass,Steer_I11 ,Steer_I22 ,Steer_Izz ,...
    Steer_Angle ,Basket_COM_X,Basket_COM_Y,Basket_mass,Basket_I11,Basket_I22,...
```

```
    Basket_Izz ,Basket_Angle,Rider_COM_X,Rider_COM_Y,Rider_mass,Rider_I11,...
    Rider_I22,Rider_Izz, Rider_Angle)

% this defines the bicycle with the rider

% system name
name = [Participant 'on' Bicycle];

%% bicycle
% wheelbase is distance between the rear and front contact pnt
wheelbase = Wheel_base; %meters
% lambda is the angle between the steer-axis and the y-axis,
% positive along the z-axis (ccw)
%%lambda = 0.332; %radians
head_angle = deg2rad(Head_Angle);

lambda = pi/2-head_angle;
% trail is the distance from front contact pnt to the intersection of
% the steer axis with the ground.
trail = Trail;

%rearwheel
% Diameter of the rear wheel
Drearwheel = RW_diameter;
% mass of the rear wheel
mrearwheel = RW_mass;
% Moments of inertia of the rear wheel along the principal axis 1, 2 and z
Irearwheel = [RW_Ixx_Iyy RW_Ixx_Iyy RW_Izz];
% alpha is angle between 1-axis and x-axis, positive along z-axis (ccw)
alphaIrearwheel = 0;

% frontwheel
Dfrontwheel = FW_diameter;
mfrontwheel = FW_mass;
% Ifrontwheel = [I11 I22 Izz]
Ifrontwheel = [FW_Ixx_Iyy FW_Ixx_Iyy FW_Izz];
alphaIfrontwheel = 0;

% frame
mframe = Frame_mass;
xcmframe = Frame_COM_X;
ycmframe = Frame_COM_Y;
% Iframe = [I11 I22 Izz]
Iframe = [Frame_I11 Frame_I22 Frame_Izz];
alphaIframe = deg2rad(Frame_Angle);

% fork
mfork = Steer_mass;
% the cm of the fork is easured in the uv-coordinate system
% uv is located at the intersection of the steer axis with the ground
% and the axis are rotated over the angle lamda
ucmfork = Steer_COM_X;
vcmfork = Steer_COM_Y;
% Ifork = [I11 I22 Izz];
Ifork = [Steer_I11 Steer_I22 Steer_Izz];
% alpha angle between 1-axis and x-axis, positive along z-axis (ccw)
alphaIfork = lambda;

% basket
mbasket = Basket_mass;
ucmbasket = Basket_COM_X;
vcmbasket = Basket_COM_Y;
% Ibasket = [I11 I22 Izz];
Ibasket = [Basket_I11 Basket_I22 Basket_Izz];
% alpha angle between 1-axis and x-axis, positive along z-axis (ccw)
alphaIbasket = deg2rad(Basket_Angle);

% rack
mrack = Rear_Rack_mass;
xcmrack = Rear_Rack_COM_X;
ycmrack = Rear_Rack_COM_Y;
```

```
% Irack = [I11 I22 Izz]
Irack = [Rear_Rack_I11 Rear_Rack_I22 Rear_Rack_Izz];
alphaIrack = deg2rad(Rear_Rack_Angle);


%% rider
mrider = Rider_mass;
% the position of the cm is measure from the origin at the rear contact pnt
xcmrider = Rider_COM_X;
ycmrider = Rider_COM_Y;
% Irider = [I11 I22 Izz]
Irider = [Rider_I11 Rider_I22 Rider_Izz];
% alpha angle between 1-axis and x-axis, positive along z-axis (ccw)
alphaIrider = deg2rad(Rider_Angle);
```

BICYCLE AND RIDER DETAILS

Figure E.16.

Details of the participants as they are put into JBike6.

Figure E.17.

Details of the bicycles as they are put into JBike6.

JBIKE6 OUTPUT

Figure E.18.

Eigenvalue output from JBike6. The **X**'s mark the unusable data.

Figure E.19.

Steer stiffness output from JBike6. The **X**'s mark the unusable data.

Ami

	COM X	COM Y	Mass	I11	I22	Izz	Angle	Free m/s	Hz 2 m/s	Hz Free	Hz 7 m/s
P1	0.399	1.034	70	7.384	1.514	6.931	-16	6.900	0.503	1.078	1.168
P2	0.335	1.026	80	9.038	1.853	8.483	-7	6.829	0.625	1.152	1.131
P3	0.361	1.069	96	10.845	2.224	10.180	-7	6.471	0.877	1.324	1.325
P4	0.312	1.091	70	7.908	1.622	7.423	-11	6.917	0.836	1.250	1.638
P5	0.358	1.051	68	8.031	1.647	7.539	-13	6.242	0.504	1.095	1.003
P6	0.283	1.088	75	9.858	2.021	9.253	-11	6.466	1.529	1.300	1.298
P7	0.327	1.054	95	10.732	2.201	10.074	-8	5.702	0.713	1.095	1.159
P8	0.386	1.060	91	11.225	2.302	10.537	-13	6.352	0.500	1.097	0.988
P9	0.332	1.044	110	14.761	3.027	13.856	-8	6.015	0.638	1.054	1.362
P10	0.328	1.089	67	7.400	1.517	6.946	-15	5.649	1.011	0.715	1.127

Balance

	COM X	COM Y	Mass	I11	I22	Izz	Angle	Free m/s	Hz 2 m/s	Hz Free	Hz 7 m/s
P1	0.381	1.068	70	7.384	1.514	6.931	-6	7.301	0.887	1.140	1.146
P2	0.371	1.074	80	9.038	1.853	8.483	-2	6.543	1.265	0.688	0.500
P3	0.344	1.125	96	10.845	2.224	10.180	-4	6.725	0.687	1.322	1.266
P4	0.371	1.113	70	7.908	1.622	7.423	-5	6.174	0.726	1.169	1.236
P5	0.352	1.079	68	8.031	1.647	7.539	-10	6.543	0.822	0.690	0.798
P6	0.274	1.127	75	9.858	2.021	9.253	-11	6.004	0.553	0.768	1.307
P7	0.395	1.065	95	10.732	2.201	10.074	-9	5.822	0.641	1.118	1.121
P8	0.398	1.071	91	11.225	2.302	10.537	-14	6.716	0.778	1.134	1.142
P9	0.322	1.096	110	14.761	3.027	13.856	-10	5.317	0.712	1.094	1.111
P10	0.365	1.101	67	7.400	1.517	6.946	-14	5.865	0.506	1.072	1.139

Orange

	COM X	COM Y	Mass	I11	I22	Izz	Angle	Free m/s	Hz 2 m/s	Hz Free	Hz 7 m/s
P1	0.364	1.137	70	7.384	1.514	6.931	-11	5.570	0.558	0.920	1.059
P2	0.317	1.129	80	9.038	1.853	8.483	-5	5.346	1.137	0.817	0.784
P3	0.353	1.133	96	10.845	2.224	10.180	-4	5.049	1.201	1.142	1.083
P4	0.297	1.137	70	7.908	1.622	7.423	-10	5.741	1.346	1.237	1.482
P5	0.354	1.129	68	8.031	1.647	7.539	-16	4.901	0.536	0.554	1.255
P6	0.286	1.174	75	9.858	2.021	9.253	-14	4.866	0.588	0.606	1.449
P7	0.346	1.096	95	10.732	2.201	10.074	-4	4.788	0.501	1.083	1.179
P8	0.360	1.133	91	11.225	2.302	10.537	-17	5.095	0.506	0.938	1.274
P9	0.320	1.166	110	14.761	3.027	13.856	-7	5.467	0.990	1.099	1.133
P10	0.356	1.120	67	7.400	1.517	6.946	-16	4.262	0.510	0.500	0.505

Orange HFP

	COM X	COM Y	Mass	I11	I22	Izz	Angle	Free m/s	Hz 2 m/s	Hz Free	Hz 7 m/s
P1	0.344	1.095	70	7.384	1.514	6.931	-10	7.036	0.695	1.205	1.210
P2	0.278	1.133	80	9.038	1.853	8.483	0	6.606	0.773	0.543	0.867
P3	0.262	1.136	96	10.845	2.224	10.180	-7	6.735	0.590	1.189	1.213
P4	0.297	1.137	70	7.908	1.622	7.423	-10	6.375	0.649	0.813	1.394
P5	0.265	1.136	68	8.031	1.647	7.539	-12	7.201	0.502	1.077	1.383
P6	0.252	1.138	75	9.858	2.021	9.253	-9	5.805	0.995	0.606	0.502
P9	0.251	1.151	110	14.761	3.027	13.856	-2	5.435	0.693	1.016	0.690

Orange HMB

	COM X	COM Y	Mass	I11	I22	Izz	Angle	Free m/s	Hz 2 m/s	Hz Free	Hz 7 m/s
P1	0.350	1.124	70	7.384	1.514	6.931	-11	6.780	0.738	1.100	0.958
P2	0.299	1.123	80	9.038	1.853	8.483	-1	6.394	0.961	0.528	0.811
P3	0.357	1.171	96	10.845	2.224	10.180	-2	6.424	0.721	1.237	1.236
P4	0.298	1.134	70	7.908	1.622	7.423	-12	6.909	0.755	1.274	1.253
P5	0.297	1.114	68	8.031	1.647	7.539	-13	6.394	0.571	1.279	1.252
P6	0.250	1.129	75	9.858	2.021	9.253	-13	5.123	0.500	0.622	0.511
P7	0.346	1.096	95	10.732	2.201	10.074	-12	5.666	0.696	1.184	1.210
P8	0.380	1.113	91	11.225	2.302	10.537	-14	5.060	0.568	0.936	1.082
P9	0.260	1.128	110	14.761	3.027	13.856	-5	6.763	0.561	1.210	1.245
P10	0.321	1.139	67	7.400	1.517	6.946	-16	6.182	0.675	1.211	1.027

Cityzen

	COM X	COM Y	Mass	I11	I22	Izz	Angle	Free m/s	Hz 2 m/s	Hz Free	Hz 7 m/s
P1	0.422	1.106	70	7.384	1.514	6.931	-25	6.827	1.244	2.147	2.113
P2	0.366	1.111	80	9.038	1.853	8.483	-20	6.460	0.839	1.085	1.215
P3	0.367	1.115	96	10.845	2.224	10.180	-19	5.409	1.118	1.196	1.263
P4	0.363	1.112	70	7.908	1.622	7.423	-29	7.165	0.853	1.374	1.540
P5	0.400	1.116	68	8.031	1.647	7.539	-28	6.788	0.877	1.459	1.366
P6	0.395	1.132	75	9.858	2.021	9.253	-29	5.640	0.501	1.117	0.512
P7	0.429	1.119	95	10.732	2.201	10.074	-27	6.405	0.507	1.192	1.325
P8	0.432	1.120	91	11.225	2.302	10.537	-32	5.667	0.505	1.056	2.385
P9	0.399	1.164	110	14.761	3.027	13.856	-22	5.277	0.505	1.156	1.424
P10	0.383	1.112	67	7.400	1.517	6.946	-27	5.138	0.680	0.941	1.216

Cityzen Speed

	COM X	COM Y	Mass	I11	I22	Izz	Angle	Free m/s	Hz 2 m/s	Hz Free	Hz 7 m/s
P1	0.433	1.126	70	7.384	1.514	6.931	-26	8.631	1.217	1.353	1.110
P2	0.377	1.146	80	9.038	1.853	8.483	-22	7.811	0.560	1.259	0.755
P3	0.412	1.166	96	10.845	2.224	10.180	-24	8.426	0.666	1.406	1.167
P4	0.363	1.112	70	7.908	1.622	7.423	-29	8.159	0.701	1.260	1.276
P5	0.392	1.152	68	8.031	1.647	7.539	-26	7.542	0.762	0.813	0.804
P6	0.324	1.159	75	9.858	2.021	9.253	-24	8.658	0.509	1.674	1.158
P7	0.384	1.105	95	10.732	2.201	10.074	-22	7.826	0.908	1.318	1.031
P8	0.461	1.075	91	11.225	2.302	10.537	-29	7.679	0.635	1.207	1.043
P9	0.365	1.150	110	14.761	3.027	13.856	-18	6.263	0.656	0.981	1.171

Tour Populair

	COM X	COM Y	Mass	I11	I22	Izz	Angle	Free m/s	Hz 2 m/s	Hz Free	Hz 7 m/s
P1	0.303	1.116	70	7.384	1.514	6.931	-3	5.489	0.512	0.925	1.082
P2	0.253	1.137	96	10.845	2.224	10.180	0	4.616	0.778	0.873	1.289
P3	0.253	1.113	68	8.031	1.647	7.539	-7	5.076	0.511	1.174	1.358
P5	0.223	1.153	75	9.858	2.021	9.253	-9	5.275	1.282	1.055	1.356
P6	0.214	1.139	110	14.761	3.027	13.856	-2	5.522	0.000	1.222	1.212
P9	0.268	1.144	67	7.400	1.517	6.946	-10	5.381	0.505	0.508	0.760
P10											

Puur NL

	COM X	COM Y	Mass	I11	I22	Izz	Angle	Free m/s	Hz 2 m/s	Hz Free	Hz 7 m/s
P1	0.322	1.128	70	7.384	1.514	6.931	-4	6.289	1.048	1.020	1.053
P2	0.256	1.106	80	9.038	1.853	8.483	6	5.450	1.194	0.728	0.661
P3	0.307	1.095	96	10.845	2.224	10.180	1	5.000	0.864	1.383	0.981
P4	0.228	1.119	70	7.908	1.622	7.423	4	5.742	0.504	1.438	0.921
P5	0.241	1.122	68	8.031	1.647	7.539	-2	5.129	0.504	0.654	1.018
P6	0.269	1.117	75	9.858	2.021	9.253	4	6.106	0.836	0.849	1.368
P7	0.261	1.113	95	10.732	2.201	10.074	-5	5.288	1.069	1.020	1.085
P10	0.323	1.112	67	7.400	1.517	6.946	-9	5.222	0.515	0.501	0.560

Van Stael

	COM X	COM Y	Mass	I11	I22	Izz	Angle	Free m/s	Hz 2 m/s	Hz Free	Hz 7 m/s
P1	0.389	1.078	70	7.384	1.514	6.931	-25	7.037	0.858	2.338	3.146
P2	0.349	1.082	80	9.038	1.853	8.483	-19	5.533	1.035	1.185	1.275
P3	0.353	1.121	96	10.845	2.224	10.180	-17	6.170	0.981	1.199	1.398
P4	0.343	1.121	70	7.908	1.622	7.423	-25	6.600	0.825	1.345	1.372
P5	0.361	1.074	68	8.031	1.647	7.539	-34	4.894	0.570	1.006	1.504
P6	0.312	1.128	75	9.858	2.021	9.253	-26	5.980	0.972	0.502	1.515
P7	0.374	1.119	95	10.732	2.201	10.074	-30	5.759	0.511	1.116	1.262
P8	0.392	1.076	91	11.225	2.302	10.537	-32	5.447	0.630	1.077	1.240
P9	0.361	1.103	110	14.761	3.027	13.856	-23	6.297	0.511	1.181	1.266
P10	0.336	1.119	67	7.400	1.517	6.946	-31	5.981	0.584	0.885	3.191

Figure E16: Details of all participants as put into JBike6

Ami

General		Wheels	Front Wheel	Rear Wheel
Head Angle [°]	69	Diameter [m]	0.661	0.661
Wheel base [m]	1.072	Mass [kg]	2.1	3.8
Trail [m]	0.068	$I_{xx\ \&\ Iyy}$ [kgm^2]	0.073	0.073
Fork Offset [m]	0.055	I_{zz} [kgm^2]	0.146	0.147

Components	Rear Frame	Front Frame
CoM X (U) [m]	0.355	0.025
CoM Y (V) [m]	0.513	0.870
Mass [kg]	15.042	3.430
I_{11} [kgm^2]	0.545	0.250
I_{22} [kgm^2]	1.534	0.043
I_{zz} [kgm^2]	2.041	0.287
Principle Angle [°]	-13.415	17.946

Balance

General		Wheels	Front Wheel	Rear Wheel
Head Angle [°]	66	Diameter [m]	0.609	0.609
Wheel base [m]	1.201	Mass [kg]	5.45	3.5
Trail [m]	0.075	$I_{xx\ \&\ Iyy}$ [kgm^2]	0.056	0.061
Fork Offset [m]	0.05	I_{zz} [kgm^2]	0.113	0.123

Components	Rear Frame	Front Frame
CoM X (U) [m]	0.303	0.019
CoM Y (V) [m]	0.523	0.818
Mass [kg]	14.930	3.670
I_{11} [kgm^2]	0.409	0.290
I_{22} [kgm^2]	1.882	0.050
I_{zz} [kgm^2]	2.246	0.333
Principle Angle [°]	12.035	23.780

Orange

General		Wheels	Front Wheel	Rear Wheel
Head Angle [°]	68.5	Diameter [m]	0.704	0.704
Wheel base [m]	1.120	Mass [kg]	2.25	2.63
Trail [m]	0.08	$I_{xx\ \&\ Iyy}$ [kgm^2]	0.083	0.077
Fork Offset [m]	0.055	I_{zz} [kgm^2]	0.167	0.145

Components	Rear Frame	Front Frame
CoM X (U) [m]	0.381	0.018
CoM Y (V) [m]	0.526	0.858
Mass [kg]	11.717	3.018
I_{11} [kgm^2]	0.415	0.229
I_{22} [kgm^2]	1.114	0.047
I_{zz} [kgm^2]	1.494	0.269
Principle Angle [°]	4.226	20.716

Orange HFP

General		Wheels	Front Wheel	Rear Wheel
Head Angle [°]	68.5	Diameter [m]	0.704	0.704
Wheel base [m]	1.120	Mass [kg]	4.705	2.63
Trail [m]	0.08	$I_{xx\ \&\ Iyy}$ [kgm^2]	0.090	0.077
Fork Offset [m]	0.055	I_{zz} [kgm^2]	0.163	0.145

Components	Rear Frame	Front Frame
CoM X (U) [m]	0.238	0.024
CoM Y (V) [m]	0.594	0.781
Mass [kg]	16.833	4.454
I_{11} [kgm^2]	0.594	0.331
I_{22} [kgm^2]	1.890	0.053
I_{zz} [kgm^2]	2.422	0.377
Principle Angle [°]	-10.481	21.050

Orange HMB

General		Wheels	Front Wheel	Rear Wheel
Head Angle [°]	68.5	Diameter [m]	0.704	0.704
Wheel base [m]	1.120	Mass [kg]	1.993	4.175
Trail [m]	0.08	$I_{xx\ \&\ Iyy}$ [kgm^2]	0.082	0.076
Fork Offset [m]	0.055	I_{zz} [kgm^2]	0.157	0.140

Components	Rear Frame	Front Frame
CoM X (U) [m]	0.312	0.024
CoM Y (V) [m]	0.537	0.781
Mass [kg]	15.746	4.454
I_{11} [kgm^2]	0.543	0.331
I_{22} [kgm^2]	1.682	0.053
I_{zz} [kgm^2]	2.180	0.377
Principle Angle [°]	-20.083	21.050

Cityzen

General		Wheels	Front Wheel	Rear Wheel
Head Angle [°]	70.5	Diameter [m]	0.7	0.7
Wheel base [m]	1.114	Mass [kg]	2.25	2.75
Trail [m]	0.08	$I_{xx\ \&\ Iyy}$ [kgm^2]	0.083	0.077
Fork Offset [m]	0.06	I_{zz} [kgm^2]	0.167	0.154

Components	Rear Frame	Front Frame
CoM X (U) [m]	0.369	0.053
CoM Y (V) [m]	0.560	0.838
Mass [kg]	8.271	2.788
I_{11} [kgm^2]	0.227	0.153
I_{22} [kgm^2]	0.982	0.044
I_{zz} [kgm^2]	1.175	0.188
Principle Angle [°]	22.520	13.019

Cityzen Speed

General		Wheels	Front Wheel	Rear Wheel
Head Angle [°]	70.5	Diameter [m]	0.7	0.7
Wheel base [m]	1.114	Mass [kg]	2.25	2.75
Trail [m]	0.08	$I_{xx\ \&\ Iyy}$ [kgm^2]	0.083	0.077
Fork Offset [m]	0.06	I_{zz} [kgm^2]	0.167	0.154

Components	Rear Frame	Front Frame
CoM X (U) [m]	0.448	0.032
CoM Y (V) [m]	0.480	0.809
Mass [kg]	14.595	3.332
I_{11} [kgm^2]	0.454	0.183
I_{22} [kgm^2]	0.920	0.034
I_{zz} [kgm^2]	1.343	0.208
Principle Angle [°]	-16.599	13.484

Tour Populair

General		Wheels	Front Wheel	Rear Wheel
Head Angle [°]	65.5	Diameter [m]	0.723	0.723
Wheel base [m]	1.138	Mass [kg]	3.1	3.79
Trail [m]	0.086	$I_{xx\ \&\ Iyy}$ [kgm^2]	0.106	0.098
Fork Offset [m]	0.072	I_{zz} [kgm^2]	0.212	0.195

Components	Rear Frame	Front Frame
CoM X (U) [m]	0.482	-0.040
CoM Y (V) [m]	0.577	0.973
Mass [kg]	11.283	4.224
I_{11} [kgm^2]	0.265	0.386
I_{22} [kgm^2]	1.025	0.074
I_{zz} [kgm^2]	1.270	0.447
Principle Angle [°]	20.070	22.218

Puur NL

General		Wheels	Front Wheel	Rear Wheel
Head Angle [°]	65	Diameter [m]	0.73	0.73
Wheel base [m]	1.121	Mass [kg]	2.55	2.98
Trail [m]	0.126	$I_{xx\ \&\ Iyy}$ [kgm^2]	0.099	0.116
Fork Offset [m]	0.04	I_{zz} [kgm^2]	0.198	0.231

Components	Rear Frame	Front Frame
CoM X (U) [m]	0.479	0.050
CoM Y (V) [m]	0.532	0.981
Mass [kg]	11.426	4.249
I_{11} [kgm^2]	0.213	0.361
I_{22} [kgm^2]	1.077	0.149
I_{zz} [kgm^2]	1.265	0.447
Principle Angle [°]	27.978	8.184

Van Stael

General		Wheels	Front Wheel	Rear Wheel
Head Angle [°]	73	Diameter [m]	0.686	0.686
Wheel base [m]	1.051	Mass [kg]	1.75	2.22
Trail [m]	0.047	$I_{xx\ \&\ Iyy}$ [kgm^2]	0.067	0.085
Fork Offset [m]	0.055	I_{zz} [kgm^2]	0.134	0.171

Components	Rear Frame	Front Frame
CoM X (U) [m]	0.422	0.018
CoM Y (V) [m]	0.515	0.796
Mass [kg]	7.743	2.661
I_{11} [kgm^2]	0.165	0.107
I_{22} [kgm^2]	0.587	0.037
I_{zz} [kgm^2]	0.736	0.139
Principle Angle [°]	31.857	22.870

Figure E17: Details of all bicycles as put into JBike6

		Ami	Balance	Orange	Orange HFP	Orange HMB	Cityzen	Cityzen Speed	Tour Populair	Puur NL	Van Stael
Real Eigenvalue 2 m/s	1	3.2147	3.0524	3.0927	2.7700	3.0138	2.9551	3.0131	2.9170	3.0800	2.8095
	2	3.0692	3.0790	3.0106	2.6101	2.8869	2.8951	2.9411	X	2.8988	2.7772
	3	3.2765	3.1290	3.2662	2.7066	3.1784	3.0488	3.1952	2.9319	3.2127	2.9141
	4	2.8928	2.9803	2.8749	2.6280	2.8552	2.8016	2.8402	X	2.7588	2.6480
	5	3.0250	2.9566	3.0448	2.5423	2.8447	2.8585	2.8496	2.7538	2.8063	2.7066
	6	2.8189	2.7755	2.8552	2.5277	2.7361	2.8940	2.7167	2.6801	2.8669	2.5822
	7	3.1774	3.3319	3.2542	X	3.2599	3.2401	3.1402	X	3.0968	3.0068
	8	3.3311	3.3072	3.3172	X	3.3025	3.1908	3.3409	X	X	3.0302
	9	3.2604	3.1816	3.2315	2.6742	2.9606	3.2113	3.1223	2.8438	X	3.0560
	10	2.9340	2.9897	3.0606	X	2.9086	2.8201	X	2.7941	3.0869	2.6088
Imaginary Eigenvalue 2 m/s	1	1.5444	1.4686	1.4470	1.4145	1.4168	1.4441	1.5801	1.4155	1.2509	1.5571
	2	1.5541	1.4616	1.4456	1.3738	1.4270	1.4100	1.5306	X	1.2638	1.5341
	3	1.5008	1.3965	1.4029	1.3438	1.3840	1.3768	1.4595	1.3614	1.2349	1.5064
	4	1.5072	1.4532	1.4269	1.3623	1.3840	1.3740	1.5193	X	1.2362	1.4862
	5	1.5445	1.4417	1.4258	1.3175	1.3849	1.4098	1.5473	1.3715	1.2301	1.4562
	6	1.4739	1.3614	1.3709	1.3122	1.3313	1.3683	1.4758	1.3157	1.2741	1.4105
	7	1.4994	1.4023	1.4307	X	1.3489	1.3265	1.5023	X	1.1888	1.4087
	8	1.4771	1.3870	1.3068	X	1.3357	1.3039	1.4899	X	X	1.4249
	9	1.4796	1.3465	1.3283	1.3472	1.3547	1.2775	1.4527	1.3180	X	1.4121
	10	1.5036	1.4304	1.4341	X	1.3812	1.4073	X	1.3652	1.2391	1.4453
Real Eigenvalue Free speed	1	-0.2460	-1.1576	-0.4152	-0.4581	-0.4227	-0.1197	0.0520	-0.5680	-0.2354	0.0019
	2	-0.2516	-0.2784	-0.1467	-0.9019	-0.7121	-0.2131	-0.0103	X	0.5224	-0.3938
	3	-0.6350	-0.2862	0.5221	-0.8950	-0.9055	-0.0678	-0.0210	0.7347	1.1646	-0.2622
	4	-0.1214	-0.0467	-0.7491	-1.0081	-0.2683	-0.0026	0.0602	X	0.1046	-0.0107
	5	-0.4269	-0.4243	0.4420	-0.2158	-0.5036	-0.0934	-0.0100	-0.1604	0.7178	-0.0864
	6	-0.2457	0.1234	0.4202	-0.2114	0.3017	-0.4206	0.1020	-0.3819	-0.1826	-0.1207
	7	-0.5307	0.4962	0.7841	X	0.1587	-0.4673	-0.0676	X	0.9159	-0.4559
	8	-0.7137	-0.2592	0.6437	X	0.8160	-0.0446	-0.1478	X	X	-0.1780
	9	-0.7447	0.8674	0.1759	0.3520	-0.6788	0.3929	-0.6764	-0.3531	X	-0.3325
	10	-0.7690	0.2152	1.1406	X	-0.7082	-0.0979	X	-0.4825	0.8574	-0.1043
Real Eigenvalue 7 m/s	1	-0.2173	-0.9916	-0.2137	-0.4795	-0.3263	-0.0850	-0.1442	-0.0469	-0.7273	-0.0023
	2	-0.1999	-0.7738	-0.2168	-0.4706	-0.3287	-0.0793	-0.1421	X	-0.7412	-0.0054
	3	-0.3616	-0.5516	-0.4190	-0.5984	-0.6466	-0.1643	-0.2805	-0.1073	-0.7712	-0.0685
	4	-0.1025	-0.9512	-0.1135	-0.3874	-0.2361	-0.0271	-0.0762	X	-0.5033	0.0365
	5	-0.1521	-1.0338	-0.1841	-0.3003	-0.2201	-0.0534	-0.0937	0.0379	-0.5059	0.0279
	6	-0.0899	-0.9009	-0.1291	-0.3428	-0.1866	-0.0862	-0.0578	0.0555	-0.7313	0.0478
	7	-0.2878	-0.5463	-0.3952	X	-0.5716	-0.2437	-0.2356	X	-0.7055	-0.0894
	8	-0.3660	-0.5572	-0.3847	X	-0.6144	-0.2263	-0.3141	X	X	-0.0941
	9	-0.4187	-0.3885	-0.4733	-0.8481	-0.5084	-0.2977	-0.2997	-0.0900	X	-0.1379
	10	-0.1056	-1.0222	-0.1796	X	-0.2510	-0.0351	X	0.0223	-0.6746	0.0526

Figure E18: Real eigenvalues for each participant on each bicycle at 2 m/s, free speed and 7 m/s and imaginary eigenvalues at 2 m/s. The **X**'s mark the unusable data

		Ami	Balance	Orange	Orange HFP	Orange HMB	Cityzen	Cityzen Speed	Tour Populair	Puur NL	Van Stael
Steer Stiffness 2 m/s Peak Hz	1	7.5279	9.6665	7.8635	8.9504	8.1582	6.1940	6.7715	8.3259	13.7883	4.0048
	2	7.3935	10.3430	7.9115	8.6697	8.1064	6.2174	6.8194	X	13.2044	4.1112
	3	8.9184	11.1572	9.7627	9.3860	10.3757	7.1625	8.2595	9.2229	16.5541	4.8119
	4	6.4727	9.5578	6.8991	8.3092	7.4185	5.6137	6.0744	X	11.4911	3.6691
	5	6.8966	9.1292	7.5545	7.7347	7.2703	5.8586	6.2538	7.3248	11.6299	3.7168
	6	6.3813	8.5234	7.0863	7.9608	7.0190	6.2504	5.9517	7.2351	13.0561	3.6156
	7	8.2590	12.0029	9.5404	X	10.0445	7.9517	7.7921	X	14.9506	4.9956
	8	8.9607	11.7123	9.5148	X	10.3689	7.7285	8.5289	X	X	4.9922
	9	9.3280	11.6960	10.1501	9.9671	9.2617	8.5088	8.4122	9.0900	X	5.4924
	10	6.4814	9.2260	7.5066	X	7.5390	5.6345	X	7.5131	13.4269	3.5022
Steer Stiffness Free speed Peak Hz	1	8.3058	5.4827	4.8665	6.7652	6.7105	8.3718	19.3869	4.6634	8.5038	8.8934
	2	7.6495	5.1730	4.5854	4.6254	5.1646	6.6041	13.2964	X	7.9285	3.6957
	3	6.6880	5.5003	6.3488	5.0803	6.3476	4.5245	17.1403	5.4850	12.1340	5.3368
	4	7.9775	4.8068	4.2761	4.3038	6.8299	9.7674	15.6898	X	6.0175	6.9178
	5	5.6858	4.3458	4.6756	6.9449	5.1280	8.0531	11.8672	3.6283	7.1425	2.5561
	6	5.9223	3.8301	4.0771	3.2376	3.7022	4.2891	19.0870	3.4489	7.0857	4.5663
	7	5.0723	7.6164	6.4593	X	6.2037	6.8007	13.2137	X	10.0538	4.2977
	8	6.5634	6.4302	6.2499	X	7.0799	5.2032	12.5386	X	X	3.8081
	9	5.8299	7.9513	6.1705	5.1257	5.9636	5.4760	6.0738	4.3815	X	5.6315
	10	4.1494	4.9870	5.2810	X	4.8363	3.4653	X	4.0197	9.0716	4.7208
Steer Stiffness 7 m/s Peak Hz	1	6.7096	5.1863	6.6876	5.5345	5.9760	6.9138	6.9470	7.7378	8.8600	6.5218
	2	6.4128	5.5516	6.4442	4.9131	5.6247	6.7291	6.7203	X	7.7295	6.4107
	3	6.7483	6.0320	6.9769	5.0997	6.6341	6.7201	6.9562	7.3087	10.3505	6.3024
	4	6.3030	4.9654	6.3647	5.0534	5.5987	6.7143	6.6797	X	6.8260	6.4417
	5	6.4715	4.6889	6.5863	4.7929	5.5850	6.8026	6.7653	7.7248	7.0913	6.3783
	6	6.1323	3.8490	6.2080	4.6637	5.2807	6.6686	6.4947	7.5412	7.6797	6.2886
	7	6.4742	7.0622	6.9140	X	6.6452	6.9850	6.8389	X	9.0158	6.2192
	8	6.8692	6.8462	6.9728	X	6.8968	6.8502	7.2336	X	X	6.2363
	9	6.6665	6.4420	6.8461	5.0115	5.6477	6.8909	6.7384	6.9853	X	6.1676
	10	6.3698	4.8220	6.6268	X	5.7206	6.7634	X	7.7446	8.7716	6.4183
Steer Stiffness 2 m/s 0 Hz	1	7.5262	9.6596	7.8596	8.9292	8.1469	6.1830	6.7751	8.3071	13.7414	4.0008
	2	7.3925	10.3397	7.9076	8.6474	8.0967	6.2043	6.8217	X	13.1505	4.1071
	3	8.9236	11.1563	9.7656	9.3613	10.3770	7.1509	8.2648	9.2040	16.5118	4.8103
	4	6.4682	9.5531	6.8893	8.2836	7.4018	5.5949	6.0698	X	11.4289	3.6622
	5	6.8941	9.1188	7.5468	7.7019	7.2520	5.8442	6.2551	7.2987	11.5685	3.7058
	6	6.3746	8.5063	7.0745	7.9289	6.9957	6.2348	5.9473	7.2054	13.0058	3.6044
	7	8.2595	12.0021	9.5414	X	10.0348	7.9408	7.7939	X	14.8950	4.9873
	8	8.9641	11.7093	9.5085	X	10.3618	7.7139	8.5318	X	X	4.9832
	9	9.3325	11.6908	10.1514	9.9478	9.2504	8.4999	8.4176	9.0662	X	5.4867
	10	6.4759	9.2159	7.4987	X	7.5223	5.6188	X	7.4881	13.3762	3.4919
Steer Stiffness Free speed 0 Hz	1	2.4799	4.9157	4.5140	3.5235	3.2864	1.2602	1.2592	3.8382	8.5818	0.0208
	2	2.3373	6.5650	4.8095	3.7887	3.7374	1.7533	0.1733	X	9.2711	1.7126
	3	4.4189	7.0573	7.0708	4.2239	6.0002	4.1545	0.4534	6.1685	13.3970	1.7177
	4	1.2150	6.2406	3.2303	3.8440	2.2505	0.0323	1.1826	X	7.0289	0.0939
	5	2.7902	5.3555	5.0654	1.8592	2.9220	0.9525	0.1491	3.5289	8.2084	1.9299
	6	1.7945	5.2963	4.5647	4.2701	4.3327	2.9792	2.4328	3.0171	8.0313	0.7031
	7	4.8381	9.0958	7.1752	X	6.7542	3.6218	1.1219	X	11.2447	2.3579
	8	4.6867	7.7193	6.7649	X	7.8647	4.4405	2.2996	X	X	2.7001
	9	5.4680	9.2577	6.8490	6.7431	4.2044	5.6692	4.2494	4.3503	X	2.2546
	10	3.1535	6.2714	5.7472	X	3.5241	3.0221	X	3.1744	10.0250	0.6254
Steer Stiffness 7 m/s 0 Hz	1	2.3192	5.3299	2.2891	3.5829	2.9347	0.9840	1.6464	0.6116	7.2107	0.0249
	2	2.0576	5.9635	2.2367	3.1307	2.7780	0.8965	1.5739	X	6.3596	0.0582
	3	3.5713	6.6815	4.1228	3.7722	5.0915	1.8112	3.0178	1.3096	9.8363	0.7248
	4	1.0761	5.1833	1.2042	2.8315	2.1014	0.3073	0.8533	X	4.5933	0.3967
	5	1.6117	4.7546	1.9702	2.2078	1.9695	0.6127	1.0593	0.4943	4.7901	0.3000
	6	0.9226	3.9995	1.3350	2.3846	1.6086	0.9662	0.6333	0.7065	6.2796	0.5072
	7	2.8603	7.6267	3.9148	X	4.7814	2.6907	2.5496	X	8.0404	0.9311
	8	3.6690	7.3418	3.8872	X	5.1601	2.4747	3.4296	X	X	0.9801
	9	3.9278	7.1787	4.4100	4.3009	3.8108	3.1572	3.0929	1.0568	X	1.4077
	10	1.1200	4.8562	1.9357	X	2.2648	0.4010	X	0.2922	6.8962	0.5680

Figure E19: Steer stiffness for each participant on each bicycle at 2 m/s, free speed and 7 m/s for the peak frequency of steering and no steering (0 Hz). The **X**'s mark the unusable data

HQM MATLAB

```
%%%%%%%%%%%%%%%%%%%%%%
% ieee_steer_Carlijn %
%%%%%%%%%%%%%%%%%%%%%%

% This script loads in the data used for the IEEE paper and creates the plots.
clc; close all; clear all

bikes = {'Ami', 'Balance', 'Orange', 'OrangeHMB', 'OrangeHFP', 'Cityzen',...
    'CityzenSpeed', 'TourPopulair', 'PuurNL', 'VanStael'};

data = load_bikes_Carlijn(bikes, 'Steer')

%% Finding the optimal Gains for each bicycle for each speed: Do once with
    %gain guess for each bicycle, then with gains for one bicycle
 steerData = generate_data('VanStael', 7.5, ...
                           'input', 'Steer', ...
                           'gainGuess', [61.0000,-0.0630,6.3400,0.3450,0.0650]);

Gains = [kDelta kPhiDot kPhi kPsi kY]

%% Use always, except when optimal gains need to be found first

create_ieee_paper_plots_Carlijn(data, steerData)


%%%%%%%%%%%%%%%%%%%%%%
% load_bikes_Carlijn %
%%%%%%%%%%%%%%%%%%%%%%

function data = load_bikes(bikes, input)
% function data = load_bikes(bikes, input)
% Returns the data for a set of bicycles at three speeds.
%
% Parameters
% ----------
% bikes : cell array
%   A cell array that lists the bicyle short names.
% input : string
%   'Steer' or 'Roll'
%
% Returns
% -------
% data : structure
%   A structure containg a node for each bicycle and each speed.

speeds = [2.0, 5.5, 7.0];
speedNames = {'Slow', 'Medium', 'Fast'};

% these are the gains that were selected manually by Ron Hess, taken from
% the paper

gains.Ami.Slow    = [5.2734  -12.8894    2.0490    0.1858    0.2199];
gains.Balance.Slow    = [6.7412,  -10.6494,    2.0792 ,   0.1828,   0.2178];
gains.Orange.Slow  = [4.5139,  -14.4851,    2.0486,    0.1898,    0.2180];
gains.OrangeHMB.Slow      = [4.6215,  -16.4084,    2.0188,    0.1930,    0.2202];
gains.OrangeHFP.Slow        = [10.9266,  -10.6697,    2.1032,    0.1753,    0.2183];
gains.Cityzen.Slow      = [5.3042,   -0.0081,  292.1501,    0.0553,    0.17976];
gains.CityzenSpeed.Slow    = [3.1842,   -0.1664,    7.7619,    0.0860,    0.1873];
gains.TourPopulair.Slow  = [6.0755,   -0.2938,    5.5430,    0.0851,    0.1930];
gains.PuurNL.Slow     = [5.4829,   -0.1861,   10.8696,    0.0838,    0.1835];
gains.VanStael.Slow       = [5.3774,   -0.0690,   27.8346,    0.0568,    0.1855];


gains.Ami.Medium  = [ 50.7070    0.0230   19.3445    1.0233    0.1010];
gains.Balance.Medium  = [  78.1025    0.0246   20.4525    1.0289    0.1004];
gains.Orange.Medium = [  52.7893    0.0193   24.4832    1.0306    0.1010];
gains.OrangeHMB.Medium    = [ 47.6081    0.0212   22.1111    1.0207    0.10111];
```

```
gains.OrangeHFP.Medium      = [ 112.2440    0.0269   17.3247    1.0097    0.1004];
gains.Cityzen.Medium     = [ 58.8532    0.0205   22.5852    1.0441    0.1010];
gains.CityzenSpeed.Medium = [ 38.3041    0.0084   58.1064    1.0125    0.1016];
gains.TourPopulair.Medium    = [ 77.5026    0.0206   23.8470    1.0244    0.1008];
gains.PuurNL.Medium      = [ 87.3751    0.0120   38.6500    1.0258    0.1010];
gains.VanStael.Medium     = [42.8803    0.0094   85.1965    0.7519    0.1373];



gains.Ami.Fast   = [ 53.6323    0.0932    3.0085    1.3136    0.0780];
gains.Balance.Fast   = [ 90.1989    0.0997    3.3400    1.2897    0.0772];
gains.Orange.Fast  = [ 57.1377    0.0986    3.0189    1.3247    0.0779];
gains.OrangeHMB.Fast     = [  41.4163    0.0950    3.0981    1.3182    0.0785];
gains.OrangeHFP.Fast       = [ 133.9923    0.0990    3.1798    1.2560    0.0770];
gains.Cityzen.Fast      = [  69.1120    0.1007    2.9164    1.3325    0.0776];
gains.CityzenSpeed.Fast  = [ 40.5916    0.1002    2.9152    1.3288    0.0786];
gains.TourPopulair.Fast     = [ 83.8969    0.1028    3.0618    1.3088    0.0775];
gains.PuurNL.Fast       = [ 100.2879    0.0945    3.0729    1.3141    0.0775];
gains.VanStael.Fast      = [ 58.9600    0.0933    2.9272    1.3515    0.0775];

% load the data for all speeds for all the bikes
for i = 1:length(bikes)
    for j = 1:length(speeds)
        data.(bikes{i}).(speedNames{j}) = ...
            generate_data(bikes{i}, speeds(j), 'input', input, ...
                          'gainGuess', gains.(bikes{i}).(speedNames{j}));
    end
end



%%%%%%%%%%%%%%%%%
% generate_data %
%%%%%%%%%%%%%%%%%

function data = generate_data(bike, speed, varargin)
% function data = generate_data(bike, speed, varargin)
% Generates data files for the human operator control model.
%
% Parameters
% ----------
% bike : char
%   The name of the bicycle model to use. This corresponds to a file in the
%   ./parameters directory named <bike>Par.txt.
% speed : double
%   The speed of the bicycle.
% varargin : pairs of strings and values
%   crossover : double (1 x 3), optional
%       The desired crossover frequencies in rad/s for the phi, psi and y
%       loops. The default for steer control is [2.0, 1.0, 0.5] and roll
%       control is [1.5, 0.75, 0.5].
%   input : char, optional
%       'Steer' or 'Roll'. 'Steer' is the default.
%   gains : double (1 x 5), optional
%       If gains are given this will manually override the search for the
%       optimal gains. In order kDelta, kPhiDot, kPhi, kPsi, kY.
%   gainGuess : double (1 x 5), optional
%       Provide these gains if you want a better starting guess for the
%       search algorithm. In order kDelta, kPhiDot, kPhi, kPsi, kY.
%   gainMuls : double (1 x 5), optional
%       General gain multipliers. The gains are applied starting at the
%       inner loop going out: kDelta, kPhiDot, kPhi, kPsi, kY. [1, 1, 1,
%       1, 1] is the default.
%   laneType : char, optional
%       'single' or 'double' for a single or double lane change maneuver.
%       'double' is the default.
%   neuroFreq : double, optional
%       The neuromuscular frequency. The default is 30 rad/sec.
%   plot : boolean, optional
%       If 1 basic plots will be shown, if 0 no plots will be shown. 0 is the
%       default.
```

```
%   simulate : boolean, optional
%       Default is true. If true the simulation results will be available in
%       the output.
%   loopTransfer : boolean, optional
%       Default is true. If true the open and closed loop transfer functions
%       will be available in the output.
%   handlingQuality : boolean, optional
%       Default is true. If true the handling quality metric will be
%       available in the output.
%   forceTransfer : cell array of strings, optional
%       The default is {'Delta', 'PhiDot', 'Phi', 'Psi', 'Y', 'Tdelta'(or
%       'Tphi')}. The output will contain the transfer functions from
%       lateral force to steer angle, roll rate, roll angle, yaw angle,
%       lateral deviation and steer torque (or roll torque if input is
%       'Roll'). If the array is empty, then none of the transfer functions
%       are computed.  You can also provide a subset of the available
%       transfer functions.
%   stateSpace : cell array, optional
%       This cell array should contain the state space matrices {A, B, C, D}
%       for the whipple pull force bicycle model. Be sure that the `bike`
%       and `speed` match this state space model. If it isn't specified, the
%       state space calculation happens inside generate_data. This option
%       allows the potentially time intensive calculation of the state space
%       to happen outside of generate data. But be careful with it because
%       the arguments `bike` and `speed` become redundant.
%   fullSystem : boolean, optional
%       If true the state space matrices for the entire system with lateral
%       force as the only input are returned.
%   display : boolean, optional
%       If true the function will display information to screen as the
%       function runs else it will display nothing. The default is true.
%
% Returns
% -------
% data : structure
%   Complete data set from the model and simulations.
%   closedLoops : structure
%       Closed loop transfer functions for each loop.
%   command : matrix (n, 5)
%       The commanded input to each loop.
%   forceTF : structure
%       Transfer functions from pull force to various outputs.
%   gainMuls : matrix (5, 1)
%       Multipliers for each gain.
%   handlingMetric : structure
%       Transfer function for the handling quality metric.
%   inputs : matrix (n, 3)
%       Inputs to the bicycle model.
%   modelPar : structure
%       Simulink model input variables.
%       A : matrix (11, 11)
%           The state matrix. Refer to the documentation in
%           whipple_pull_force_abdc.m for details.
%       B : matrix (11, 3)
%           The input matrix.
%       C : matrix
%           The output matrix.
%       D : matrix
%           The feed forward matrix.
%       speed : float
%           The forward speed of the bicycle.
%       track : vector
%           The lateral coordinates of the desired track.
%       stoptime : float
%           The final time of the simulation.
%       initialConditions : matrix (11, 1)
%           The initial conditions for the simulation.
%       neuroNum : float
%           The numerator of the neuromuscular transfer function.
%       neuroDen : matrix (1, 3)
%           The coefficients to the denominator of the neuromuscular transfer
```

```
%           function.
%       pathFilterNum : float
%           The numerator of the path filter transfer function.
%       pathFileterDen : matrix (1, 3)
%           The coefficients to the denominator of the path filter transfer
%           function.
%       handlingFilterNum : float
%           The numerator of the handling quality metric filter transfer function.
%       handlingFileterDen : matrix (1, 3)
%           The coefficients to the denominator of the handling quality
%           metric filter transfer function.
%   openLoops : structure
%       Open loop transfer functions.
%   outputs : matrix (n, 18)
%       Outputs of the bicycle system.
%   outputsDots : matrix (n, 18)
%       Time derivatives of the outputs.
%   par : structure
%       Bicycle parameters.
%   path : matrix (n, 1)
%       Time delay adjusted path.
%   speed : float
%       Speed of bicycle.
%   time : matrix (n, 1)
%       Time.
%   system : structure
%       A : matrix (11, 11)
%           The state matrix.
%       B : matrix (11, 1)
%           The input matrix.
%       C : matrix (11, 1)
%           The output matrix.
%       D : matrix
%           The feed forward matrix.
%
% Examples
% --------
% % Generate the data set for the Benchmark bicycle at 5.0 m/s with roll as the
% % input.
% >>data = generate_data('Benchmark', 5.0, 'input', 'Roll');
%
% % Generate the data set for the Fisher bicycle at 7.5 m/s with steer input
% % and show the graphs.
% >>data = generate_data('Fisher', 7.5, 'input', 'Steer', 'plot', 1);
%
% % Generate the data set for the Browser bicycle at 2.5 m/s with steer as an
% % input and multiply the five gains by various values and show the graphs.
% >>data = generate_data('Browser', 2.5, 'plot', 1, 'gainMuls', [1.1, 1.1, 0.9, 1.0, 0.8])
%
% % Generate the data set for the Bianchi Pista bicycle at 7.5 m/s with steer as the
% % input and a single lane change as the manuever.
% >>data = generate_data('Pista', 7.5, 'laneType', 'single');

global CURRENT_DIRECTORY
% get the directory which this m-file is in
S = dbstack('-completenames');
[CURRENT_DIRECTORY, ~, ~] = fileparts(S(1).file);

% there are some unconnected ports in the simulink model that send out warnings
warning off

%% parse function arguments
% set the defaults for the optional arguments
defaults.crossover = [];
defaults.input = 'Steer';
defaults.laneType = 'double';
defaults.gains = [];
defaults.gainGuess = [];
defaults.gainMuls = [1, 1, 1, 1, 1];
defaults.neuroFreq = 30;
defaults.plot = 0;
```

```
defaults.simulate = 1;
defaults.loopTransfer = 1;
defaults.handlingQuality = 1;
defaults.forceTransfer = {'Delta', 'PhiDot', 'Phi', 'Psi', 'Y', 'Tdelta'};
defaults.stateSpace = {};
defaults.fullSystem = 1;
defaults.display = 1;

% load in user supplied settings
if size(varargin, 2) >= 1
    userSettings = varargin_to_structure(varargin);
else
    userSettings = struct();
end

% combine the defaults with the user settings
settings = overwrite_settings(defaults, userSettings);

global PRINT_TO_SCREEN
if settings.display
    PRINT_TO_SCREEN = 1;
else
    PRINT_TO_SCREEN = 0;
end

% show the bike and speed on the screen
display_if(sprintf(repmat('-', 1, 79)))
display_if(sprintf('%s at %1.2f m/s.', bike, speed))
display_if(sprintf(repmat('-', 1, 79)))

%% set model parameters
[modelPar, startLoop, par] = ...
    set_initial_model_parameters(bike, speed, settings);

% the name of the loops starting with the inner loop
loopNames = {'Delta', 'PhiDot', 'Phi', 'Psi', 'Y'};

%% set the gains
% if the user did not supply the gains, try to calculate them
if isempty(settings.gains)
    % give a warning that the program doesn't work well for low speeds
    if speed < 2.5
        display_if(sprintf(repmat('*', 1, 76)))
        display_if('Warning')
        display_if(sprintf(repmat('*', 1, 76)))
        s = ['The speed, %1.2f m/s, is less than 2.5 m/s. The PhiDot ', ...
             'loop often has a\nhard time converging. It is suggested ', ...
             'to supply the gains manually for these\nlower speeds.'];
        display_if(sprintf(s, speed))
        display_if(sprintf(repmat('*', 1, 76)))
    end
    % load the gain guesses
    if isempty(settings.gainGuess)
        pathToGainFile = [CURRENT_DIRECTORY filesep 'gains' filesep bike settings.input 'Gains.txt'];
        [modelPar.kDelta, modelPar.kPhiDot, modelPar.kPhi, ...
         modelPar.kPsi, modelPar.kY] = lookup_gains(pathToGainFile, speed);
    else
        modelPar.kDelta = settings.gainGuess(1);
        modelPar.kPhiDot = settings.gainGuess(2);
        modelPar.kPhi = settings.gainGuess(3);
        modelPar.kPsi = settings.gainGuess(4);
        modelPar.kY = settings.gainGuess(5);
    end
    % now calculate exact feedback gains using successive loop closure
    modelPar = exact_gains(startLoop, loopNames, modelPar, settings);
else % set the gains as the user specified
    modelPar.kDelta = settings.gains(1);
    modelPar.kPhiDot = settings.gains(2);
    modelPar.kPhi = settings.gains(3);
    modelPar.kPsi = settings.gains(4);
    modelPar.kY = settings.gains(5);
```

```
end

% scale the gains
k = {'kDelta', 'kPhiDot', 'kPhi', 'kPsi', 'kY'};
kString = '';
for i = 1:length(k)
    modelPar.(k{i}) = settings.gainMuls(i) * modelPar.(k{i});
    kString = [kString sprintf('%s = %1.3f\n                    ', ...
               k{i}, modelPar.(k{i}))];
end
display_if(['Gains are set to: ', strtrim(kString)])

%% store transfer function data
if settings.loopTransfer
    perturbTable = [zeros(1, 5) % do not perturb any loop
                    eye(5)]; % perturb each loop individually
    % all the loops are closed at first
    closedTable = ones(6, 5);

    if strcmp(settings.input, 'Roll')
        % don't feed back delta
        closedTable(:, 1) = zeros(6, 1);
    end

    update_model_variables(modelPar)

    % store the transfer functions for the closed loops
    for i = startLoop:length(loopNames)
        str = 'Finding the %s closed loop transfer function.';
        display_if(sprintf(str, loopNames{i}))
        modelPar.loopNumber = i;
        modelPar.perturb = perturbTable(i + 1, :);
        modelPar.closed = closedTable(i + 1, :);
        update_model_variables(modelPar)
        [num, den] = linmod_switch('WhippleModel');
        closedLoops.(loopNames{i}).num = num;
        closedLoops.(loopNames{i}).den = den;
    end

    % make a truth table for closing the loops sequentially
    closedTable = ~perturbTable;

    % don't feed back delta if looking at roll control
    if strcmp(settings.input, 'Roll')
        closedTable(:, 1) = zeros(6, 1);
    end

    % get the transfer functions for the open loops
    for i = startLoop:length(loopNames)
        str = 'Finding the %s open loop transfer function.';
        display_if(sprintf(str, loopNames{i}));
        modelPar.loopNumber = i;
        modelPar.perturb = perturbTable(i + 1, :);
        modelPar.closed = closedTable(i + 1, :);
        update_model_variables(modelPar);
        [num, den] = linmod_switch('WhippleModel');
        openLoops.(loopNames{i}).num = num;
        openLoops.(loopNames{i}).den = den;
    end

    % store the loop transfer functions
    data.closedLoops = closedLoops;
    data.openLoops = openLoops;

    if settings.plot
        display_if('Generating loop transfer plots.')
        figure()
        % go through each loop and plot the bode plot for the closed loops
        hold all
        for i = startLoop:length(loopNames)
            num = closedLoops.(loopNames{i}).num;
```

```
            den = closedLoops.(loopNames{i}).den;
            bode(tf(num, den), {0.1, 100.0})
        end
        legend(loopNames(startLoop:end))
        title('Closed loop transfer functions')
        hold off

        figure()
        % go through each loop and plot the open loop bode plot
        hold all
        for i = startLoop:length(loopNames)
            num = openLoops.(loopNames{i}).num;
            den = openLoops.(loopNames{i}).den;
            bode(tf(num, den), {0.1, 100.0})
        end
        legend(loopNames(startLoop:end))
        title('Open loop transfer functions')
        hold off
    end
end

%% get the handling quality metric
if settings.handlingQuality
    display_if('Finding the handling quality metric.')
    % the handling qualities must be calculated with the phi loop at 2 rad/sec
    % crossover
    if strcmp(settings.input, 'Roll')
        origkPhi = modelPar.kPhi;
        % find the gain needed to move the current phi loop to a crossover of 2
        num = openLoops.Phi.num;
        den = openLoops.Phi.den;
        w = logspace(-1, 2, 1000);
        [mag,phase] = bode(tf(num,den), w);
        mag = mag(:)';
        phase = phase(:)';
        % get the magnitude at the desired crossover frequency
        MagCO = interp1(w, mag, 2.0);
        % calculate the gain needed to get the desired crossover frequency
        modelPar.kPhi = 1 / MagCO * origkPhi;
    end

    modelPar.isHandling = 1;
    modelPar.loopNumber = 3;
    modelPar.closed = [0, 0, 1, 1, 1];
    modelPar.perturb = [0, 0, 1, 0, 0];

    update_model_variables(modelPar);

    [num, den] = linmod_switch('WhippleModel');
    handlingMetric.num = num;
    handlingMetric.den = den;

    % change the gain
    if strcmp(settings.input, 'Roll')
        modelPar.kPhi = origkPhi;
    end

    % store the handling quality metric
    data.handlingMetric = handlingMetric;
    if settings.plot
        display_if('Generating handling quality plot.')
        figure()
        num = handlingMetric.num;
        den = handlingMetric.den;
        wl = linspace(0.01, 20, 100);
        [mag, phase, freq] = bode(tf(num, den), wl);
        plot(wl, mag(:)')
        title('Handling quality metric')
    end
end
```

```
%% find the transfer functions from pull force to various outputs
if ~isempty(settings.forceTransfer)
    ftf = settings.forceTransfer;
    modelPar.isHandling = 0;
    modelPar.isPullPerturb = 1;
    modelPar.perturb = [0, 0, 0, 0, 0];
    modelPar.closed = [1, 1, 1, 1, 1];

    % handle the fact that the user can specify both the control input and
    % either pull force to steer torque or roll torque
    if strcmp(settings.input, 'Steer')
        % replace 'Tphi'
        if any(ismember(ftf, 'Tphi'))
            display_if(['You have specified Steer as the input so Tphi ' ...
                    'will be replaced with Tdelta'])
            ftf{find(ismember(ftf, 'Tphi')==1)} = 'Tdelta';
        end
    elseif strcmp(settings.input, 'Roll')
        % don't feed back delta
        modelPar.closed = [0, 1, 1, 1, 1];
        % replace 'Tdelta'
        if any(ismember(ftf, 'Tdelta'))
            display_if(['You have specified Roll as the input so Tdelta ' ...
                    'will be replaced with Tphi'])
            ftf{find(ismember(ftf, 'Tdelta')==1)} = 'Tphi';
        end
    end

    % calculate each transfer function
    for i = 1:length(ftf)
        display_if(sprintf(['Calculating the pull force to %s transfer ' ...
                        'function.'], ftf{i}))
        if strcmp(ftf{i}, 'Tdelta') || strcmp(ftf{i}, 'Tphi')
            % Tdelta is connected to the 0 port in the multiswitch
            modelPar.loopNumber = 0;
        else
            modelPar.loopNumber = find(ismember(loopNames, ftf{i})==1);
        end

        update_model_variables(modelPar)

        [num, den] = linmod_switch('WhippleModel');
        data.forceTF.(ftf{i}).num = num;
        data.forceTF.(ftf{i}).den = den;
    end

    if settings.plot
        figure()
        hold all
        for i = 1:length(ftf)
            bode(tf(data.forceTF.(ftf{i}).num, ...
                    data.forceTF.(ftf{i}).den))
            legend(ftf)
        end
        hold off
    end
end

% get the full system state space
display_if('Calculating the full system state space with lateral input.')
modelPar.isHandling = 0;
modelPar.isPullPerturb = 1;
modelPar.isFullSystem = 1;
modelPar.perturb = [0, 0, 0, 0, 0];
modelPar.closed = [1, 1, 1, 1, 1];
modelPar.loopNumber = 0;

update_model_variables(modelPar)

[A, B, C, D] = linmod('WhippleModel');
% check to see if the final system is unstable
```

```
if any(real(eig(A)) > 0)
    display(sprintf(repmat('*', 1, 76)))
    display('Warning')
    display(sprintf(repmat('*', 1, 76)))
    s = ['The system is not stable with these gains. If the ', ...
         'simulation completes, the\ndata may be invalid. ', ...
         'Please give better gain guesses or supply the gains\n', ...
         'manually.'];
    display(sprintf(s))
    display(sprintf(repmat('*', 1, 76)))
    eig(A)
    display(settings.gains)
else % if not unstable
    % only save gains if not user supplied and the neuro frequency is
    % default
    if isempty(settings.gains) && (settings.neuroFreq - 30) < 1e-8 && ...
        isempty(settings.crossover)
        % write the gains to file if the system is stable
        pathToGainFile = [CURRENT_DIRECTORY filesep 'gains' filesep bike ...
            settings.input 'Gains.txt'];
        newGains = [modelPar.kDelta, modelPar.kPhiDot, modelPar.kPhi, ...
        modelPar.kPsi, modelPar.kY];
        write_gains(pathToGainFile, speed, newGains)
        display_if(sprintf('Gains written to %s', pathToGainFile))
    else
        display_if('Gains were not saved to file.')
    end
end

if settings.fullSystem
    data.system.A = A;
    data.system.B = B;
    data.system.C = C;
    data.system.D = D;
    data.system.outputs = {'xP','yP','psi','phi','thetaB','thetaR','delta',
                           'thetaF','xPDot','yPDot','psiDot','phiDot','thetaBDot',
                           'thetaRDot','deltaDot','thetaFDot','xQ','yQ','tDelta'};
end

%% Simulate the system
if settings.simulate
    % close all the loops and simulate
    modelPar.loopNumber = 0;
    modelPar.isHandling = 0;
    modelPar.isPullPerturb = 0;
    modelPar.isFullSystem = 0;
    modelPar.perturb = [0, 0, 0, 0, 0];
    modelPar.closed = [1, 1, 1, 1, 1];

    update_model_variables(modelPar)

    display_if('Simulating the tracking task.')
    tic;
    sim('WhippleModel.mdl')
    elapsedTime = toc;
    display_if(sprintf('Simulation finished in %1.3f seconds.', elapsedTime))

    % set the initial point of the front wheel ahead of the rear wheel by the
    % wheelbase length
    y(:, 17) = y(:, 17) + par.w;

    % store simulation data
    data.time = t;
    data.command = command;
    data.inputs = u;
    data.outputs = y;
    data.outputsDot = yDot;
    data.path = yc;

    if settings.plot
        display_if('Generating simulation plots.')
```

```
        outputPlot = plot_outputs(t, y, yc);

        figure()
        plot(t, u)
        title('Inputs')
        xlabel('Time [s]')
        legend({'Roll Torque', 'Steer Torque', 'Pull Force'})
    end
end

% write data for export
data.speed = speed;
data.par = par;
data.modelPar = modelPar;
data.bicycle.states = {'xP', 'yP', 'psi', 'phi', 'thetaB', 'thetaR', 'delta', ...
             'thetaF', 'phiDot', 'thetaRDot', 'deltaDot'};
data.bicycle.outputs = {'xP', 'yP', 'psi', 'phi', 'thetaB', 'thetaR', 'delta', ...
             'thetaF', 'xPDot', 'yPDot', 'psiDot', 'phiDot', ...
             'thetaBDot', 'thetaRDot', 'deltaDot', 'thetaFDot', 'xQ', 'yQ'};
data.bicycle.inputs = {'tPhi', 'tDelta', 'fB'};

display_if(sprintf('Done. \n'))

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Sub Functions
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function update_model_variables(modelPar)
% Puts all the variables needed for the simulink model in to the base
% workspace. This is a hack because linmod has no way to operate inside a
% function.
%
% Parameters
% ----------
% modelPar : structure
%   A structure that contains a field for each unknown variable in the simulink
%   model.

modelParNames = fieldnames(modelPar);
for i = 1:length(modelParNames)
    assignin('base', modelParNames{i}, modelPar.(modelParNames{i}))
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function outputPlot = plot_outputs(t, y, yc)
% Returns a plot of the model outputs.
%
% Parameters
% ----------
% t : matrix, size(n, 1)
%   The time vector.
% y : matrix, size(n, 18)
%   The outputs of the bicycle system.
% yc : matrix, size(n, 1)
%   The path that was tracked.

outputs = {'$x_P$','$y_P$','$\psi$','$\phi$','$\theta_B$','$\theta_R$',
           '$\delta$','$\theta_F$','$\dot{x}_P$','$\dot{y}_P$','$\dot{\psi}$',
           '$\dot{\phi}$','$\dot{\theta}_B$','$\dot{\theta}_R$','$\dot{\delta}$',
           '$\dot{\theta}_F$','$x_Q$','$y_Q$'};
outputPlot = figure();
% plot the wheel contact points
subplot(6, 1, 1)
plot(y(:, 17), yc, ...
     y(:, 1), y(:, 2), ...
     y(:, 17), y(:, 18))
legend({'Path', 'Rear Wheel', 'Front Wheel'})

plt.angles = [3, 4, 5, 7];
```

```
plt.wheelAngles = [6, 8];
plt.contactRates = [9, 10];
plt.rates = [11, 12, 13, 15];
plt.wheelRates = [14, 16];

pltFields = fieldnames(plt);
numPlots = length(pltFields);

for i = 1:numPlots
    subplot(numPlots + 1, 1, i + 1)
    hold all
    numbers = plt.(pltFields{i});
    for j = 1:length(numbers)
        plot(t, y(:, numbers(j)))
    end
    hold off
    leg = legend(outputs{plt.(pltFields{i})});
    set(leg, 'interpreter', 'latex')
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function k = find_closed_gain(loop, guess)
% Returns the gain required for a 10dB resonant peak in the closed loop
% transfer function.
%
% Parameters
% ----------
% loop : str
%   The name of the loop.
% guess : float
%   An initial guess for the gain.

k = fzero(@(x) delta_mag_closed(x, loop), guess);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function k = find_open_gain(loop, input, settings)
% Returns the gain needed to set the crossover frequency at a desired value.
%
% Parameters
% ----------
% loop : string
%   The name of the loop.
% input : string
%   Whether this is 'Steer' or 'Roll' torque input
% settings : structure
%   The user supplied and default settings.
%
% Returns
% -------
% k : float
%   The gain needed for the desired crossover frequency.
%
% Notes
% -----
% This function assumes that all model parameters are set in the base workspace
% for the 'WhippleModel'.

% set the gain for this loop to unity
assignin('base', ['k' loop], 1)
% get the transfer function
[num, den] = linmod_switch('WhippleModel');
w = logspace(-1,2,1000);
[mag,phase] = bode(tf(num,den), w);
mag = mag(:)';
phase = phase(:)';

% set the desired open loop crossover frequency (this a mess of an if
% statement!)
if strcmp(loop, 'Phi')
```

```
    if ~isempty(settings.crossover)
        wBW = settings.crossover(1);
    elseif strcmp(input, 'Steer')
        wBW = 2.0;
    elseif strcmp(input, 'Roll')
        wBW = 1.5;
    end
elseif strcmp(loop, 'Psi')
    if ~isempty(settings.crossover)
        wBW = settings.crossover(2);
    elseif strcmp(input, 'Steer')
        wBW = 1.0;
    elseif strcmp(input, 'Roll')
        wBW = 0.75;
    end
elseif strcmp(loop, 'Y')
    if ~isempty(settings.crossover)
        wBW = settings.crossover(3);
    elseif strcmp(input, 'Steer')
        wBW = 0.5;
    elseif strcmp(input, 'Roll')
        wBW = 0.375;
    end
end

% get the magnitude at the desired crossover frequency
MagCO = interp1(w, mag, wBW);
% calculate the gain needed to get the desired crossover frequency
k = 1 / MagCO;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function delta = delta_mag_closed(gain, loop)
% Returns the difference between a 10db overshoot and the overshoot calculated
% with the given gain.
%
% Parameters
% ----------
% gain : float
%   The gain for the closed loop.
% loop : str
%   The name of the loop.
%
% Returns
% -------
% delta : float
%   The difference in the resonant peak height and the desired height of 10db.

% set the gain for this loop
assignin('base', ['k' loop], gain)

% get the closed loop transfer function
[num, den] = linmod_switch('WhippleModel');
w = logspace(-2, 2, 1000);

% check for stability
%G = tf(num, den);
%if any(real(roots(G.den{:})) > 0)
    %display_if('Loop is not stable with this gain.')
    %roots(G.den{:})
%end

% uncomment to show the bode diagram at each step
%figure(25)
%bode(tf(num, den), w)

[mag, phase] = bode(tf(num, den), w);
% rewrite mag and phase so the dimension is reduced
mag = mag(:)';
phase = phase(:)';
% get the maximum magitude and index, this is the peak of the neurmuscular mode
```

```
[magmax, iMaxMag] = max(mag);
% find lower cutoff of 2 rad/sec
%lowi = min(find(w > 2));
% truncate the magnitude and frequency below resonance
magtrunc = mag(1:iMaxMag);
wtrunc = w(1:iMaxMag);
% differentiate the truncated magnitude
dmag = [0 diff(magtrunc)];
% differentiate it again
ddmag = [0 diff(dmag)];
% find the maximum which is just left of the far right zero crossing
[maxDD, indMaxDD] = max(ddmag);
% find the zero crossing in ddmag just left of its peak, this should occur
% at the local minima of dmag that corresponds to the flat point in mag, but
% sometimes it doesn't cross the zero line so just choose a point a certain
% distance from the peak (4 rad/sec to the left of the peak)
for i = indMaxDD:-1:2
    if ddmag(i - 1) < 0 && ddmag(i) > 0
        iMinDmag = i;
        %display_if(sprintf(['Found a zero crossing in ddmag ' ...
                        %'at the inflection point at %f.'], ...
                        %wtrunc(iMinDmag)))
        break
    else
        iMinDmag = 1;
    end
end

if iMinDmag == 1
    %display_if('Did not find a zero crossing in ddmag at the inflection point.')
    if strcmp(loop, 'Delta')
        [tmp, iMinDmag] = min(dmag);
        %display_if(sprintf('Setting the Delta low point to %f', ...
                        %wtrunc(iMinDmag)))
    elseif strcmp(loop, 'PhiDot')
        wMid = wtrunc(end) - 4;
        wMid = 3;
        [tmp, iMinDmag] = min(abs(wMid - wtrunc));
        %display_if(sprintf('Setting the PhiDot low point to %f', ...
                        %wtrunc(iMinDmag)))
    end
end

% uncomment to show the derivative of the magnitude at each step
%figure(20)
%subplot(3, 1, 1)
%plot(wtrunc, magtrunc, wtrunc(iMinDmag), magtrunc(iMinDmag), 'o')
%subplot(3, 1, 2)
%plot(wtrunc, dmag, wtrunc(iMinDmag), dmag(iMinDmag), 'o')
%subplot(3, 1, 3)
%plot(wtrunc, ddmag, wtrunc(iMinDmag), ddmag(iMinDmag), 'o')
%grid on
%pause

% get the magnitude at the flat part on the slope
magmin = magtrunc(iMinDmag);
% the ratio of magnitude of the resonant peak to the valley just left of the
% peak
rmag = magmax / magmin;
% the difference in the magnitude and the desired 10db peak
delta = rmag - sqrt(10);  % 10 dB corresponds to a magnitude ratio of sqrt(10)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function modelPar = exact_gains(startLoop, loopNames, modelPar, settings)
% function modelPar = exact_gains(startLoop, loopNames, modelPar, settings)
% Finds the exact values for the gains for each loop given the guesses
% provided in modelPar.
%
% Parameters
% ----------
```

```
% startLoop : integer
%   Either 1 or 2. If 1, all loops are set and if the Delta loop is skipped.
% loopNames : cell array of strings
%   The names of the loops starting with the Delta loop.
% modelPar : structure
%   The complete model parametes with the gains set as initial guesses.
% settings : structure
%   The combined default and user supplied optional settings.
%
% Returns
% -------
% modelPar : structure
%   The complete model parameters with the exact gains.

% make truth tables for perturbing and closing the loops
% the first row is default setup
perturbTable = [zeros(1, 5) % do not perturb any loop
                eye(5)]; % perturb each loop individually
closedTable = [1 1 1 1 1 % all loops closed
               1 0 0 0 0 % delta loop closed
               1 1 0 0 0 % delta, phidot loops closed
               1 1 0 0 0 % delta, phidot loops closed
               1 1 1 0 0 % delta, phidot, phi loops closed
               1 1 1 1 0]; % delta, phidot, phi, psi loops closed

if strcmp(settings.input, 'Roll')
    % don't feed back delta
    closedTable(:, 1) = zeros(6, 1);
end

for i = startLoop:length(loopNames)
    guess = modelPar.(['k' loopNames{i}]);
    str = ['Finding the loop transfer function ' ...
           'of the %s loop with a start guess of %1.4f.'];
    display_if(sprintf(str, loopNames{i}, guess))
    % set the logic for this loop calculation
    modelPar.loopNumber = i;
    modelPar.perturb = perturbTable(i + 1, :);
    modelPar.closed = closedTable(i + 1, :);
    update_model_variables(modelPar);
    if i == 1 || i == 2
        gain = find_closed_gain(loopNames{i}, guess);
    elseif i == 3 || i == 4 || i == 5
        gain = find_open_gain(loopNames{i}, settings.input, settings);
    else
        error(sprintf('%s loop not found', loopNames{i}))
    end
    modelPar.(['k' loopNames{i}]) = gain;
    str = '%s loop gain set to %1.4f.';
    display_if(sprintf(str, loopNames{i}, gain))
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function [modelPar, startLoop, par] = ...
    set_initial_model_parameters(bike, speed, settings)
% function [modelPar, startLoop, par] = set_initial_model_parameters(bike, speed, settings)
% Sets the model parameters based on the user input.
%
% Parameters
% ----------
% bike : string
%   The name of the bicycle model to use. This corresponds to a file in the
%   ./Parameters directory named <bike>Par.txt.
% speed : float
%   The speed of the bicycle.
% settings : structure
%   The combine default and user supplied optional settings.
%
% Returns
% -------
```

```
% modelPar : structure
%   The initial parameters for the simulink model.
% startLoop : integer
%   Either 1 or 2 depending if the input is steer or roll.
% par : structure
%   The physical parameters of the bicycle and rider.

global CURRENT_DIRECTORY

% set the speed
modelPar.speed = speed;

% generate the path to track
[pathX, pathY, pathT] = lane_change(35, 2, 0.2, 250, speed, ...
                                    500, settings.laneType, 60);
modelPar.track = [pathT, pathY];
modelPar.stopTime = pathT(end);

% load the bicycle parameters
pathToParFile = [CURRENT_DIRECTORY filesep 'parameters' filesep bike 'Par.txt'];
par = par_text_to_struct(pathToParFile);
str = 'Parameters for the %s bicycle and rider have been loaded.';
display_if(sprintf(str, bike))

% calculate the A, B, C, and D matrices of the bicycle model
if isempty(settings.stateSpace)
    display_if(sprintf('Calculating the A, B, C, D matrices for %1.2f m/s', speed))
    tic
    [modelPar.A, modelPar.B, modelPar.C, modelPar.D] = ...
        whipple_pull_force_abcd(par, speed);
    elapsedTime = toc;
    display_if(sprintf('A, B, C, D calculated in %1.4f seconds.', elapsedTime))
else
    display_if('A, B, C, D matrices already supplied')
    mats = {'A', 'B', 'C', 'D'};
    for i = 1:4
        modelPar.(mats{i}) = settings.stateSpace{i};
    end
end

% Keep in mind that the there is a function that relates steer angle, roll
% angle and pitch angle that must be enforced when setting any three of those
% initial conditions.
modelPar.initialConditions = [-par.w, ... rear wheel contact x
                              0, ... rear wheel contact y
                              0, ... yaw angle
                              0, ... roll angle
                              0, ... pitch angle
                              0, ... rear wheel rotation
                              0, ... steer angle
                              0, ... front wheel rotation
                              0, ... roll rate
                              -speed / par.rR, ... rear wheel rate
                              0]; % steer rate

% human neuromuscular system
wnm = settings.neuroFreq;
display_if(sprintf('Neuromuscular frequency set to: %1.1f', wnm))
modelPar.neuroNum = wnm^2;
modelPar.neuroDen = [1, 2 * 0.707 * wnm, wnm^2];

% path filter
modelPar.pathFilterNum = 2.4^2;
modelPar.pathFilterDen = [1, 2 * 2.4, 2.4^2];

% handling qualities metric filter
modelPar.handlingFilterNum = 400;
modelPar.handlingFilterDen = [1, 40, 400];

% handling quality calculation flag
modelPar.isHandling = 0;
```

```
% set the pull perturb flag
modelPar.isPullPerturb = 0;

% set the full system flag to default
modelPar.isFullSystem = 0;

% set parameters for steer or roll inputs
if strcmp(settings.input, 'Steer')
    % start at the delta loop
    startLoop = 1;
    % use steer torque control
    modelPar.isRollInput = 0;
    % preview time delay
    modelPar.timeDelay = 2.75;
elseif strcmp(settings.input, 'Roll')
    % start at the phiDot loop
    startLoop = 2;
    % use the roll torque control
    modelPar.isRollInput = 1;
    % preview time delay
    modelPar.timeDelay = 3.5;
else
    error('Choose Steer or Roll as the input')
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function [num, den] = linmod_switch(model)
% Returns the numerator and denominator of the current transfer function
% specified by the input and output blocks. This function is a hack and only
% exists because the full system state space switch has one vector input and
% one scalar input, which forces the output to always be a vector. A better
% solution for this may be to remove the switches related to the output and
% simply have one output that always outputs all the variables, instead of
% select ones.

[num, den] = linmod(model);

num = num(1, :);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function display_if(string)
% Prints the string to screen only if the print to screen global is true.

global PRINT_TO_SCREEN

if PRINT_TO_SCREEN
    disp(string)
end



%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% create_ieee_paper_plots_Carlijn %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function create_ieee_paper_plots(data, rollData)
% Creates all of the figures for the IEEE paper.
%
% Parameters
% ----------
% data : structure
%   A structure contating the data from generate_data.m for all of the bicycles
%   and speeds for the IEEE paper.
% rollData : structure
%   The data for a single bicycle at a single speed with roll torque as the
%   input.

global goldenRatio
```

```
% used for figure width to height ratio
goldenRatio = (1 + sqrt(5)) / 2;

% create a plot directory if one doesn't already exist
if exist('plots/', 'dir') ~= 7
    mkdir('plots/')
end

% Define some linestyles and colors for each of the six bicycles
linestyles = {'-', '-', '-.', ...
              '--', '-.', '--', ':', '-.', '-.', ':',''};
colors = {'k', 'b', 'r','g','m','y','c',[0.5430 0 0],[0.50196 0.50196 0],[0 0.50196 0.50196]};

loop_shape_example(data.Ami.Medium, 'Steer')
loop_shape_example(rollData, 'Roll')
plot_io_roll(rollData, 'Distance')
plot_io_roll(rollData, 'Time')
open_loop_all_bikes(data, linestyles, colors)
handling_all_bikes(data, rollData, linestyles, colors)
path_plots(data, linestyles, colors)
var = {'delta', 'phi', 'psi', 'Tdelta'};
io = {'output', 'output', 'output', 'input'};
typ = {'Distance', 'Time'};
for i = 1:length(var)
    for j = 1:length(typ)
        plot_io(var{i}, io{i}, typ{j}, data, linestyles, colors)
    end
end
phase_portraits(data.Ami.Medium)
eigenvalues(data, linestyles, colors)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function loop_shape_example(bikeData, input)
% Creates the example loop shaping for the bicycle at medium speed.
%
% Parameters
% ----------
% bikeData : structure
%   Contains data for a single bicycle at a single speed.
% input : string
%   'Steer' or 'Roll' depending on what input was used to control the bicycle.

global goldenRatio

% closed loop bode plots
figure()
figWidth = 5.5;
figHeight = figWidth / goldenRatio;
set(gcf, ...
    'Color', [1, 1, 1], ...
    'PaperOrientation', 'portrait', ...
    'PaperUnits', 'inches', ...
    'PaperPositionMode', 'manual', ...
    'OuterPosition', [424, 305 - 50, 518, 465], ...
    'PaperPosition', [0, 0, figWidth, figHeight], ...
    'PaperSize', [figWidth, figHeight])

freq = {0.1, 30.0};

hold all

closedLoops = bikeData.closedLoops;

% make sure all bode plots display 'rad/s' instead of 'rad/sec'
bops = bodeoptions;
bops.FreqUnits = 'rad/s';

if strcmp(input, 'Steer')
    linestyles = {'', '', '-.', '-.', '-', '-.', '-.', '-'};
    gray = [0.6, 0.6, 0.6];
    colors = {'k', 'k', 'k', gray, 'k', 'k', gray, 'k'};
```

```
    % the closed delta loop
    deltaNum = closedLoops.Delta.num;
    deltaDen = closedLoops.Delta.den;
    bodeplot(tf(deltaNum, deltaDen), freq, bops);
    % a typical neuromuscular model
    neuroNum = 2722.0;
    neuroDen = [1, 13.96, 311.85, 2722.0];
    bodeplot(tf(neuroNum, neuroDen), freq, bops);
    whichLines = 5:-1:3;
elseif strcmp(input, 'Roll')
    linestyles = {'', '', '-', '-'};
    colors = {'k', 'k', 'k', 'k'};
    whichLines = 4:-1:2;
else
    error('Bad input, use Steer or Roll')
end

% the closed phi dot loop
phiDotNum = closedLoops.PhiDot.num;
phiDotDen = closedLoops.PhiDot.den;
closedBode = bodeplot(tf(phiDotNum, phiDotDen), freq, bops);

hold off

% clean it up
opts = getoptions(closedBode);
if strcmp(input, 'Steer')
    opts.YLim = {[-45, 30], [-360, 90]};
else
    opts.YLim = {[-30, 10], [-180, 90]};
end
opts.PhaseMatching = 'on';
opts.PhaseMatchingValue = 0;
opts.Title.String = '';
setoptions(closedBode, opts)

% find all the lines in the current figure
lines = findobj(gcf, 'type', 'line');
for i = 3:length(lines)
    set(lines(i), 'LineStyle', linestyles{i}, ...
                  'Color', colors{i}, ...
                  'LineWidth', 2.0)
end

% there seems to be a bug such that the xlabel is too low, this is a hack to
% get it to work
raise = 0.05;
plotAxes = findobj(gcf, 'type', 'axes');
set(plotAxes, 'XColor', 'k', 'YColor', 'k')
curPos1 = get(plotAxes(1), 'Position');
curPos2 = get(plotAxes(2), 'Position');
set(plotAxes(1), 'Position', curPos1 + [0, raise, 0, 0])
set(plotAxes(2), 'Position', curPos2 + [0, raise, 0, 0])
xLab = get(plotAxes(1), 'Xlabel');
set(xLab, 'Units', 'normalized')
set(xLab, 'Position', get(xLab, 'Position') + [0, raise + 0.05, 0])

% make the tick labels smaller
set(plotAxes, 'Fontsize', 8)
if strcmp(input, 'Steer')
    legWords = {'$\delta$ Loop',
                'Neuromuscular model from [27]',
                '$\dot{\phi}$ Loop'};
elseif strcmp(input, 'Roll')
    legWords = {'$\dot{\phi}$ Loop'};
end
closeLeg = legend(lines(whichLines), ...
                  legWords, ...
                  'Location', 'Southwest', ...
                  'Interpreter', 'Latex', ...
                  'Fontsize', 8);
```

```
% add the annotation showing a 10 dB peak
if strcmp(input, 'Steer')
    axes(plotAxes(2))
    db1 = text(2.7, 5.5, '~10dB');
    db2 = text(2.0, -10.0, '~10dB');
    set([db1, db2], 'Fontsize', 8)
    dArrow1 = annotation('doublearrow', ...
                         [0.7, 0.7], ...
                         [0.755 + raise, 0.818 + raise]);
    annotation('line', [0.69, 0.87], [0.818 + raise, 0.818 + raise])
    dArrow2 = annotation('doublearrow', ...
                         [0.685, 0.685], ...
                         [0.665 + raise, 0.725 + raise]);
    annotation('line', [0.675, 0.87], [0.725 + raise, 0.725 + raise])
    set([dArrow1, dArrow2], 'Head1width', 3, 'Head1length', 3, ...
        'Head2width', 3, 'Head2length', 3)
else
    axes(plotAxes(2))
    db1 = text(0.67, -3.7, '~10dB');
    set(db1, 'Fontsize', 8)
    dArrow = annotation('doublearrow', ...
                        [0.5, 0.5], ...
                        [0.697 + raise, 0.795 + raise]);
    set(dArrow, 'Head1width', 3, 'Head1length', 3, ...
        'Head2width', 3, 'Head2length', 3)
    annotation('line', [0.49, 0.75], [0.795 + raise, 0.795 + raise])
end

filename = ['Ami' input 'Closed'];
pathToFile = ['plots' filesep filename];
print(gcf, '-deps2c', '-loose', [pathToFile '.eps'])
fix_ps_linestyle([pathToFile '.eps'])

% open loop plots
figure()
set(gcf, ...
    'Color', [1, 1, 1], ...
    'PaperOrientation', 'portrait', ...
    'PaperUnits', 'inches', ...
    'PaperPositionMode', 'manual', ...
    'PaperPosition', [0, 0, figWidth, figHeight], ...
    'PaperSize', [figWidth, figHeight])

openLoops = bikeData.openLoops;

hold all

num = openLoops.Phi.num;
den = openLoops.Phi.den;
bodeplot(tf(num, den), freq, bops);

num = openLoops.Psi.num;
den = openLoops.Psi.den;
bodeplot(tf(num, den), freq, bops);

num = openLoops.Y.num;
den = openLoops.Y.den;
openBode = bodeplot(tf(num, den), freq, bops);

hold off

% clean it up
opts = getoptions(openBode);
opts.Title.String = '';
opts.YLim = {[-80, 30], [-540, -60]};
opts.PhaseMatching = 'on';
opts.PhaseMatchingValue = 0;
setoptions(openBode, opts)

% find all the lines in the current figure
```

```
lines = findobj(gcf, 'type', 'line');
linestyles = {'', '', '-.', '-', '--', '-.', '-', '--'};
for i = 3:length(lines)
    set(lines(i), 'LineStyle', linestyles{i}, ...
                  'Color', 'k', ...
                  'LineWidth', 2.0)
end


plotAxes = findobj(gcf, 'type', 'axes');
set(plotAxes, 'Fontsize', 8, 'XColor', 'k', 'YColor', 'k')
closeLeg = legend(lines(8:-1:6), ...
                  {'$\phi$ Loop', '$\psi$ Loop','$y$ Loop'}, ...
                  'Location', 'Southwest', ...
                  'Interpreter', 'Latex');

% add zero crossing lines
%axes(plotAxes(1))
%line([0.1, 20], [-180, -180], 'Color', 'k')
axes(plotAxes(2))
line([0.1, 30], [0, 0], 'Color', 'k')

% add some lines and labels for the cross over frequencies
if strcmp(input, 'Steer')
    wc = 2;
    wShift = [0.42, 0.35, 0.175];
else strcmp(input, 'Roll')
    wc = 1.5;
    wShift = [0.31, 0.26, 0.1325];
end
axes(plotAxes(2))
hold on
gray = [0.5, 0.5, 0.5];

line([wc, wc], [-40, 0], 'Color', gray)
text(wc - wShift(1), -43, ['$\omega_c=' num2str(wc) '$'], ...
     'Interpreter', 'Latex', 'Fontsize', 8)

line([wc / 2, wc / 2], [-30, 0], 'Color', gray)
text(wc / 2 - wShift(2), -33, ['$\omega_c/2=' num2str(wc / 2) '$'], ...
     'Interpreter', 'Latex', 'Fontsize', 8)

line([wc / 4, wc / 4], [-20, 0], 'Color', gray)
text(wc / 4 - wShift(3), -23, ['$\omega_c/4=' num2str(wc / 4) '$'], ...
     'Interpreter', 'Latex', 'Fontsize', 8)

hold off

curPos1 = get(plotAxes(1), 'Position');
curPos2 = get(plotAxes(2), 'Position');
set(plotAxes(1), 'Position', curPos1 + [0, raise, 0, 0])
set(plotAxes(2), 'Position', curPos2 + [0, raise, 0, 0])
xLab = get(plotAxes(1), 'Xlabel');
set(xLab, 'Units', 'normalized')
set(xLab, 'Position', get(xLab, 'Position') + [0, raise + 0.05, 0])

filename = ['Ami' input 'Open.eps'];
pathToFile = ['plots' filesep filename];
print(gcf, '-deps2c', '-loose', pathToFile)
fix_ps_linestyle(pathToFile)

% handling qualities plot
num = bikeData.handlingMetric.num;
den = bikeData.handlingMetric.den;
w = linspace(0.01, 30, 200);
[mag, phase, freq] = bode(tf(num, den), w);
figure()
set(gcf, ...
    'Color', [1, 1, 1], ...
    'PaperOrientation', 'portrait', ...
    'PaperUnits', 'inches', ...
```

```
    'PaperPositionMode', 'manual', ...
    'PaperPosition', [0, 0, figWidth, figHeight], ...
    'PaperSize', [figWidth, figHeight])

hold on

metricLine = plot(freq, mag(:)', 'k-', 'Linewidth', 2.0);
level1 = line([0, 30], [5, 5]);
level2 = line([0, 30], [8, 8]);
set(level1, 'Color', 'k', 'Linestyle', '--', 'Linewidth', 2.0)
set(level2, 'Color', 'k', 'Linestyle', '--', 'Linewidth', 2.0)

ylim([0, 10]);

ylabel('Handling Quality Metric')
xlabel('Frequency (rad/s)')
text(3, 3, 'Level 1')
text(3, 6.5, 'Level 2')
text(3, 9, 'Level 3')
box on

filename = ['Ami' input 'Handling.eps'];
pathToFile = ['plots' filesep filename];
print(gcf, '-deps2', '-loose', pathToFile)
fix_ps_linestyle(pathToFile)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function open_loop_all_bikes(data, linestyles, colors)
% Creates open loop Bode plots of all the bikes.

global goldenRatio

bikes = fieldnames(data);

figure()
figWidth = 5.5;
figHeight = figWidth / goldenRatio;
set(gcf, ...
    'Color', [1, 1, 1], ...
    'PaperOrientation', 'portrait', ...
    'PaperUnits', 'inches', ...
    'PaperPositionMode', 'manual', ...
    'PaperPosition', [0, 0, figWidth, figHeight], ...
    'PaperSize', [figWidth, figHeight])

freq = {0.1, 30.0};

% make sure all bode plots display 'rad/s' instead of 'rad/sec'
bops = bodeoptions;
bops.FreqUnits = 'rad/s';

hold all
for i = 2:length(bikes)
    num = data.(bikes{i}).Medium.openLoops.Phi.num;
    den = data.(bikes{i}).Medium.openLoops.Phi.den;
    openBode = bodeplot(tf(num, den), freq, bops);
end
hold off

% clean it up
opts = getoptions(openBode);
%opts.Title.String = '$\phi$ Open Loop Bode Diagrams at 5 m/s';
opts.Title.String = '';
%opts.Title.Interpreter = 'Latex';
opts.YLim = {[-30, 10], [-540, -90]};
opts.PhaseMatching = 'on';
opts.PhaseMatchingValue = 0;
setoptions(openBode, opts)

% find all the lines in the current figure
plotAxes = findobj(gcf, 'type', 'axes');
```

```
magLines = findobj(plotAxes(2), 'type', 'line');
phaseLines = findobj(plotAxes(1), 'type', 'line');

for i = 2:length(magLines)
    set(magLines(i), ...
        'LineStyle', linestyles{i - 1}, ...
        'Color', colors{i - 1}, ...
        'LineWidth', 1.0)
    set(phaseLines(i), ...
        'LineStyle', linestyles{i - 1}, ...
        'Color', colors{i - 1}, ...
        'LineWidth', 1.0)
end

closeLeg = legend(magLines(1:10), ...
                  {'Ami', 'Balance', 'Orange', 'OrangeHMB', 'OrangeHFP',...
                  'Cityzen', 'CityzenSpeed', 'TourPopulair','PuurNL', ...
                  'VanStael'},'Location', 'Southwest', ...
                  'Fontsize', 8);

set(plotAxes, 'YColor', 'k', 'XColor', 'k', 'Fontsize', 8)

% add a zero lines
axes(plotAxes(1))
line([0.1, 30], [-180, -180], 'Color', 'k')
axes(plotAxes(2))
line([0.1, 30], [0, 0], 'Color', 'k')

% raise the axes cause the xlabel is cut off
raise = 0.05;
curPos1 = get(plotAxes(1), 'Position');
curPos2 = get(plotAxes(2), 'Position');
set(plotAxes(1), 'Position', curPos1 + [0, raise, 0, 0])
set(plotAxes(2), 'Position', curPos2 + [0, raise, 0, 0])
xLab = get(plotAxes(1), 'Xlabel');
set(xLab, 'Units', 'normalized')
set(xLab, 'Position', get(xLab, 'Position') + [0, raise + 0.05, 0])

filename = 'openBode.eps';
pathToFile = ['plots' filesep filename];
print(pathToFile, '-deps2c', '-loose')
fix_ps_linestyle(pathToFile)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function handling_all_bikes(data, rollData, linestyles, colors)
% Creates handling quality metric for all bikes.
%
% Parameters
% ----------
% data : structure
%   Contains data for all bikes a the three speeds for steer input.
% rollData : structure
%   Contains the data for the benchmark bike with roll input at medium speed.
% linestyles : cell array
%   Linestyle strings, one for each of the six bikes.
% colors : cell array
%   Colorspecs for each of the six bikes.

%% Creates handling quality metric for 2.0 m/s
global goldenRatio

bikes = fieldnames(data);
figure()
figWidth = 5.5;
figHeight = figWidth / goldenRatio;
set(gcf, ...
    'Color', [1, 1, 1], ...
    'PaperOrientation', 'portrait', ...
    'PaperUnits', 'inches', ...
    'PaperPositionMode', 'manual', ...
    'PaperPosition', [0, 0, figWidth, figHeight], ...
```

```
    'PaperSize', [figWidth, figHeight])

w = linspace(0.01, 30, 200);
speedNames = fieldnames(data.Balance);
fillColors = {[0.82, 0.82, 0.82]
              [0.68, 0.68, 0.68]
              [0.95, 0.95, 0.95]};
hold all

% plot the background area for each family of curves
for j = 1
    % get the max values for the set of curves
    magnitudes = zeros(length(w), length(bikes));
    for i = 1:length(bikes)
        num = data.(bikes{i}).(speedNames{j}).handlingMetric.num;
        den = data.(bikes{i}).(speedNames{j}).handlingMetric.den;
        [mag, phase, freq] = bode(tf(num, den), w);
        magnitudes(:, i) = mag(:)';
    end
    maxMag = max(magnitudes, [], 2);
    % fill the area under the curve
    area(freq, maxMag, ...
         'Facecolor', fillColors{j}, ...
         'Edgecolor', 'none')
end

% this makes sure that the edges of the fill area don't cover the axes
set(gca, 'Layer', 'top')

% plot the actual curves
for j = 1
    metricLines = zeros(length(bikes), 1);
    for i = 1:length(bikes)
        num = data.(bikes{i}).(speedNames{j}).handlingMetric.num;
        den = data.(bikes{i}).(speedNames{j}).handlingMetric.den;
        [mag, phase, freq] = bode(tf(num, den), w);
        metricLines(i) = plot(freq, mag(:)', ...
                              'Color', colors{i}, ...
                              'Linestyle', linestyles{i}, ...
                              'Linewidth', 2.0);
    end
end

% add the roll input bike
% num = rollData.handlingMetric.num;
% den = rollData.handlingMetric.den;
% [mag, phase, freq] = bode(tf(num, den), w);
% rollLine = plot(freq, mag(:)', 'k', 'Linewidth', 2.0, 'Linestyle', ':');

hold off

% move the roll input line down so it shows on the legend
chil = get(gca, 'Children');
% legLines = [chil(end:-1:13)', rollLine];
legend([{'2.0 m/s', 'Ami', 'Balance', 'Orange', 'OrangeHMB', 'OrangeHFP',...
    'Cityzen', 'CityzenSpeed', 'TourPopulair','PuurNL', 'VanStael'}], ...
        'Fontsize', 8)

ylim([0, 10]);
level1 = line([0, 30], [5, 5]);
level2 = line([0, 30], [8, 8]);
set(level1, 'Color', 'k', 'Linestyle', '--', 'Linewidth', 1.0)
set(level2, 'Color', 'k', 'Linestyle', '--', 'Linewidth', 1.0)
ylabel('Handling Quality Metric')
xlabel('Frequency (rad/s)')
title('Handling Quality Metric at 2.0 m/s')
text(3.1, 4.3, 'Level 1')
text(1.9, 6.5, 'Level 2')
text(3, 9.5, 'Level 3')
box on
```

```
set(gca, 'YColor', 'k')

filename = 'handling.eps';
pathToFile = ['plots' filesep filename];
print(pathToFile, '-deps2c', '-loose')
fix_ps_linestyle(pathToFile)

%% Creates handling quality for 5.5 m/s
global goldenRatio

bikes = fieldnames(data);
figure()
figWidth = 5.5;
figHeight = figWidth / goldenRatio;
set(gcf, ...
    'Color', [1, 1, 1], ...
    'PaperOrientation', 'portrait', ...
    'PaperUnits', 'inches', ...
    'PaperPositionMode', 'manual', ...
    'PaperPosition', [0, 0, figWidth, figHeight], ...
    'PaperSize', [figWidth, figHeight])

w = linspace(0.01, 30, 200);
speedNames = fieldnames(data.Balance);
fillColors = {[0.82, 0.82, 0.82]
              [0.68, 0.68, 0.68]
              [0.95, 0.95, 0.95]};
hold all

% plot the background area for each family of curves
for j = 2
    % get the max values for the set of curves
    magnitudes = zeros(length(w), length(bikes));
    for i = 1:length(bikes)
        num = data.(bikes{i}).(speedNames{j}).handlingMetric.num;
        den = data.(bikes{i}).(speedNames{j}).handlingMetric.den;
        [mag, phase, freq] = bode(tf(num, den), w);
        magnitudes(:, i) = mag(:)';
    end
    maxMag = max(magnitudes, [], 2);
    % fill the area under the curve
    area(freq, maxMag, ...
         'Facecolor', fillColors{j}, ...
         'Edgecolor', 'none')
end

% this makes sure that the edges of the fill area don't cover the axes
set(gca, 'Layer', 'top')

% plot the actual curves
for j = 2
    metricLines = zeros(length(bikes) - 1, 1);
    for i = 1:length(bikes)
        num = data.(bikes{i}).(speedNames{j}).handlingMetric.num;
        den = data.(bikes{i}).(speedNames{j}).handlingMetric.den;
        [mag, phase, freq] = bode(tf(num, den), w);
        metricLines(i) = plot(freq, mag(:)', ...
                              'Color', colors{i}, ...
                              'Linestyle', linestyles{i}, ...
                              'Linewidth', 2.0);
    end
end

% add the roll input bike
% num = rollData.handlingMetric.num;
% den = rollData.handlingMetric.den;
% [mag, phase, freq] = bode(tf(num, den), w);
% rollLine = plot(freq, mag(:)', 'k', 'Linewidth', 2.0, 'Linestyle', ':');

hold off
```

```
% move the roll input line down so it shows on the legend
chil = get(gca, 'Children');
legend([{'5.5 m/s', 'Ami', 'Balance', 'Orange', 'OrangeHMB', 'OrangeHFP',...
    'Cityzen', 'CityzenSpeed', 'TourPopulair','PuurNL', 'VanStael'}], ...
        'Fontsize', 8)

ylim([0, 10]);
level1 = line([0, 30], [5, 5]);
level2 = line([0, 30], [8, 8]);
set(level1, 'Color', 'k', 'Linestyle', '--', 'Linewidth', 1.0)
set(level2, 'Color', 'k', 'Linestyle', '--', 'Linewidth', 1.0)
ylabel('Handling Quality Metric')
xlabel('Frequency (rad/s)')
title('Handling Quality Metric at 5.5 m/s')
text(3.1, 4.3, 'Level 1')
text(1.9, 6.5, 'Level 2')
text(3, 9.5, 'Level 3')
box on

set(gca, 'YColor', 'k')

filename = 'handling.eps';
pathToFile = ['plots' filesep filename];
print(pathToFile, '-deps2c', '-loose')
fix_ps_linestyle(pathToFile)

%% Creates handling quality for 7.0 m/s
global goldenRatio

bikes = fieldnames(data);
figure()
figWidth = 5.5;
figHeight = figWidth / goldenRatio;
set(gcf, ...
    'Color', [1, 1, 1], ...
    'PaperOrientation', 'portrait', ...
    'PaperUnits', 'inches', ...
    'PaperPositionMode', 'manual', ...
    'PaperPosition', [0, 0, figWidth, figHeight], ...
    'PaperSize', [figWidth, figHeight])

w = linspace(0.01, 30, 200);
speedNames = fieldnames(data.Balance);
fillColors = {[0.82, 0.82, 0.82]
              [0.68, 0.68, 0.68]
              [0.95, 0.95, 0.95]};
hold all

% plot the background area for each family of curves
for j = 3
    % get the max values for the set of curves
    magnitudes = zeros(length(w), length(bikes) - 1);
    for i = 1:length(bikes)
        num = data.(bikes{i}).(speedNames{j}).handlingMetric.num;
        den = data.(bikes{i}).(speedNames{j}).handlingMetric.den;
        [mag, phase, freq] = bode(tf(num, den), w);
        magnitudes(:, i) = mag(:)';
    end
    maxMag = max(magnitudes, [], 2);
    % fill the area under the curve
    area(freq, maxMag, ...
         'Facecolor', fillColors{j}, ...
         'Edgecolor', 'none')
end

% this makes sure that the edges of the fill area don't cover the axes
set(gca, 'Layer', 'top')

% plot the actual curves
for j = 3
    metricLines = zeros(length(bikes), 1);
```

```
    for i = 1:length(bikes)
        num = data.(bikes{i}).(speedNames{j}).handlingMetric.num;
        den = data.(bikes{i}).(speedNames{j}).handlingMetric.den;
        [mag, phase, freq] = bode(tf(num, den), w);
        metricLines(i) = plot(freq, mag(:)', ...
                              'Color', colors{i}, ...
                              'Linestyle', linestyles{i}, ...
                              'Linewidth', 2.0);
    end
end

% add the roll input bike
% num = rollData.handlingMetric.num;
% den = rollData.handlingMetric.den;
% [mag, phase, freq] = bode(tf(num, den), w);
% rollLine = plot(freq, mag(:)', 'k', 'Linewidth', 2.0, 'Linestyle', ':');

hold off

% move the roll input line down so it shows on the legend
chil = get(gca, 'Children');
legend([{'7.0 m/s', 'Ami', 'Balance', 'Orange', 'OrangeHMB', 'OrangeHFP',...
    'Cityzen', 'CityzenSpeed', 'TourPopulair','PuurNL', 'VanStael'}], ...
        'Fontsize', 8)

ylim([0, 10]);
level1 = line([0, 30], [5, 5]);
level2 = line([0, 30], [8, 8]);
set(level1, 'Color', 'k', 'Linestyle', '--', 'Linewidth', 1.0)
set(level2, 'Color', 'k', 'Linestyle', '--', 'Linewidth', 1.0)
ylabel('Handling Quality Metric')
xlabel('Frequency (rad/s)')
title('Handling Quality Metric at 7.0 m/s')
text(3.1, 4.3, 'Level 1')
text(1.9, 6.5, 'Level 2')
text(3, 9.5, 'Level 3')
box on

set(gca, 'YColor', 'k')

filename = 'handling.eps';
pathToFile = ['plots' filesep filename];
print(pathToFile, '-deps2c', '-loose')
fix_ps_linestyle(pathToFile)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function path_plots(data, linestyles, colors)
% Creates a plot of the path tracking for all bikes at all speeds.

global goldenRatio

bikes = fieldnames(data);
speedNames = fieldnames(data.Balance);

figure()
figWidth = 5.5;
figHeight = figWidth / goldenRatio;
set(gcf, ...
    'Color', [1, 1, 1], ...
    'PaperOrientation', 'portrait', ...
    'PaperUnits', 'inches', ...
    'PaperPositionMode', 'manual', ...
    'PaperPosition', [0, 0, figWidth, figHeight], ...
    'PaperSize', [figWidth, figHeight])

hold all

% shifts the paths by this many meters
shift = [0, 15, 35];
for j = 1:length(speedNames)
    time = data.(bikes{2}).(speedNames{j}).time;
```

```
    path = data.(bikes{2}).(speedNames{j}).path;
    speed = data.(bikes{2}).(speedNames{j}).speed;
    plot(time * speed + shift(j), -path * j, 'k-')
    for i = 2:length(bikes)
        x = data.(bikes{i}).(speedNames{j}).outputs(:, 17);
        x = x + shift(j);
        y = data.(bikes{i}).(speedNames{j}).outputs(:, 18);
        plot(x, -y * j, ...
             'Linestyle', linestyles{i - 1}, ...
             'Color', colors{i - 1}, ...
             'Linewidth', 0.75)
    end
    [minPath, minPathI] = min(-path * j);
    dis = time * speed + shift(j);
    lab = sprintf('%1.1f m/s', speed);
    text(dis(minPathI) - 15, minPath - 0.4, lab)
end

hold off

% change the y tick labels to positive and to reflect the 2 meter width
set(gca, 'YTick', [-7, -6, -4, -2, 0, 1])
set(gca, 'YTickLabel', {'', '2', '2', '2', '0', ''})

xlim([30 200])
box on
legend(['Path', {'Ami', 'Balance', 'Orange', 'OrangeHMB', 'OrangeHFP', ...
    'Cityzen', 'CityzenSpeed', 'TourPopulair','PuurNL', 'VanStael'}], ...
       'Fontsize', 8, 'Location', 'Southeast')
xlabel('Distance (m)')
ylabel('Lateral Deviation (m)')
filename = 'paths.eps';
pathToFile = ['plots' filesep filename];
print(pathToFile, '-deps2c', '-loose')
fix_ps_linestyle(pathToFile)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function plot_io(variable, io, xAxis, data, linestyles, colors)
% Creates a plot of the time histories of a particular output or input variable
% for three different speeds with either time or distance on the x axis.
%
% Parameters
% ----------
% variable : string
%   The name of the variable you'd like to plot.
% io : string
%   'input' for input and 'output' for output.
% data : structure
%   Data for a set of bicycles, the first being the benchmark bicycle.
% xAxis : string
%   'Distance' or 'Time' on the x axis.
% linestyles : cell array
%   An array of linestyle types, one for each bicycle.
% colors : cell array
%   An array of colors, one for each bicycle.

global goldenRatio

if strcmp(io, 'input')
    names = {'Tphi','Tdelta','F'};
    prettyNames = {'$T_\phi$','$T_\delta$','$F$'};
    units = {'(N-m)','(N-m)', '(N)'};
elseif strcmp(io, 'output')
    names = {'xP','yP','psi','phi','thetaP','thetaR','delta','thetaF','xPDot',
             'ypDot','psiDot','phiDot','thetaPDot','thetaRDot','deltaDot',
             'thetaFDot','xQ','yQ'};
    prettyNames = {'$x_P$','$y_P$','$\psi$','$\phi$','$\theta_P$','$\theta_R$',
                   '$\delta$','$\theta_F$','$\dot{x}_P$','$\dot{y}_P$',
                   '$\dot{\psi}$','$\dot{\phi}$','$\dot{\theta}_P$','$\dot{\theta}_R$',
                   '$\dot{\delta}$','$\dot{\theta}_F$','$x_Q$','$y_Q$'};
    units = {'(m)','(m)','(rad)','(rad)','(rad)','(rad)','(rad)','(rad)',
```

```
            '(m/s)','(m/s)','(rad/s)','(rad/s)','(rad/s)','(rad/s)','(rad/s)',
            '(rad/s)','(m)','(m)'};
else
    error('Please choose i or o')
end

index = find(ismember(names, variable) == 1);

bikes = fieldnames(data);
speedNames = fieldnames(data.Balance);

figure()
figWidth = 5.5;
figHeight = figWidth / goldenRatio;
set(gcf, ...
    'Color', [1, 1, 1], ...
    'PaperOrientation', 'portrait', ...
    'PaperUnits', 'inches', ...
    'PaperPositionMode', 'manual', ...
    'PaperPosition', [0, 0, figWidth, figHeight], ...
    'PaperSize', [figWidth, figHeight])

% find the maximum value of the variable
maxValue = 0;
for i = 2:length(bikes)
    for j = 1:length(speedNames)
        oneSpeed = data.(bikes{i}).(speedNames{j});
        history = oneSpeed.([io 's'])(:, index);
        if max(history) > maxValue
            maxValue = max(history);
        end
    end
end

m = round(maxValue * 100) / 100;
pad = 0.15 * m;
yShift = [0, 2 * (m + pad), 4 * (m + pad)];

% shifts the paths by this many meters along the x axis
xShift = [0, 15, 35];
hold all
for j = 1:length(speedNames)
    for i = 2:length(bikes)
        oneSpeed = data.(bikes{i}).(speedNames{j});
        time = oneSpeed.time;
        speed = oneSpeed.speed;
        distance = time * speed + xShift(j);
        % time history of the value
        history = oneSpeed.([io 's'])(:, index) + yShift(j);
        if strcmp(xAxis, 'Distance')
            xData = distance;
            textX = 165;
        elseif strcmp(xAxis, 'Time')
            xData = time;
            textX = 2;
        else
            error('Choose Time or Distance, no other')
        end
        plot(xData, history, ...
             'Linestyle', linestyles{i - 1}, ...
             'Color', colors{i - 1}, ...
             'Linewidth', 0.75)
    end
    % add labels for the speeds
    text(textX, yShift(j) + 4 * pad, [num2str(speed) ' m/s'])
end

ylim([-m - pad, yShift(3) + m + pad])
set(gca, 'YTick', ...
    [-m, yShift(1), m, ...
     yShift(2) - m, yShift(2), yShift(2) + m, ...
```

```
     yShift(3) - m, yShift(3), yShift(3) + m])
ticks = {num2str(-m), '0', num2str(m)};
set(gca, 'YTickLabel', [ticks, ticks ticks])

if strcmp(xAxis, 'Distance')
    xlabel('Distance (m)')
    xLimits = [35, 190];
    xlim(xLimits)
    loc = 'Northwest';
else
    xlabel('Time (s)')
    xLimits = [0, 50];
    xlim(xLimits)
    loc = 'Northeast';
end
l1 = line(xLimits, [yShift(1) + m + pad, yShift(1) + m + pad]);
l2 = line(xLimits, [yShift(2) + m + pad, yShift(2) + m + pad]);
set([l1, l2], 'Color', 'k')
hold off
set(gca, 'Fontsize', 8)
first = [prettyNames{index} ' ' units{index}];
ylabel(first, 'Interpreter', 'Latex')
box on
legend({'Ami', 'Balance', 'Orange', 'OrangeHMB', 'OrangeHFP', 'Cityzen', ...
     'CityzenSpeed', 'TourPopulair','PuurNL', 'VanStael'}, 'Fontsize', 8, ...
     'Location', loc)

% if it is the steer angle plot for distance, add a magnifier for the
% countersteer
if strcmp(variable, 'delta') && strcmp(xAxis, 'Distance')
    % Specify the position and the size of the rectangle
    x_r = 37; y_r = 0; w_r = 4; h_r = 0.01;
    rectangle('Position', [x_r-w_r/2, y_r-h_r/2, w_r, h_r], ...
              'EdgeColor', 'k');
    % Specify the position and the size of the 2. axis
    x_a = 0.2; y_a = 0.29; w_a = 0.15; h_a = w_a * h_r / w_r * 20 / 0.05;
    ax = axes('Units', 'Normalized', ...
              'Position', [x_a, y_a, w_a, h_a], ...
              'XTick', [], ...
              'YTick', [], ...
              'Box', 'on', ...
              'LineWidth', 0.5, ...
              'Color', 'w');
    hold on
    j = 1;
    for i = 2:length(bikes)
        oneSpeed = data.(bikes{i}).(speedNames{j});
        time = oneSpeed.time;
        speed = oneSpeed.speed;
        distance = time * speed + xShift(j);
        % time history of the value
        history = oneSpeed.([io 's'])(:, index) + yShift(j);
        plot(distance, history, ...
             'Linestyle', linestyles{i - 1}, ...
             'Color', colors{i - 1}, ...
             'Linewidth', 0.75)
    end
    hold off
    axis([x_r-w_r/2, x_r+w_r/2, y_r-h_r/2, y_r+h_r/2]);
    text(35.3, -0.003, 'Countersteer', 'Fontsize', 8)
    % bottom left
    annotation('line', [x_a, 0.129], [y_a, 0.235])
    % top left
    annotation('line', [x_a, 0.132], [y_a + h_a, 0.26])
    % bottom right
    annotation('line', [x_a + w_a, 0.15], [y_a, 0.235])
    % top right
    annotation('line', [x_a, 0.15], [y_a + 0.02, 0.26])
end

% save the file
```

```
filename = [variable xAxis '.eps'];
print(['plots' filesep filename], '-deps2c', '-loose')
fix_ps_linestyle(['plots' filesep filename])

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function plot_io_roll(rollData, xAxis)

global goldenRatio

% closed loop bode plots
figure()
figWidth = 5.5;
figHeight = figWidth / goldenRatio;
set(gcf, ...
    'Color', [1, 1, 1], ...
    'PaperOrientation', 'portrait', ...
    'PaperUnits', 'inches', ...
    'PaperPositionMode', 'manual', ...
    'PaperPosition', [0, 0, figWidth, figHeight], ...
    'PaperSize', [figWidth, figHeight])

speed = rollData.speed;
time = rollData.time;
path = rollData.path;
frontWheel = rollData.outputs(:, 18);
rollAngle = rollData.outputs(:, 4);
steerAngle = rollData.outputs(:, 7);
rollTorque = rollData.inputs(:, 1);

% plot the path
subplot(2, 1, 1)
hold all
if strcmp(xAxis, 'Distance')
    plot(speed * time, -path, 'k-', 'Linewidth', 1.0)
    plot(speed * time, -frontWheel, 'k:', 'Linewidth', 1.0)
    xlabel('Distance (m)')
    xlim([30, 150])
elseif strcmp(xAxis, 'Time')
    plot(time, -path, 'k-', 'Linewidth', 1.0)
    plot(time, -frontWheel, 'k:', 'Linewidth', 1.0)
    xlabel('Time (s)')
    xlim([30 / speed, 150 / speed])
else
    error('Bad xAxis, choose Distance or Time')
end
hold off
box on
ylabel('Lateral Deviation (m)')
ylim([-2.2, 0.2])
set(gca, 'YTickLabel', {'2', '1', '0'})
legend({'Path'}, ...
       'Interpreter', 'Latex', ...
       'Fontsize', 8, ...
       'Location', 'Southeast')

subplot(2, 1, 2)
hold all
if strcmp(xAxis, 'Distance')
    plot(speed * time, rollAngle, 'k-', 'Linewidth', 1.0)
    [ax, h1, h2] = plotyy(speed * time, steerAngle, speed * time, rollTorque);
    xlabel('Distance (m)')
    xlim(ax(1), [30, 150])
    xlim(ax(2), [30, 150])
elseif strcmp(xAxis, 'Time')
    plot(time, rollAngle, 'k-', 'Linewidth', 1.0)
    [ax, h1, h2] = plotyy(time, steerAngle, time, rollTorque);
    xlabel('Time (s)')
    xlim(ax(1), [30 / speed, 150 / speed])
    xlim(ax(2), [30 / speed, 150 / speed])
else
    error('Bad xAxis, choose Distance or Time')
```

```
end
hold off
box on

set(get(ax(1), 'Ylabel'), ...
    'String', 'Angle (rad)', ...
    'Color', 'k')
set(get(ax(2), 'Ylabel'), ...
    'String', 'Torque (N-m)', ...
    'Color', 'k')
set(ax, 'YColor', 'k', 'Fontsize', 8)
set(h1, 'Linestyle', '--', 'Color', 'k', 'Linewidth', 1.0)
set(h2, 'Linestyle', '-.', 'Color', 'k', 'Linewidth', 1.0)
legend({'$\phi$', '$\delta$', '$T_\phi$'}, ...
       'Interpreter', 'Latex', ...
       'Fontsize', 8, ...
       'Location', 'Northeast')

if strcmp(xAxis, 'Distance')
    axes(ax(2))
    % magnifier rectangle
    x_r = 38; y_r = 0; w_r = 10; h_r = 0.3;
    rectangle('Position', [x_r-w_r/2, y_r-h_r/2, w_r, h_r], ...
              'EdgeColor', 'k');
    % magnify it
    x_a = 0.14; y_a = 0.432; w_a = 0.28; h_a = 0.12;
    inset = axes('Units', 'Normalized', ...
                 'Position', [x_a, y_a, w_a, h_a], ...
                 'Box', 'on', ...
                 'LineWidth', 0.5, ...
                 'Color', [0.8, 0.8, 0.8]);
    hold on
    plot(inset, time, rollAngle, 'k-', 'Linewidth', 1.0)
    [ax, h1, h2] = plotyy(inset, time, steerAngle, time, rollTorque);
    set(ax, 'XTick', [], ...
            'YTick', [], ...
            'YColor', 'k')
    set(h1, 'Linestyle', '--', 'Color', 'k', 'Linewidth', 1.0)
    set(h2, 'Linestyle', '-.', 'Color', 'k', 'Linewidth', 1.0)
    axis(ax(1), [7, 8.5, -0.0025, 0.0025])
    axis(ax(2), [7, 8.5, -0.0025 / 0.02, 0.0025 / 0.02])

    % draw some lines connecting the corners
    annotation('line', [x_a, 0.149], [y_a, 0.287])
    annotation('line', [x_a + w_a, 0.213], [y_a, 0.287])
    annotation('textbox', [0.26, 0.47, 0.1, 0.02], ...
               'String', 'Countersteer', ...
               'Fontsize', 8, ...
               'Edgecolor', 'none')
end

filename = ['roll' xAxis '.eps'];
print(gcf, ['plots' filesep filename], '-deps2c', '-loose')
fix_ps_linestyle(['plots' filesep filename])

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function phase_portraits(bikeData)
% Creates four phase portrait plots to demonstrate the effects on the phase
% portraits when adjusting the gains.

global goldenRatio

figure()
figWidth = 6.0;
figHeight = figWidth / goldenRatio;
set(gcf, ...
    'Color', [1, 1, 1], ...
    'PaperOrientation', 'portrait', ...
    'PaperUnits', 'inches', ...
    'PaperPositionMode', 'manual', ...
    'OuterPosition', [424, 305 - 50, 518, 465], ...
```

```
    'PaperPosition', [0, 0, figWidth, figHeight], ...
    'PaperSize', [figWidth, figHeight])

% this is the gain multiplier for the non-nominal plot
gainChanges = [1.2, 1, 1, 1, 1;
               1, 1.2, 1, 1, 1;
               1, 1, 1.2, 1, 1;
               1, 1, 1.2, 0.8, 0.8];

loopNames = {'kDelta', 'kPhiDot', 'kPhi', 'kPhi'};
% the x and y indices for each plot
xy = [7, 15; 4, 12; 4, 12; 4, 12];
% where to get the x and y data from
xySource = {'outputs', 'outputsDot', 'outputs', 'outputs'};

% axis labels
xlabels = {'(a) $\delta$ (rad)','(b) $\dot{\phi}$ (rad/s)',
           '(c) $\phi$ (rad)','(d) $\phi$ (rad)'};
ylabels = {'$\dot{\delta}$ (rad/s)','$\ddot{\phi}$ (rad/s$^2$)',
           '$\dot{\phi}$ (rad/s)','$\dot{\phi}$ (rad/s)'};

% legend starts
legends = {'$k_\delta$ = ','$k_{\dot{\phi}}$ = ','$k_\phi$ = ','$k_\phi$ = '};
% how many decimals to show for each legend
floatSpec = {'%1.1f', '%1.3f', '%1.1f', '%1.1f'};

for i = 1:length(loopNames)

    display(sprintf('Calculating phase portrait %d', i))

    % adjust the gains and get the data
    twentyPercent = generate_data('Ami', 5.5, ...
                                  'gainMuls', gainChanges(i, :));
    subplot(2, 2, i)
    hold on

    if i == 4
        display('Phase portrait 4 comparison data.')
        nominalData = generate_data('Ami', 5.5, ...
                                  'gainMuls', [1, 1, 1, 0.8, 0.8]);
        x = nominalData.(xySource{i})(:, xy(i, 1));
        y = nominalData.(xySource{i})(:, xy(i, 2));
    else
        x = bikeData.(xySource{i})(:, xy(i, 1));
        y = bikeData.(xySource{i})(:, xy(i, 2));
    end
    plot(x, y, 'k-', 'Linewidth', 1.0)

    x = twentyPercent.(xySource{i})(:, xy(i, 1));
    y = twentyPercent.(xySource{i})(:, xy(i, 2));
    plot(x, y, 'k--', 'Linewidth', 1.0)

    hold off

    box on
    axis equal
    xlabel(xlabels{i}, 'Interpreter', 'Latex', 'Fontsize', 8)
    ylabel(ylabels{i}, 'Interpreter', 'Latex', 'Fontsize', 8)

    % make the legend
    leg1 = sprintf(floatSpec{i}, bikeData.modelPar.(loopNames{i}));
    leg2 = sprintf(floatSpec{i}, twentyPercent.modelPar.(loopNames{i}));
    legend({[legends{i} leg1], [legends{i} leg2]} , ...
           'Interpreter', 'Latex', ...
           'Fontsize', 6)
end

plotAxes = findobj(gcf, 'Type', 'Axes');
set(plotAxes, 'Fontsize', 8)

% save the plot
```

```
filename = 'phasePortraits.eps';
print(gcf, ['plots' filesep filename], '-deps2c', '-loose')
fix_ps_linestyle(['plots' filesep filename])

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function eigenvalues(data, linestyles, colors)

global goldenRatio

figure()
figWidth = 5.5;
figHeight = figWidth / goldenRatio;
set(gcf, ...
    'Color', [1, 1, 1], ...
    'PaperOrientation', 'portrait', ...
    'PaperUnits', 'inches', ...
    'PaperPositionMode', 'manual', ...
    'PaperPosition', [0, 0, figWidth, figHeight], ...
    'PaperSize', [figWidth, figHeight])

bikes = fieldnames(data);
%bikes(1) = [];
speeds = 0:0.1:10;
eVals = zeros(length(bikes), length(speeds), 11);
for i = 1:length(bikes)
    % load the bicycle parameters
    pathToParFile = ['parameters' filesep bikes{i} 'Par.txt'];
    par = par_text_to_struct(pathToParFile);
    str = 'Calculating eigenvalues for the %s bicycle and rider.';
    display(sprintf(str, bikes{i}))
    for j = 1:length(speeds)
        % calculate the A, B, C, and D matrices of the bicycle model
        [A, B, C, D] = whipple_pull_force_abcd(par, speeds(j));
        eigenValues = eig(A);
        eVals(i, j, :) = real(eig(A));
    end
end

% reduce to the maximum values
zeroIndices = find(abs(eVals) <= 0.000001);
eVals(zeroIndices) = -100 * ones(size(zeroIndices));
maxEvals = max(eVals, [], 3);

lines = plot(speeds, maxEvals);

for i = 1:length(lines)
    set(lines(i),  'Linestyle', linestyles{i}, 'Color', colors{i},'Linewidth', 1)
end

legend({'Ami', 'Balance', 'Orange', 'OrangeHMB', 'OrangeHFP', 'Cityzen', 'CityzenSpeed',...
    'TourPopulair','PuurNL', 'VanStael'})
xlabel('Speed (m/s)')
ylabel('Maximum real part of the eigenvalue (1/s)')

% set the tick marks differently
%set(gca, 'XTick', 0:0.5:10)
%set(gca, 'XTickLabel', {'0', '', '1', '', ...
                        %'2', '2.0', '3', '', ...
                        %'4', '', '5.5', '', ...
                        %'6', '', '7', '7.0', ...
                        %'8', '', '9', '', '10'})
%
% add some lines and labels for the speeds we looked at
hold on
maxLine = max(maxEvals, [], 1);
minLine = min(maxEvals, [], 1);
lines = zeros(4, 1);
speedInd = find(speeds == 2.0);
lines(1) = line([2.0, 2.0], ...
                [minLine(speedInd) - 0.4, maxLine(speedInd) + 0.4]);
text(2, maxLine(speedInd) + 0.7, '2.0 m/s')
```

```
speedInd = find(speeds == 5.5);
lines(2) = line([5.5, 5.5], ...
                [minLine(speedInd) - 0.4, maxLine(speedInd) + 0.4]);
text(4.5, maxLine(speedInd) + 0.7, '5.5 m/s')
speedInd = find(speeds == 7.0);
lines(3) = line([7.0, 7.0], ...
                [minLine(speedInd) - 0.4, maxLine(speedInd) + 0.4]);
text(7, maxLine(speedInd) + 0.7, '7.0 m/s')

lines(4) = line([0, 10], [0, 0]);
hold off

set(lines, 'Color', 'k', 'Linewidth', 2)

% save the plot
filename = 'eigenvalues.eps';
print(gcf, ['plots' filesep filename], '-deps2c', '-loose')
fix_ps_linestyle(['plots' filesep filename])
```

HQM GAINS

Figure E.20.

Gains guessed by the HQM-Matlab option gainGuess. The gains are provided for each bicycle for each speed.

Gains at 2 m/s

Bicycle	K_δ	$K_{\varphi,dot}$	K_φ	K_ψ	K_y
Ami	5.2734	-12.8894	2.0490	0.1858	0.2199
Balance	6.7412	-10.6494	2.0792	0.1828	0.2178
Orange	4.5139	-14.4851	2.0486	0.1898	0.2180
Orange HFP	10.9266	-10.6697	2.1032	0.1753	0.2183
Orange HMB	4.6215	-16.4084	2.0188	0.1930	0.2202
Cityzen	5.3042	-0.0081	292.1501	0.0553	0.1798
Cityzen Speed	3.1842	-0.1664	7.7619	0.0860	0.1873
Tour Populair	6.0755	-0.2938	5.5430	0.0851	0.1930
Puur NL	5.4829	-0.1861	10.8696	0.0838	0.1835
Van Stael	5.3774	-0.0690	27.8346	0.0568	0.1855

Gains at 5.5 m/s

Bicycle	K_δ	$K_{\varphi,dot}$	K_φ	K_ψ	K_y
Ami	50.7070	0.0230	19.3445	1.0233	0.1010
Balance	78.1025	0.0246	20.4542	1.0289	0.1004
Orange	52.7893	0.0193	24.4832	1.0306	0.1010
Orange HFP	112.2440	0.0269	17.3247	1.0097	0.1004
Orange HMB	47.6081	0.0212	22.1111	1.0207	0.1011
Cityzen	58.8532	0.0205	22.5852	1.0441	0.1010
Cityzen Speed	38.3041	0.0084	58.1064	1.0125	0.1016
Tour Populair	77.5026	0.0206	23.8470	1.0244	0.1008
Puur NL	87.3751	0.0120	38.6500	1.0258	0.1010
Van Stael	42.8803	0.0094	85.1965	0.7519	0.1373

Gains at 7.0 m/s

Bicycle	K_δ	$K_{\varphi,dot}$	K_φ	K_ψ	K_y
Ami	53.6323	0.0932	3.0085	1.3136	0.0780
Balance	90.1989	0.0997	3.3400	1.2897	0.0772
Orange	57.1377	0.0986	3.0189	1.3247	0.0779
Orange HFP	133.9923	0.0990	3.1798	1.2560	0.0770
Orange HMB	41.4163	0.0950	3.0981	1.3182	0.0785
Cityzen	69.1120	0.1007	2.9164	1.3325	0.0776
Cityzen Speed	40.5916	0.1002	2.9152	1.3288	0.0786
Tour Populair	83.8969	0.1028	3.0618	1.3088	0.0775
Puur NL	100.2879	0.0945	3.0729	1.3141	0.0775
Van Stael	58.9600	0.0933	2.9272	1.3515	0.0775

Figure E20: Gains for the HQM.

F

CORRELATIONS

MATLAB FILES CORRELATIONS

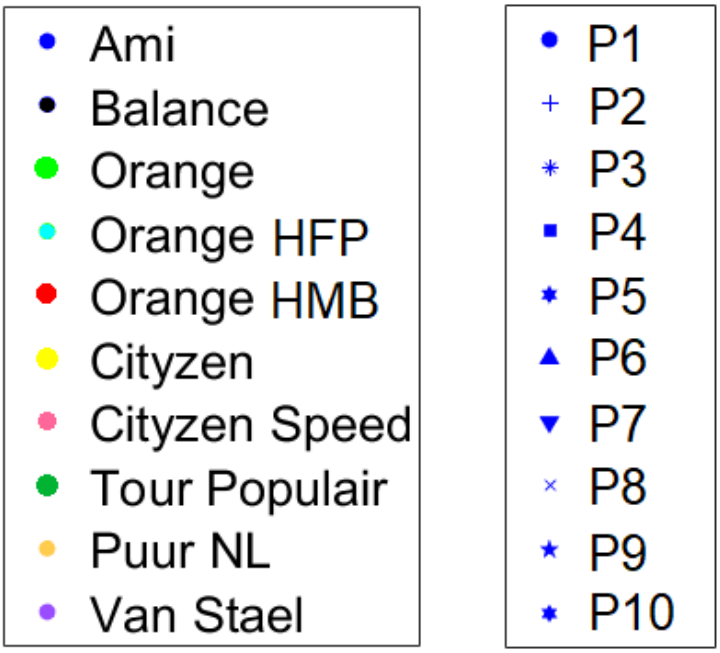
```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Scatter Plots All Together %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear all
close all

[values, text, raw] = xlsread('Data File Filtered');
Bicycle = text(2:end,1);
Participant = text(2:end,2);

Vraag_1 = values(:,90); Vraag_2 = values(:,91); Vraag_3 = values(:,92); Vraag_4 = values(:,93);
Vraag_5 = values(:,94); Vraag_6 = values(:,95); Vraag_7 = values(:,96); Vraag_8 = values(:,97);
Vraag_9 = values(:,98); Vraag_10 = values(:,99); Vraag_11 = values(:,100); Vraag_12 = values(:,101);
Vraag_13 = values(:,102); Vraag_14 = values(:,103);

Real_Largest_2 = values(:,65); Imag_Largest_2 = values(:,66);
Real_Largest_7 = values(:,73); Imag_Largest_7 = values(:,74);
Real_Largest_Free = values(:,81); Imag_Largest_Free = values(:,82);

Steer_2_Peak = values(:,59); Steer_7_Peak = values(:,60); Steer_Free_Peak = values(:,61);
Steer_2_0 = values(:,62); Steer_7_0 = values(:,63); Steer_Free_0 = values(:,64);

Surface_Yaw_2 = values(:,54); Surface_Yaw_7 = values(:,56); Surface_Yaw_Free = values(:,52);

title_vraag =  ["Question 1" "Question 2" "Question 3" "Question 4" ...
    "Question 5" "Question 6" "Question 7" "Question 8" "Question 9" ...
    "Question 10" "Question 11" "Question 12" "Question 13" "Question 14"];
Vraag = [Vraag_1 Vraag_2 Vraag_3 Vraag_4 Vraag_5 Vraag_6 Vraag_7 Vraag_8 ...
    Vraag_9 Vraag_10 Vraag_11 Vraag_12 Vraag_13 Vraag_14];

title_variable = ["Steer Stiffness at 2ms-1 with peak frequency" ...
    "Steer Stiffness at 7ms-1 with peak frequency" ...
    "Steer Stiffness at free speed with peak frequency" ...
    "Steer Stiffness at 2ms-1 with 0 Hz" "Steer Stiffness at 7ms-1 with 0 Hz"...
    "Steer Stiffness at free speed with 0 Hz" "Largest Real Eigenvalue at 2ms-1"...
    "Largest Real Eigenvalue at 7ms-1" "Largest Real Eigenvalue at free speed"...
    "Imaginairy Eigenvalue at 2ms-1" "Imaginairy Eigenvalue at 7ms-1"...
    "Imaginairy Eigenvalue at free speed" "Surface PSD at 2ms-1" ...
    "Surface PSD at 7ms-1" "Surface PSD at free speed"];
Variable = [Steer_2_Peak Steer_7_Peak Steer_Free_Peak Steer_2_0 Steer_7_0...
    Steer_Free_0 Real_Largest_2 Real_Largest_7 Real_Largest_Free Imag_Largest_2...
    Imag_Largest_7 Imag_Largest_Free Surface_Yaw_2 Surface_Yaw_7 Surface_Yaw_Free];

for l = 1:length(title_variable)
    Variable_now = Variable(:,l);
    Unit = ["Steerstiffness [T_\delta/\delta]" "Steerstiffness [T_\delta/\delta]"...
```

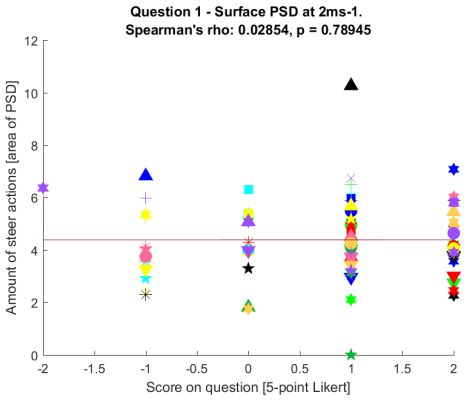
```
    "Steerstiffness [T_\delta/\delta]" "Steerstiffness [T_\delta/\delta]"...
    "Steerstiffness [T_\delta/\delta]" "Steerstiffness [T_\delta/\delta]"...
    "Real Eigenvalue []" "Real Eigenvalue []" "Real Eigenvalue[]"...
    "Imaginairy Eigenvalue []" "Imaginairy Eigenvalue []"...
    "Imaginairy Eigenvalue []" "Amount of steer actions [area of PSD]"...
    "Amount of steer actions [area of PSD]" "Amount of steer actions [area of PSD]"];
for k = 1:length(title_vraag)
Vraag_now = Vraag(:,k);
    for i = 1:length(Bicycle)
        bicycle = Bicycle(i);
        participant = Participant(i);
        if bicycle == "Ami"
            colour = 'b';
        elseif bicycle == "Balance"
            colour = 'k';
        elseif bicycle == "Orange"
            colour = 'g';
        elseif bicycle == "Orange HFP"
            colour = 'c';
        elseif bicycle == "Orange HBM"
            colour = 'r';
        elseif bicycle == "Cityzen"
            colour = 'y';
        elseif bicycle == "Cityzen Speed"
            colour = [1 0.4 0.6];
        elseif bicycle == "Tour Populair"
            colour = [0 0.7 0.2];
        elseif bicycle == "Puur NL"
            colour = [1 0.8 0.3];
        else  %Bicycle = Van Stael
            colour = [0.6 0.3 1];
        end

        if participant == "P1"
            shape = 'o';
        elseif participant == "P2"
            shape = '+';
        elseif participant == "P3"
            shape = '*';
        elseif participant == "P4"
            shape = 's';
        elseif Participant == "P5"
            shape = 'd';
        elseif participant == "P6"
            shape = '^';
        elseif participant == "P7"
            shape = 'v';
        elseif participant == "P8"
            shape = 'x';
        elseif participant == "P9"
            shape = 'p';
        else %Participant = P10
            shape = 'h' ;
        end
       Marker = strcat(shape, colour);
       figure(1)
       scatter(Vraag_now(i),Variable_now(i),[90],shape,'MarkerEdgeColor',...
           colour,'MarkerFaceColor',colour);
       hold on
    end

    P = polyfit(Vraag_now,Variable_now,1);
    yfit = polyval(P,Vraag_now);
    plot(Vraag_now,yfit)
    Richting = P(1);
    [r,p] = corr(Vraag_now, Variable_now,'type','Spearman');
    title([strcat(title_vraag(k), " - ", title_variable(l), ". "); ...
        strcat("Spearman's rho: ", num2str(r), ", p = ", num2str(p))])
    xlabel('Score on question [5-point Likert]')
    ylabel(Unit(l))
    hold off
```

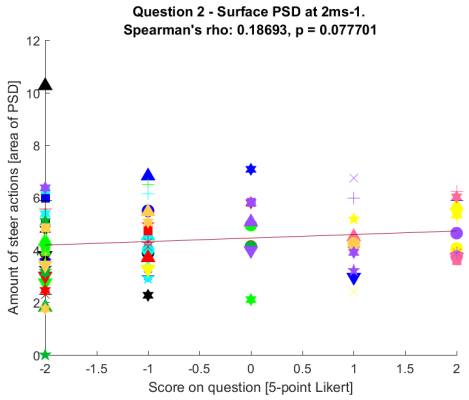
```
        filename = char(strcat(title_vraag(k), " - ", title_variable(l), ".png"));
        path = 'C:\Users\carli\Documents\Afstudeer Project\Project\Jbike6\Scatter Plots';
        saveas(figure(1),fullfile(path,filename));
    end
end
```

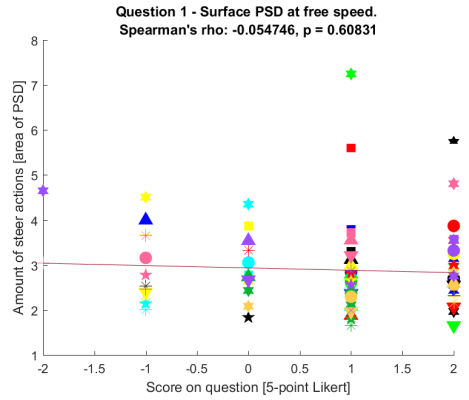
PSD CORRELATIONS

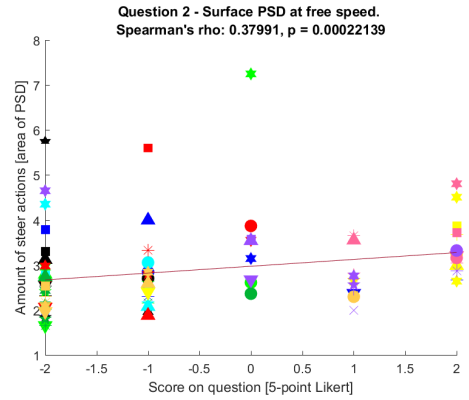
The following figures show the correlations of the PSD for 2 m/s, the free speed and 7 m/s with every question of the questionnaire. A correlation of $\rho = 1$ describes a perfect linear relationship between the two variables, with a correlation $\rho = 0$ there is none and with $\rho = 0.5$ there is a moderate correlation. The results are found to be significant when $p < 0.05$.

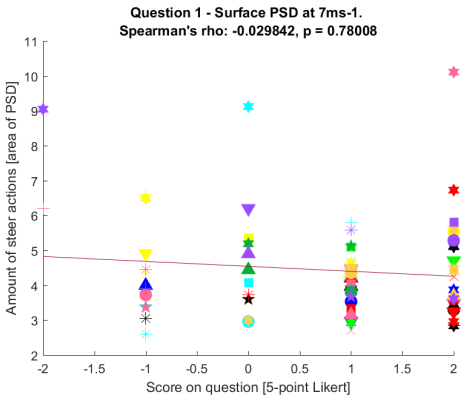


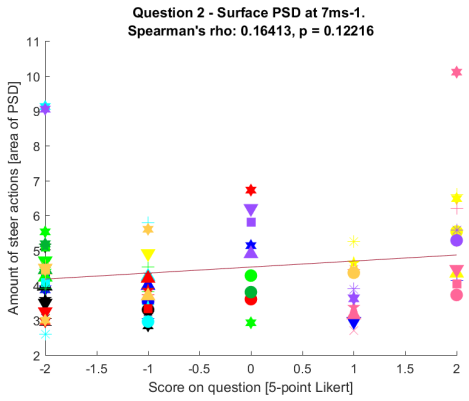

Question 1 - Surface PSD at 2ms-1.
Spearman's rho: 0.02854, p = 0.78945
Amount of steer actions [area of PSD]
Score on question [5-point Likert]

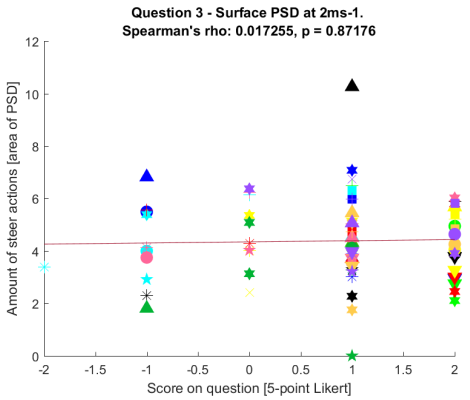

Question 2 - Surface PSD at 2ms-1.
Spearman's rho: 0.18693, p = 0.077701
Amount of steer actions [area of PSD]
Score on question [5-point Likert]

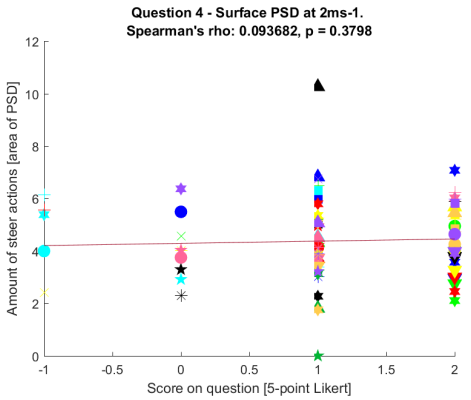

Question 1 - Surface PSD at free speed.
Spearman's rho: -0.054746, p = 0.60831
Amount of steer actions [area of PSD]
Score on question [5-point Likert]

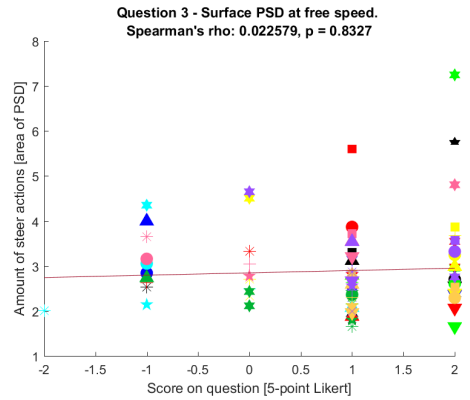

Question 2 - Surface PSD at free speed.
Spearman's rho: 0.37991, p = 0.00022139
Amount of steer actions [area of PSD]
Score on question [5-point Likert]

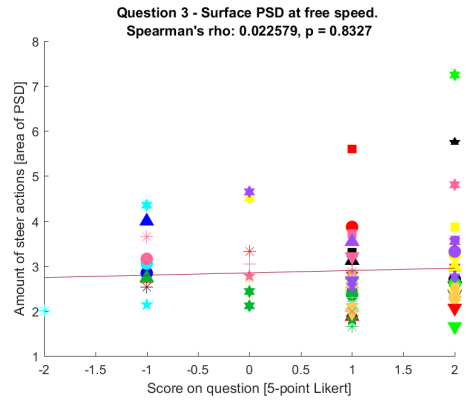

Question 1 - Surface PSD at 7ms-1.
Spearman's rho: -0.029842, p = 0.78008
Amount of steer actions [area of PSD]
Score on question [5-point Likert]

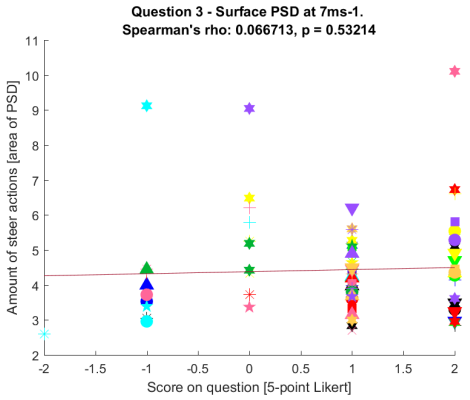

Question 2 - Surface PSD at 7ms-1.
Spearman's rho: 0.16413, p = 0.12216
Amount of steer actions [area of PSD]
Score on question [5-point Likert]

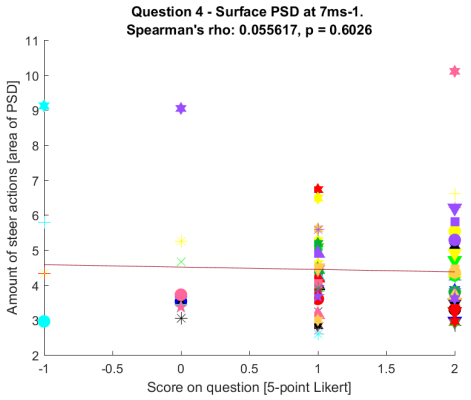

Question 3 - Surface PSD at 2ms-1.
Spearman's rho: 0.017255, p = 0.87176
Amount of steer actions [area of PSD]
Score on question [5-point Likert]

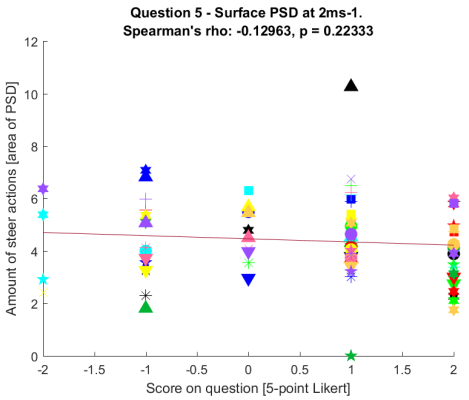

Question 4 - Surface PSD at 2ms-1.
Spearman's rho: 0.093682, p = 0.3798
Amount of steer actions [area of PSD]
Score on question [5-point Likert]

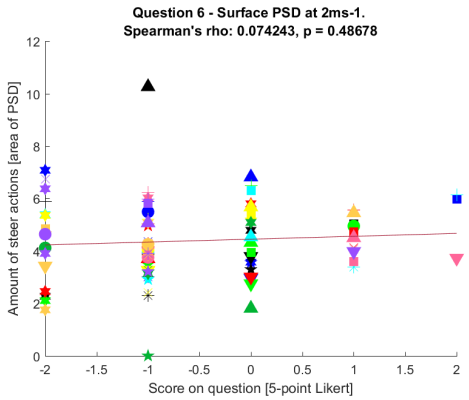

Question 3 - Surface PSD at free speed.
Spearman's rho: 0.022579, p = 0.8327
Amount of steer actions [area of PSD]
Score on question [5-point Likert]

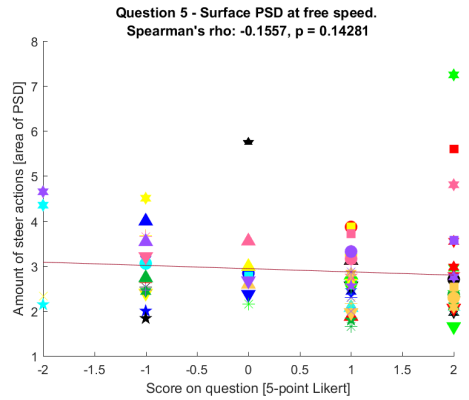

Question 3 - Surface PSD at free speed.
Spearman's rho: 0.022579, p = 0.8327
Amount of steer actions [area of PSD]
Score on question [5-point Likert]

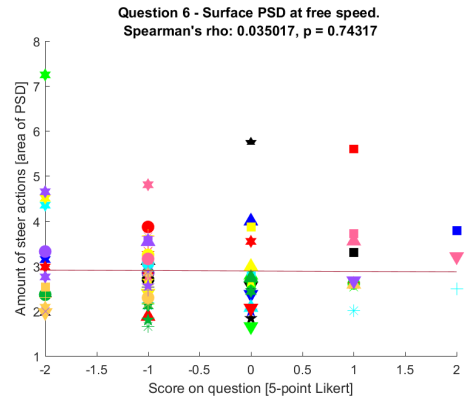

Question 3 - Surface PSD at 7ms-1.
Spearman's rho: 0.066713, p = 0.53214
Amount of steer actions [area of PSD]
Score on question [5-point Likert]

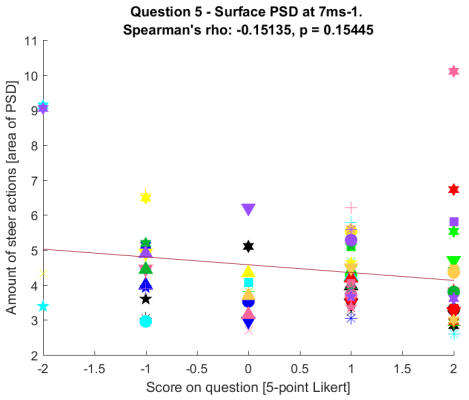

Question 4 - Surface PSD at 7ms-1.
Spearman's rho: 0.055617, p = 0.6026
Amount of steer actions [area of PSD]
Score on question [5-point Likert]

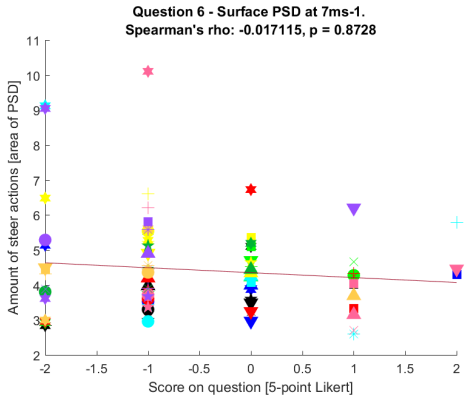

Question 5 - Surface PSD at 2ms-1.
Spearman's rho: -0.12963, p = 0.22333
Amount of steer actions [area of PSD]
Score on question [5-point Likert]

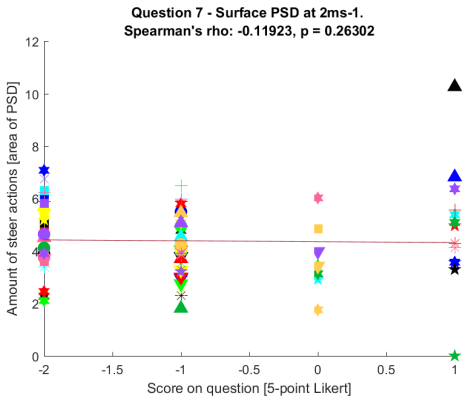

Question 6 - Surface PSD at 2ms-1.
Spearman's rho: 0.074243, p = 0.48678
Amount of steer actions [area of PSD]
Score on question [5-point Likert]

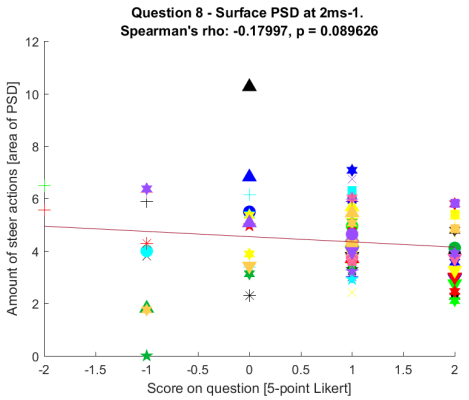

Question 5 - Surface PSD at free speed.
Spearman's rho: -0.1557, p = 0.14281
Amount of steer actions [area of PSD]
Score on question [5-point Likert]

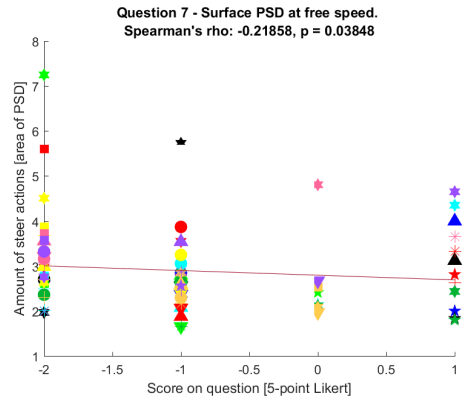

Question 6 - Surface PSD at free speed.
Spearman's rho: 0.035017, p = 0.74317
Amount of steer actions [area of PSD]
Score on question [5-point Likert]

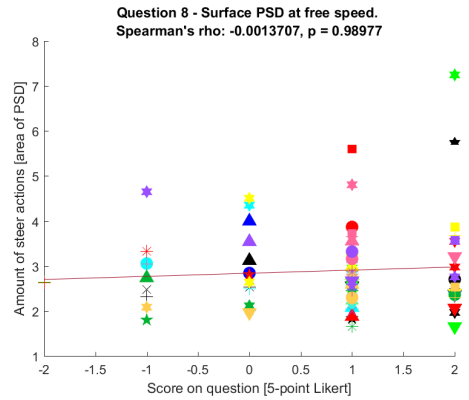

Question 5 - Surface PSD at 7ms-1.
Spearman's rho: -0.15135, p = 0.15445
Amount of steer actions [area of PSD]
Score on question [5-point Likert]

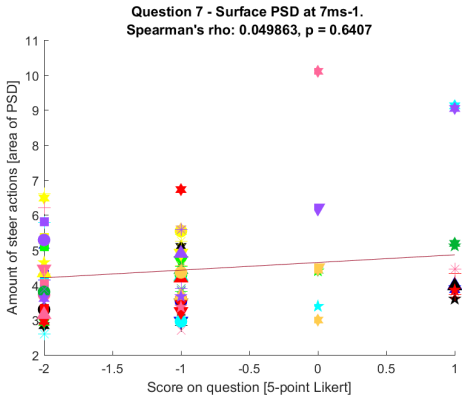

Question 6 - Surface PSD at 7ms-1.
Spearman's rho: -0.017115, p = 0.8728
Amount of steer actions [area of PSD]
Score on question [5-point Likert]

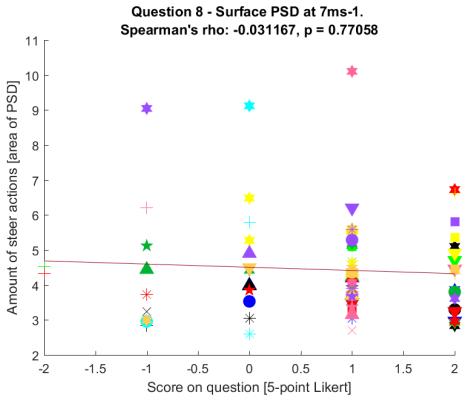

Question 7 - Surface PSD at 2ms-1.
Spearman's rho: -0.11923, p = 0.26302
Amount of steer actions [area of PSD]
Score on question [5-point Likert]


Question 8 - Surface PSD at 2ms-1.
Spearman's rho: -0.17997, p = 0.089626
Amount of steer actions [area of PSD]
Score on question [5-point Likert]


Question 7 - Surface PSD at free speed.
Spearman's rho: -0.21858, p = 0.03848
Amount of steer actions [area of PSD]
Score on question [5-point Likert]


Question 8 - Surface PSD at free speed.
Spearman's rho: -0.0013707, p = 0.98977
Amount of steer actions [area of PSD]
Score on question [5-point Likert]


Question 7 - Surface PSD at 7ms-1.
Spearman's rho: 0.049863, p = 0.6407
Amount of steer actions [area of PSD]
Score on question [5-point Likert]


Question 8 - Surface PSD at 7ms-1.
Spearman's rho: -0.031167, p = 0.77058
Amount of steer actions [area of PSD]
Score on question [5-point Likert]

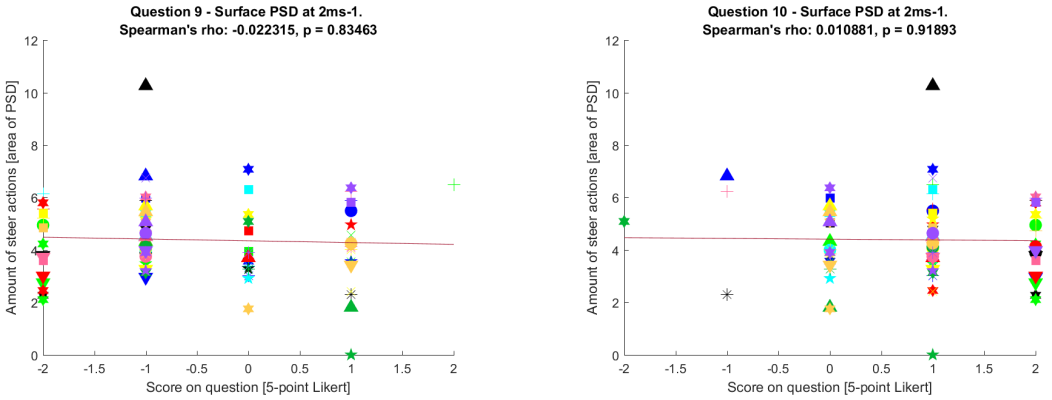
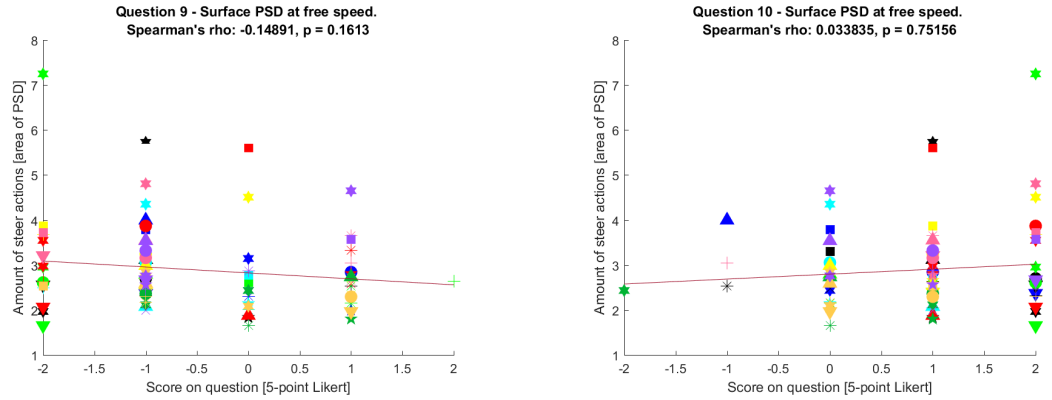
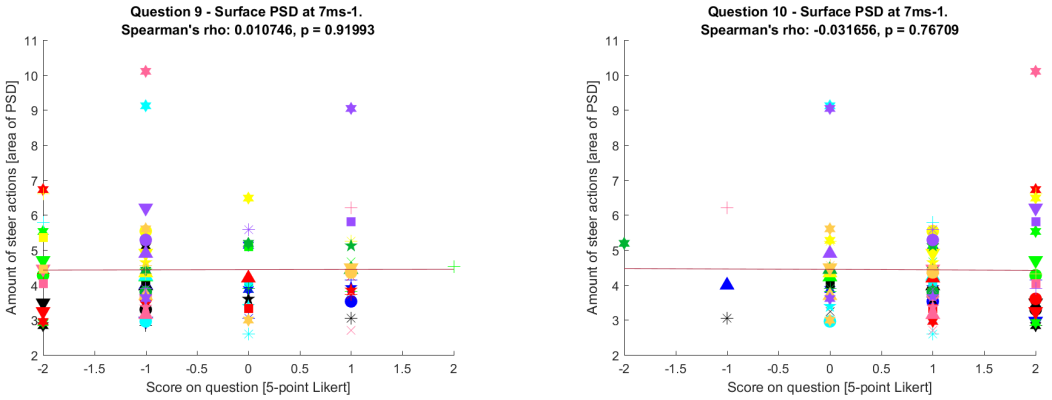
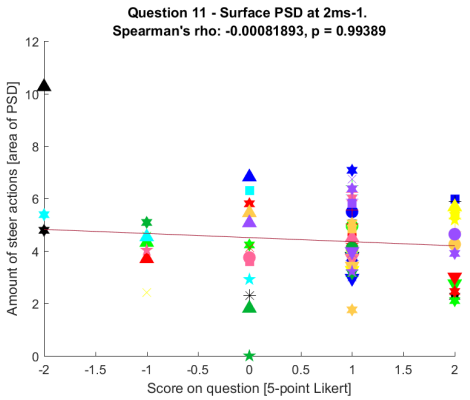
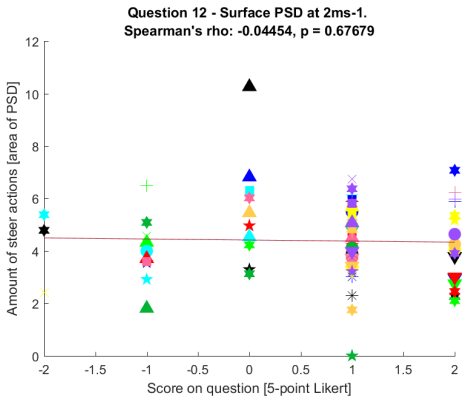


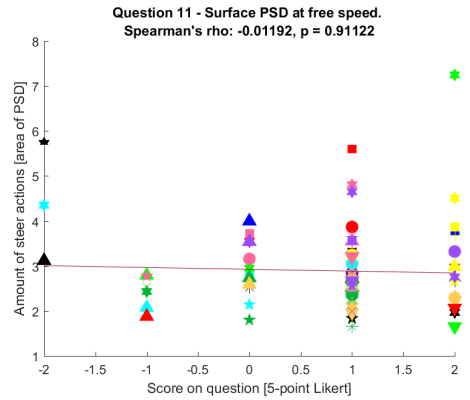
Figure F1: 2 Figures side by side

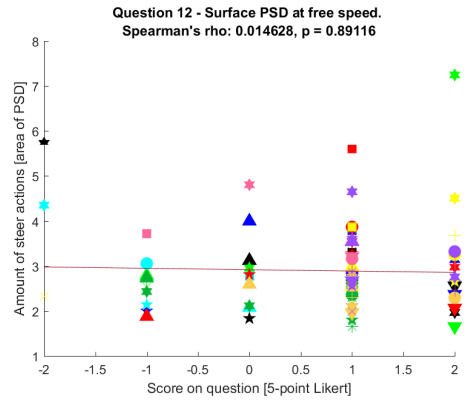


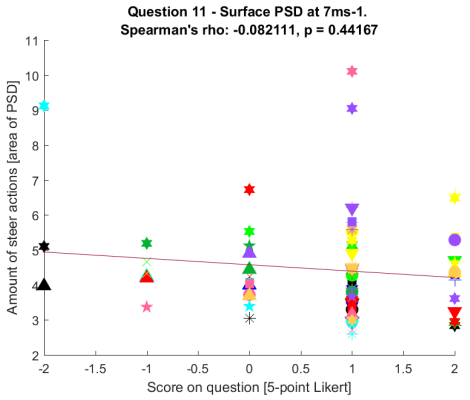


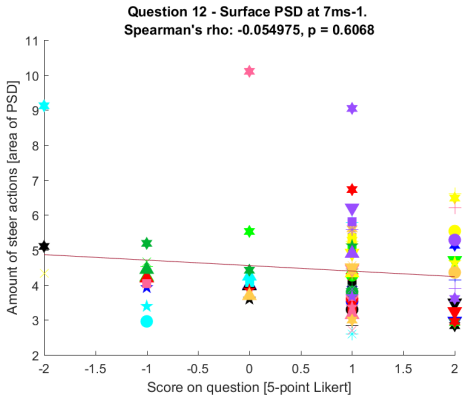

Question 11 - Surface PSD at 2ms-1.
Spearman's rho: -0.00081893, p = 0.99389
Amount of steer actions [area of PSD]
Score on question [5-point Likert]

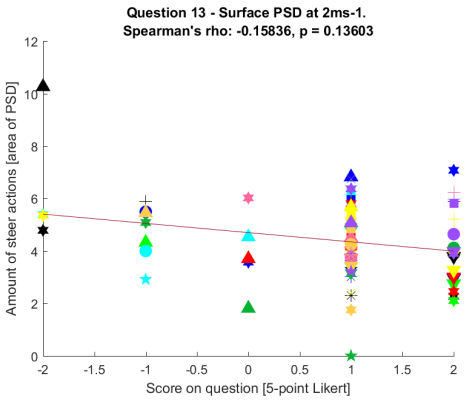

Question 12 - Surface PSD at 2ms-1.
Spearman's rho: -0.04454, p = 0.67679
Amount of steer actions [area of PSD]
Score on question [5-point Likert]

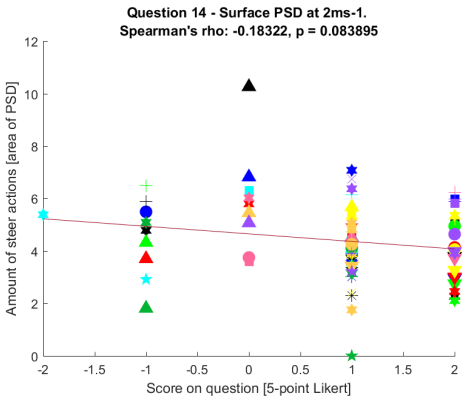

Question 11 - Surface PSD at free speed.
Spearman's rho: -0.01192, p = 0.91122
Amount of steer actions [area of PSD]
Score on question [5-point Likert]

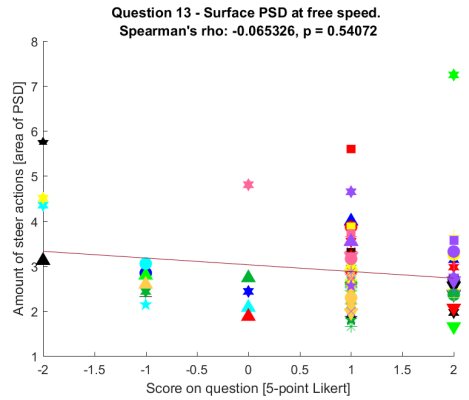

Question 12 - Surface PSD at free speed.
Spearman's rho: 0.014628, p = 0.89116
Amount of steer actions [area of PSD]
Score on question [5-point Likert]

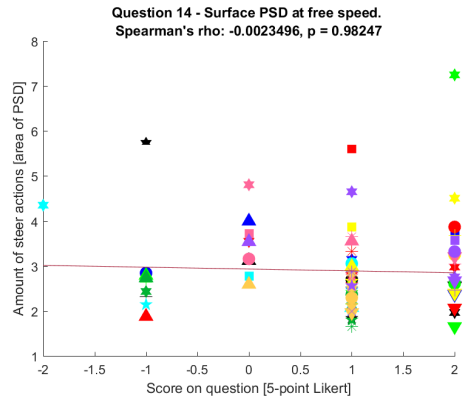

Question 11 - Surface PSD at 7ms-1.
Spearman's rho: -0.082111, p = 0.44167
Amount of steer actions [area of PSD]
Score on question [5-point Likert]

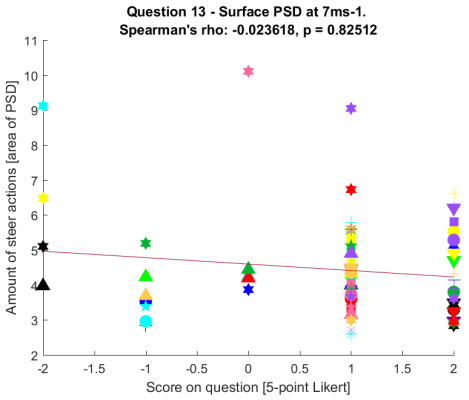

Question 12 - Surface PSD at 7ms-1.
Spearman's rho: -0.054975, p = 0.6068
Amount of steer actions [area of PSD]
Score on question [5-point Likert]

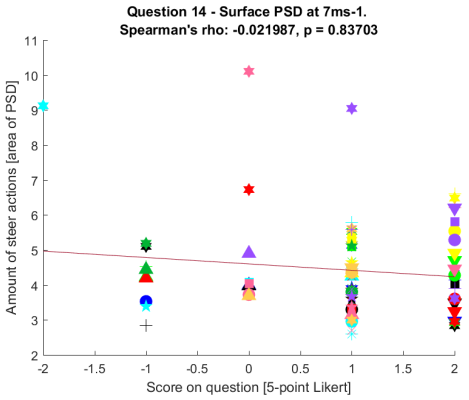

Question 13 - Surface PSD at 2ms-1.
Spearman's rho: -0.15836, p = 0.13603
Amount of steer actions [area of PSD]
Score on question [5-point Likert]


Question 14 - Surface PSD at 2ms-1.
Spearman's rho: -0.18322, p = 0.083895
Amount of steer actions [area of PSD]
Score on question [5-point Likert]


Question 13 - Surface PSD at free speed.
Spearman's rho: -0.065326, p = 0.54072
Amount of steer actions [area of PSD]
Score on question [5-point Likert]

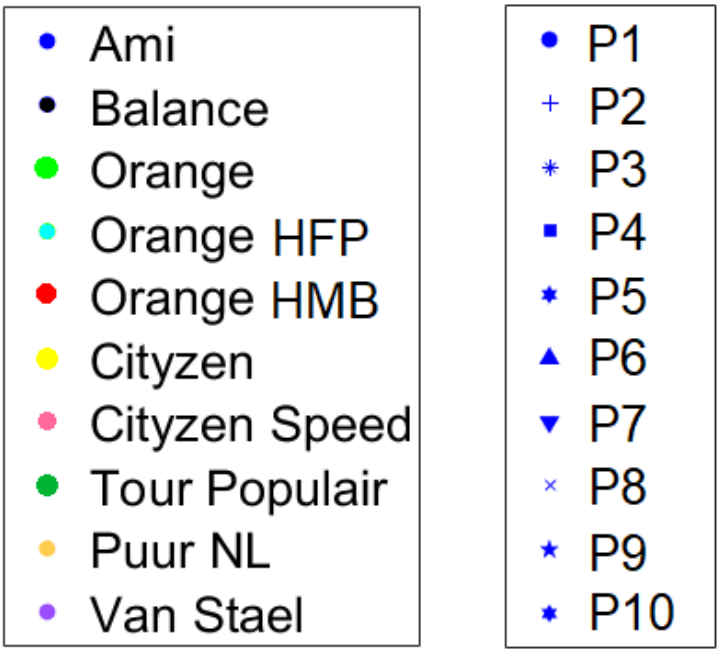

Question 14 - Surface PSD at free speed.
Spearman's rho: -0.0023496, p = 0.98247
Amount of steer actions [area of PSD]
Score on question [5-point Likert]

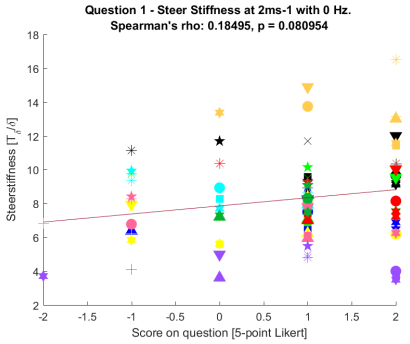

Question 13 - Surface PSD at 7ms-1.
Spearman's rho: -0.023618, p = 0.82512
Amount of steer actions [area of PSD]
Score on question [5-point Likert]

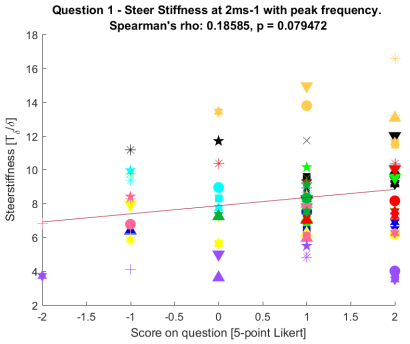

Question 14 - Surface PSD at 7ms-1.
Spearman's rho: -0.021987, p = 0.83703
Amount of steer actions [area of PSD]
Score on question [5-point Likert]

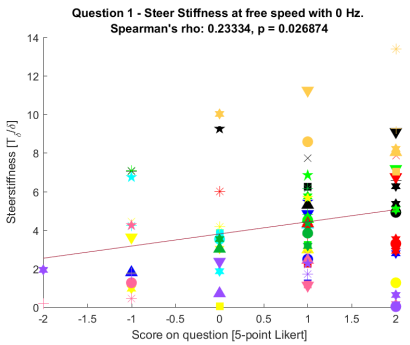
EIGENVALUE AND STEER STIFFNESS CORRELATIONS

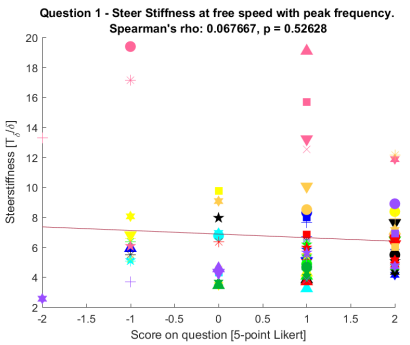
The following figures show the correlations of the eigenvalues and steer stiffness for 2 m/s, the free speed and 7 m/s with every question of the questionnaire. A correlation of $\rho = 1$ describes a perfect linear relationship between the two variables, with a correlation $\rho = 0$ there is none and with $\rho = 0.5$ there is a moderate correlation. The results are found to be significant when $p < 0.05$.

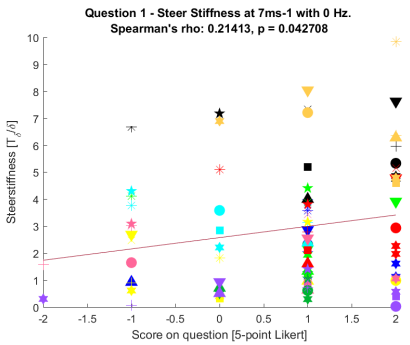


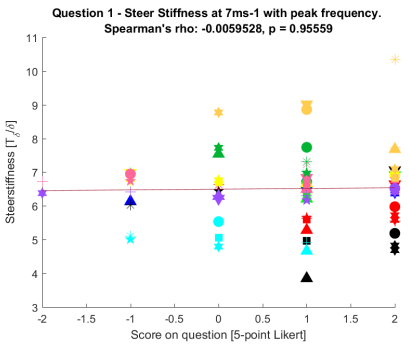

Question 1 - Steer Stiffness at 2ms-1 with 0 Hz.
Spearman's rho: 0.18495, p = 0.080954
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

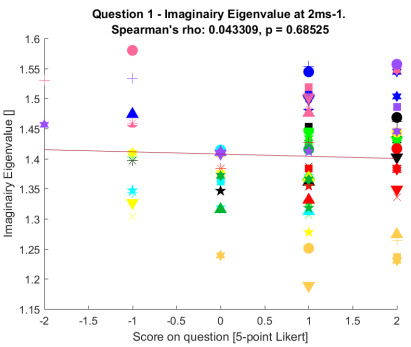

Question 1 - Steer Stiffness at 2ms-1 with peak frequency.
Spearman's rho: 0.18585, p = 0.079472
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

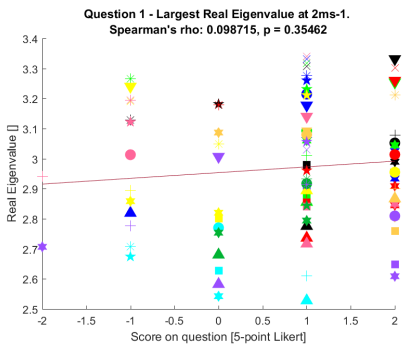

Question 1 - Steer Stiffness at free speed with 0 Hz.
Spearman's rho: 0.23334, p = 0.026874
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

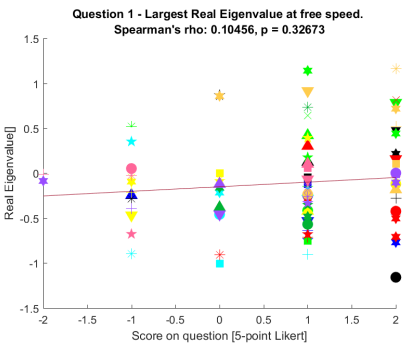

Question 1 - Steer Stiffness at free speed with peak frequency.
Spearman's rho: 0.067667, p = 0.52628
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

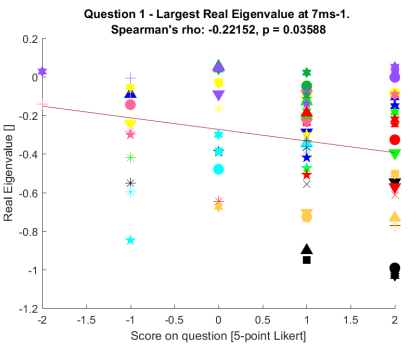

Question 1 - Steer Stiffness at 7ms-1 with 0 Hz.
Spearman's rho: 0.21413, p = 0.042708
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

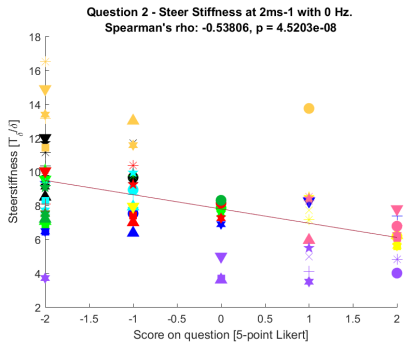

Question 1 - Steer Stiffness at 7ms-1 with peak frequency.
Spearman's rho: -0.0059528, p = 0.95559
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

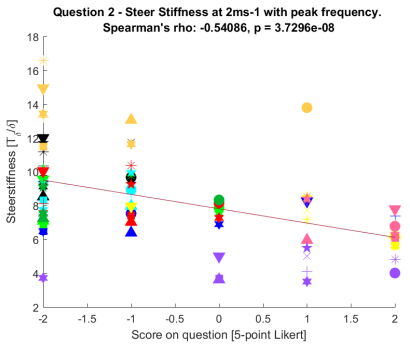

Question 1 - Imaginairy Eigenvalue at 2ms-1.
Spearman's rho: 0.043309, p = 0.68525
Imaginairy Eigenvalue []
Score on question [5-point Likert]

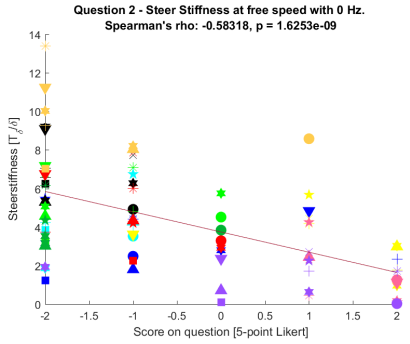

Question 1 - Largest Real Eigenvalue at 2ms-1.
Spearman's rho: 0.098715, p = 0.35462
Real Eigenvalue []
Score on question [5-point Likert]

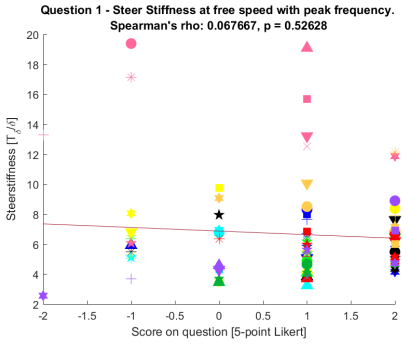

Question 1 - Largest Real Eigenvalue at free speed.
Spearman's rho: 0.10456, p = 0.32673
Real Eigenvalue[]
Score on question [5-point Likert]

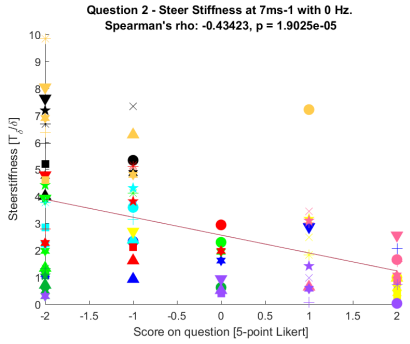

Question 1 - Largest Real Eigenvalue at 7ms-1.
Spearman's rho: -0.22152, p = 0.03588
Real Eigenvalue []
Score on question [5-point Likert]

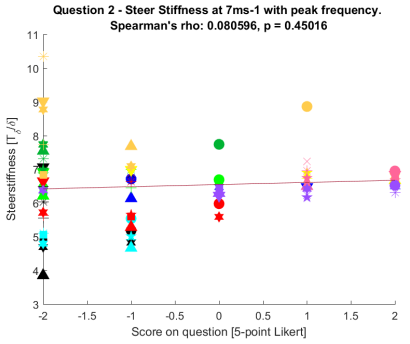

Question 2 - Steer Stiffness at 2ms-1 with 0 Hz.
Spearman's rho: -0.53806, p = 4.5203e-08
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

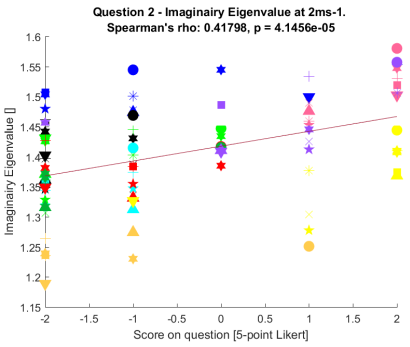

Question 2 - Steer Stiffness at 2ms-1 with peak frequency.
Spearman's rho: -0.54086, p = 3.7296e-08
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

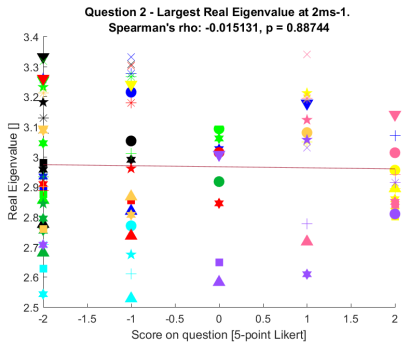

Question 2 - Steer Stiffness at free speed with 0 Hz.
Spearman's rho: -0.58318, p = 1.6253e-09
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

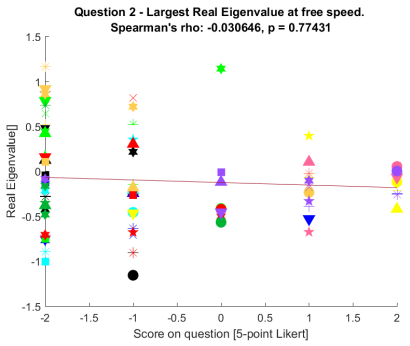

Question 1 - Steer Stiffness at free speed with peak frequency.
Spearman's rho: 0.067667, p = 0.52628
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

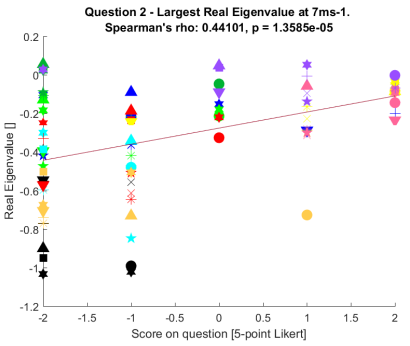

Question 2 - Steer Stiffness at 7ms-1 with 0 Hz.
Spearman's rho: -0.43423, p = 1.9025e-05
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

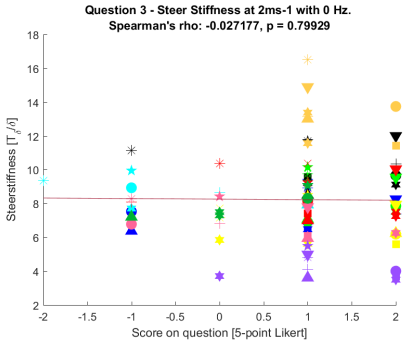

Question 2 - Steer Stiffness at 7ms-1 with peak frequency.
Spearman's rho: 0.080596, p = 0.45016
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

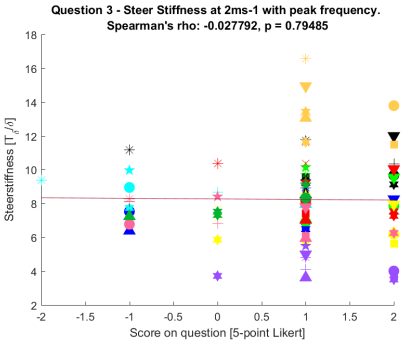

Question 2 - Imaginairy Eigenvalue at 2ms-1.
Spearman's rho: 0.41798, p = 4.1456e-05
Imaginairy Eigenvalue []
Score on question [5-point Likert]

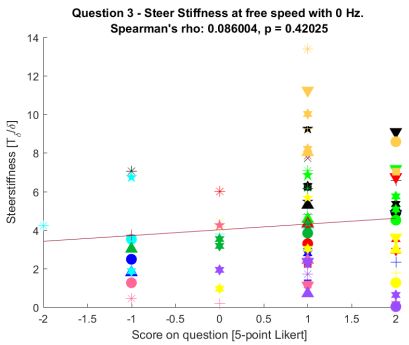

Question 2 - Largest Real Eigenvalue at 2ms-1.
Spearman's rho: -0.015131, p = 0.88744
Real Eigenvalue []
Score on question [5-point Likert]

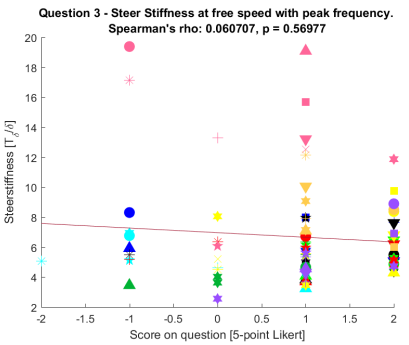

Question 2 - Largest Real Eigenvalue at free speed.
Spearman's rho: -0.030646, p = 0.77431
Real Eigenvalue[]
Score on question [5-point Likert]

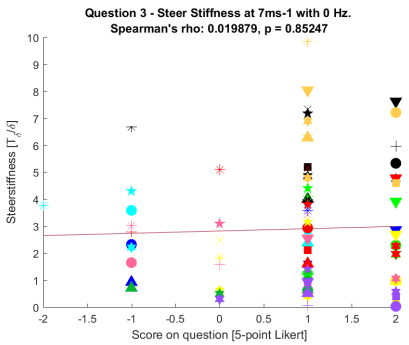

Question 2 - Largest Real Eigenvalue at 7ms-1.
Spearman's rho: 0.44101, p = 1.3585e-05
Real Eigenvalue []
Score on question [5-point Likert]

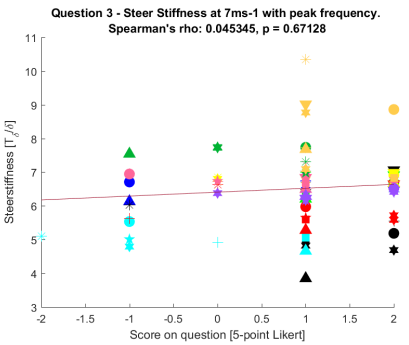

Question 3 - Steer Stiffness at 2ms-1 with 0 Hz.
Spearman's rho: -0.027177, p = 0.79929
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

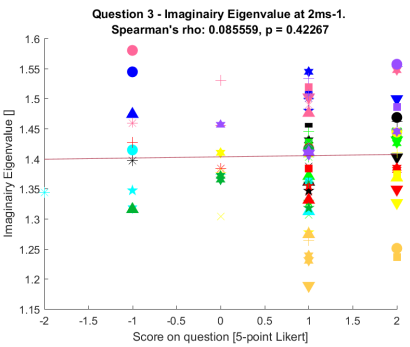

Question 3 - Steer Stiffness at 2ms-1 with peak frequency.
Spearman's rho: -0.027792, p = 0.79485
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

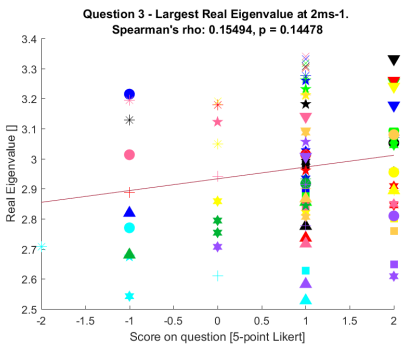

Question 3 - Steer Stiffness at free speed with 0 Hz.
Spearman's rho: 0.086004, p = 0.42025
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

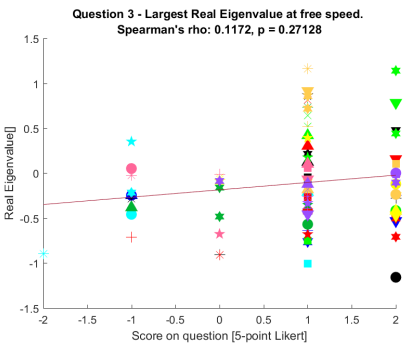

Question 3 - Steer Stiffness at free speed with peak frequency.
Spearman's rho: 0.060707, p = 0.56977
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

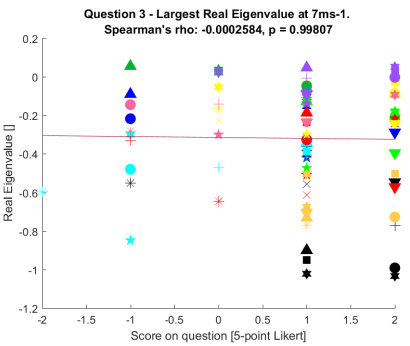

Question 3 - Steer Stiffness at 7ms-1 with 0 Hz.
Spearman's rho: 0.019879, p = 0.85247
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

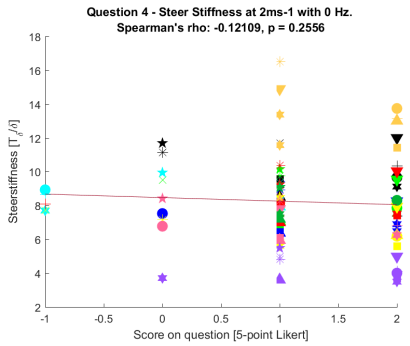

Question 3 - Steer Stiffness at 7ms-1 with peak frequency.
Spearman's rho: 0.045345, p = 0.67128
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

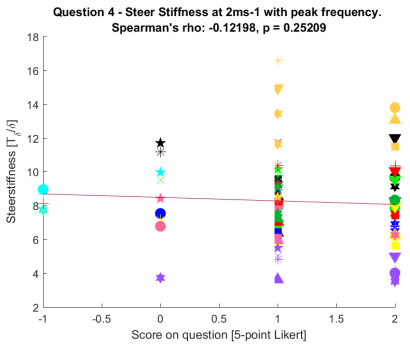

Question 3 - Imaginairy Eigenvalue at 2ms-1.
Spearman's rho: 0.085559, p = 0.42267
Imaginairy Eigenvalue []
Score on question [5-point Likert]

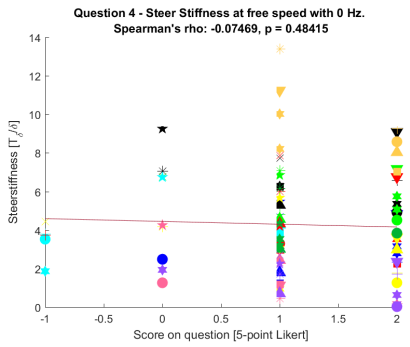

Question 3 - Largest Real Eigenvalue at 2ms-1.
Spearman's rho: 0.15494, p = 0.14478
Real Eigenvalue []
Score on question [5-point Likert]

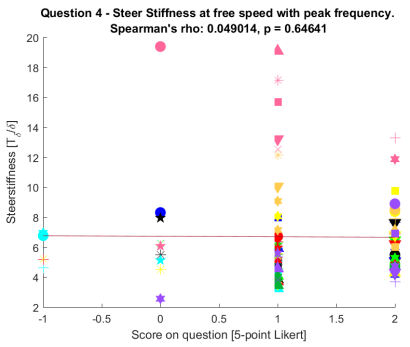

Question 3 - Largest Real Eigenvalue at free speed.
Spearman's rho: 0.1172, p = 0.27128
Real Eigenvalue[]
Score on question [5-point Likert]

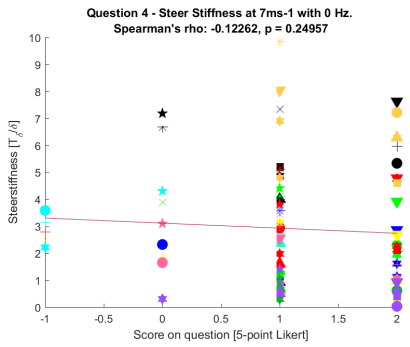

Question 3 - Largest Real Eigenvalue at 7ms-1.
Spearman's rho: -0.0002584, p = 0.99807
Real Eigenvalue []
Score on question [5-point Likert]

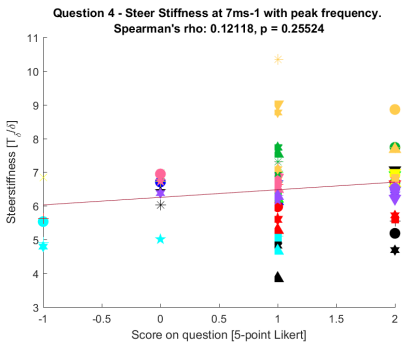

Question 4 - Steer Stiffness at 2ms-1 with 0 Hz.
Spearman's rho: -0.12109, p = 0.2556
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

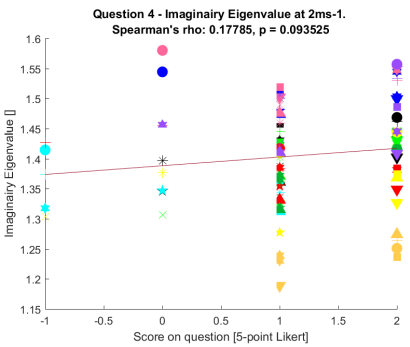

Question 4 - Steer Stiffness at 2ms-1 with peak frequency.
Spearman's rho: -0.12198, p = 0.25209
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

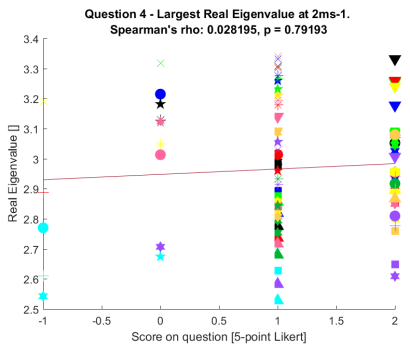

Question 4 - Steer Stiffness at free speed with 0 Hz.
Spearman's rho: -0.07469, p = 0.48415
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

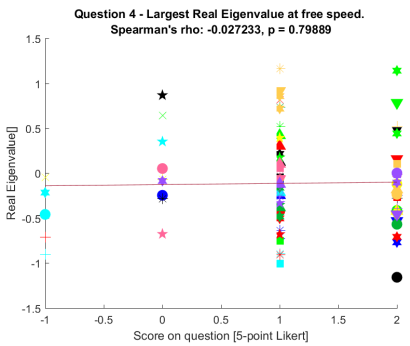

Question 4 - Steer Stiffness at free speed with peak frequency.
Spearman's rho: 0.049014, p = 0.64641
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

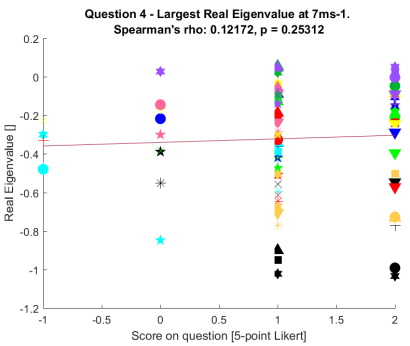

Question 4 - Steer Stiffness at 7ms-1 with 0 Hz.
Spearman's rho: -0.12262, p = 0.24957
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

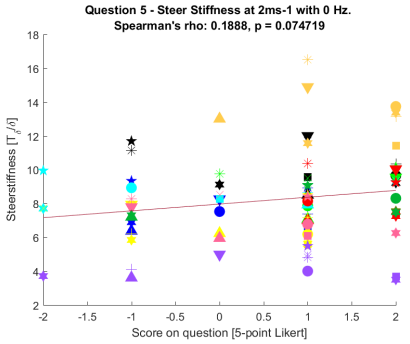

Question 4 - Steer Stiffness at 7ms-1 with peak frequency.
Spearman's rho: 0.12118, p = 0.25524
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

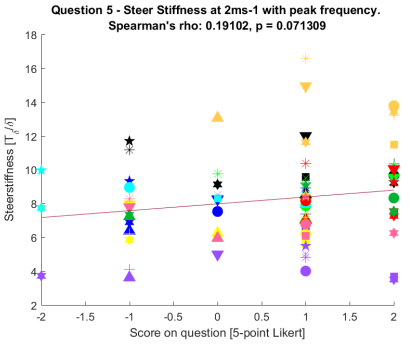

Question 4 - Imaginairy Eigenvalue at 2ms-1.
Spearman's rho: 0.17785, p = 0.093525
Imaginairy Eigenvalue []
Score on question [5-point Likert]

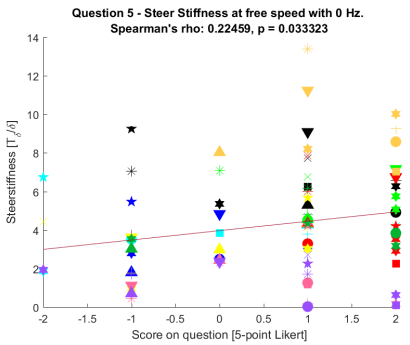

Question 4 - Largest Real Eigenvalue at 2ms-1.
Spearman's rho: 0.028195, p = 0.79193
Real Eigenvalue []
Score on question [5-point Likert]

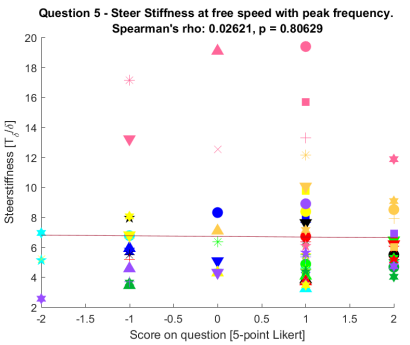

Question 4 - Largest Real Eigenvalue at free speed.
Spearman's rho: -0.027233, p = 0.79889
Real Eigenvalue[]
Score on question [5-point Likert]

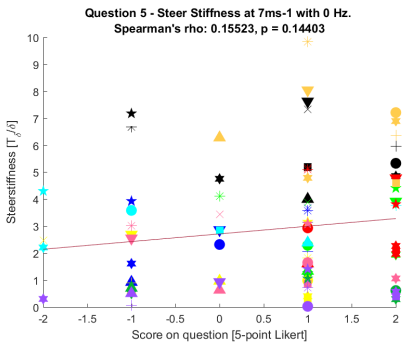

Question 4 - Largest Real Eigenvalue at 7ms-1.
Spearman's rho: 0.12172, p = 0.25312
Real Eigenvalue []
Score on question [5-point Likert]

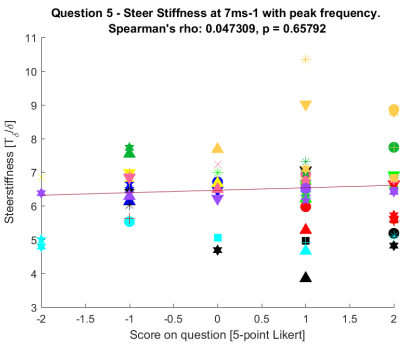

Question 5 - Steer Stiffness at 2ms-1 with 0 Hz.
Spearman's rho: 0.1888, p = 0.074719
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

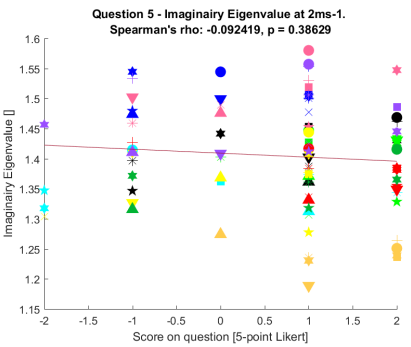

Question 5 - Steer Stiffness at 2ms-1 with peak frequency.
Spearman's rho: 0.19102, p = 0.071309
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

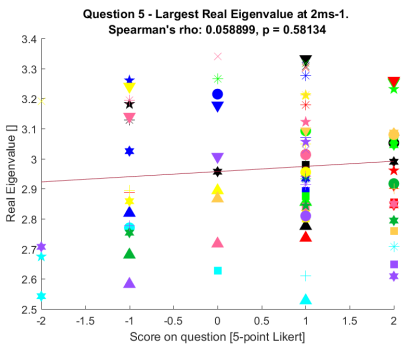

Question 5 - Steer Stiffness at free speed with 0 Hz.
Spearman's rho: 0.22459, p = 0.033323
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

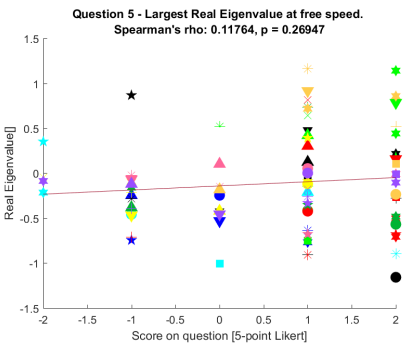

Question 5 - Steer Stiffness at free speed with peak frequency.
Spearman's rho: 0.02621, p = 0.80629
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

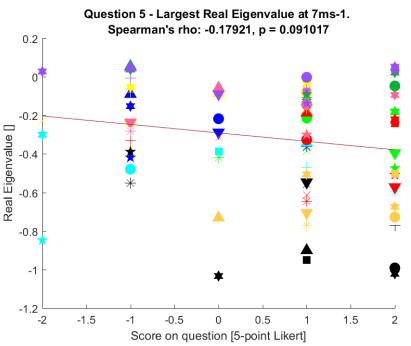

Question 5 - Steer Stiffness at 7ms-1 with 0 Hz.
Spearman's rho: 0.15523, p = 0.14403
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

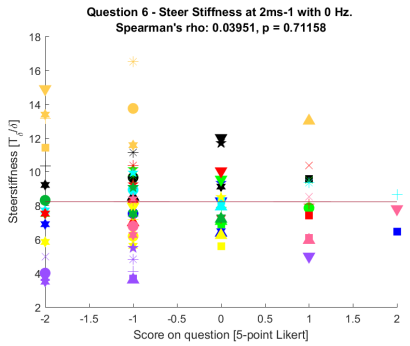

Question 5 - Steer Stiffness at 7ms-1 with peak frequency.
Spearman's rho: 0.047309, p = 0.65792
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

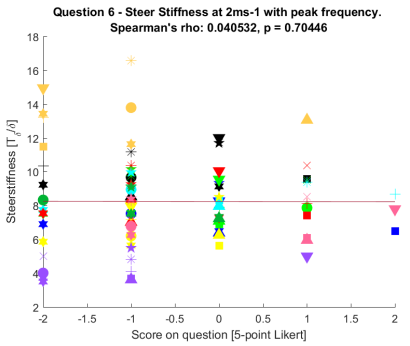

Question 5 - Imaginairy Eigenvalue at 2ms-1.
Spearman's rho: -0.092419, p = 0.38629
Imaginairy Eigenvalue []
Score on question [5-point Likert]

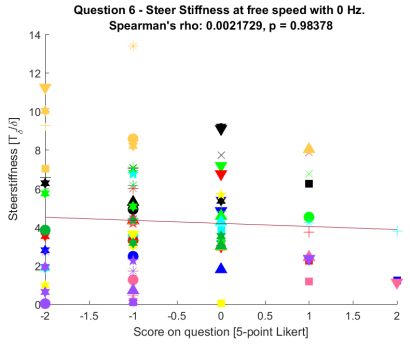

Question 5 - Largest Real Eigenvalue at 2ms-1.
Spearman's rho: 0.058899, p = 0.58134
Real Eigenvalue []
Score on question [5-point Likert]

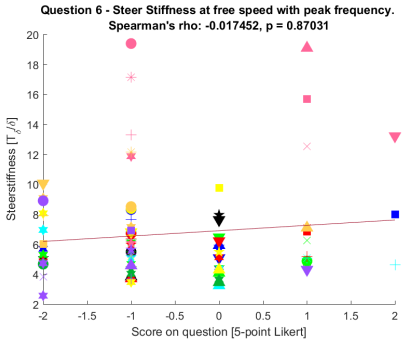

Question 5 - Largest Real Eigenvalue at free speed.
Spearman's rho: 0.11764, p = 0.26947
Real Eigenvalue[]
Score on question [5-point Likert]

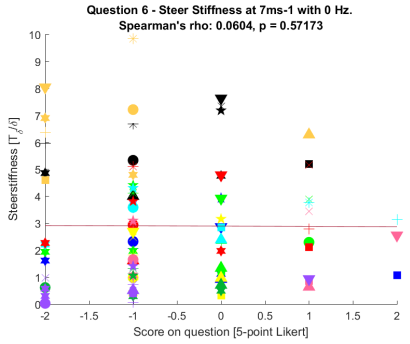

Question 5 - Largest Real Eigenvalue at 7ms-1.
Spearman's rho: -0.17921, p = 0.091017
Real Eigenvalue []
Score on question [5-point Likert]

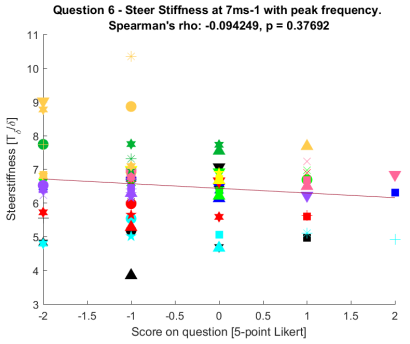

Question 6 - Steer Stiffness at 2ms-1 with 0 Hz.
Spearman's rho: 0.03951, p = 0.71158
Steerstiffness [T_δ/δ]
Score on question [5-point Likert]

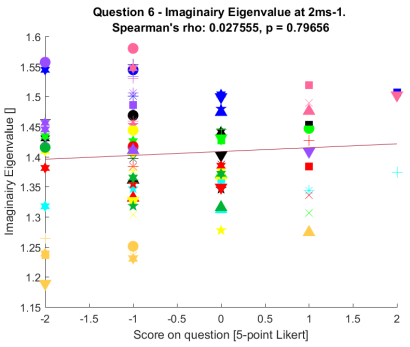

Question 6 - Steer Stiffness at 2ms-1 with peak frequency.
Spearman's rho: 0.040532, p = 0.70446
Steerstiffness [T_δ/δ]
Score on question [5-point Likert]

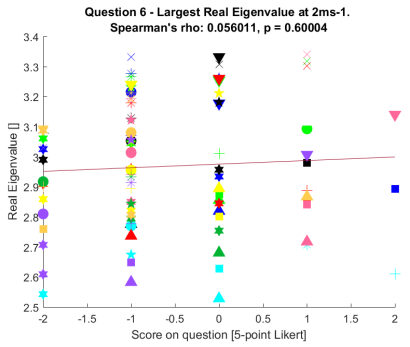

Question 6 - Steer Stiffness at free speed with 0 Hz.
Spearman's rho: 0.0021729, p = 0.98378
Steerstiffness [T_δ/δ]
Score on question [5-point Likert]

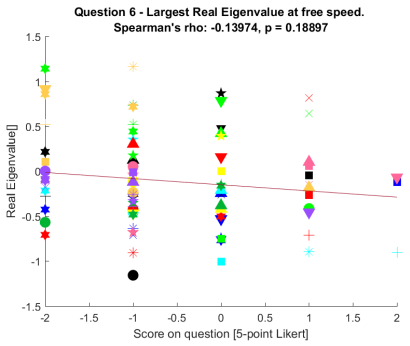

Question 6 - Steer Stiffness at free speed with peak frequency.
Spearman's rho: -0.017452, p = 0.87031
Steerstiffness [T_δ/δ]
Score on question [5-point Likert]

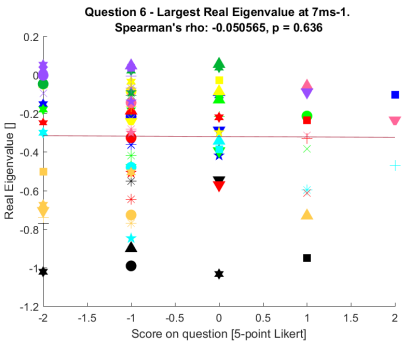

Question 6 - Steer Stiffness at 7ms-1 with 0 Hz.
Spearman's rho: 0.0604, p = 0.57173
Steerstiffness [T_δ/δ]
Score on question [5-point Likert]

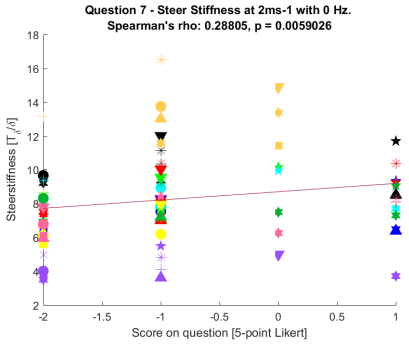

Question 6 - Steer Stiffness at 7ms-1 with peak frequency.
Spearman's rho: -0.094249, p = 0.37692
Steerstiffness [T_δ/δ]
Score on question [5-point Likert]

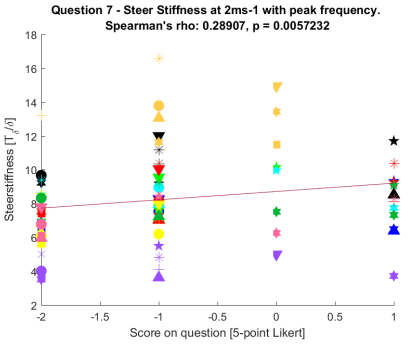

Question 6 - Imaginairy Eigenvalue at 2ms-1.
Spearman's rho: 0.027555, p = 0.79656
Imaginairy Eigenvalue []
Score on question [5-point Likert]

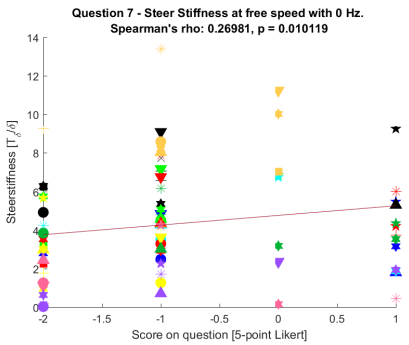

Question 6 - Largest Real Eigenvalue at 2ms-1.
Spearman's rho: 0.056011, p = 0.60004
Real Eigenvalue []
Score on question [5-point Likert]

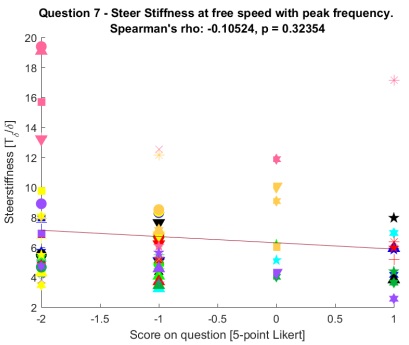

Question 6 - Largest Real Eigenvalue at free speed.
Spearman's rho: -0.13974, p = 0.18897
Real Eigenvalue[]
Score on question [5-point Likert]

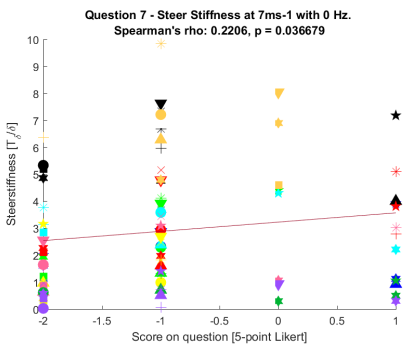

Question 6 - Largest Real Eigenvalue at 7ms-1.
Spearman's rho: -0.050565, p = 0.636
Real Eigenvalue []
Score on question [5-point Likert]

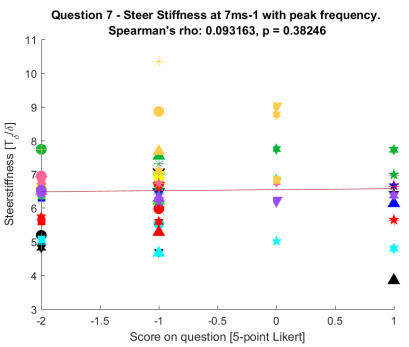

Question 7 - Steer Stiffness at 2ms-1 with 0 Hz.
Spearman's rho: 0.28805, p = 0.0059026
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

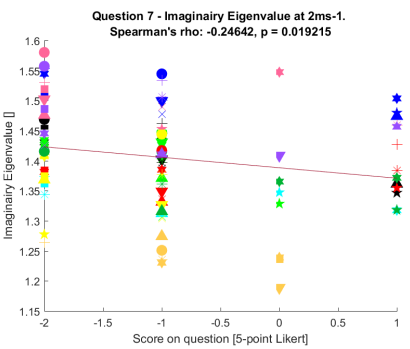

Question 7 - Steer Stiffness at 2ms-1 with peak frequency.
Spearman's rho: 0.28907, p = 0.0057232
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

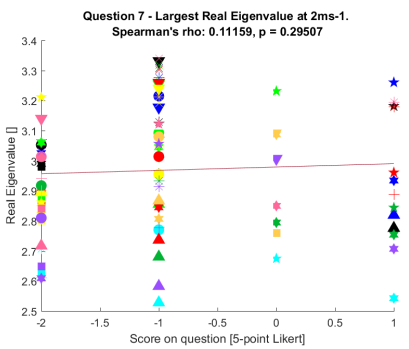

Question 7 - Steer Stiffness at free speed with 0 Hz.
Spearman's rho: 0.26981, p = 0.010119
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

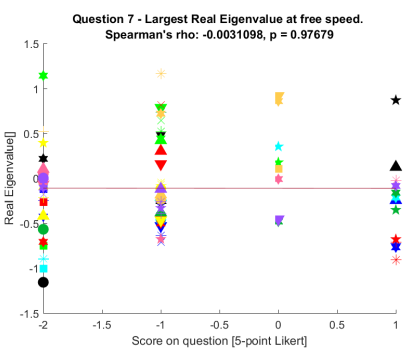

Question 7 - Steer Stiffness at free speed with peak frequency.
Spearman's rho: -0.10524, p = 0.32354
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

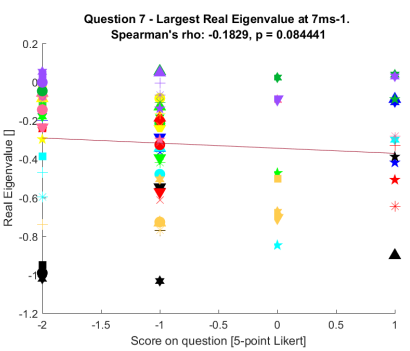

Question 7 - Steer Stiffness at 7ms-1 with 0 Hz.
Spearman's rho: 0.2206, p = 0.036679
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

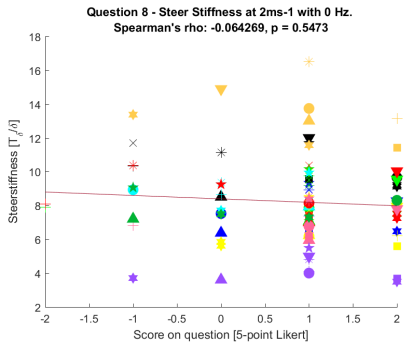

Question 7 - Steer Stiffness at 7ms-1 with peak frequency.
Spearman's rho: 0.093163, p = 0.38246
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

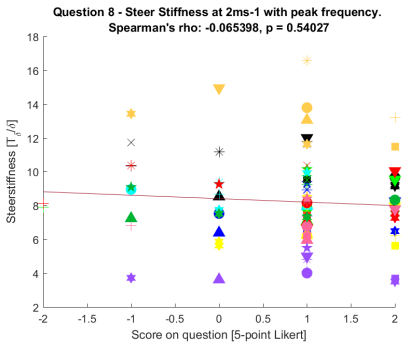

Question 7 - Imaginairy Eigenvalue at 2ms-1.
Spearman's rho: -0.24642, p = 0.019215
Imaginairy Eigenvalue []
Score on question [5-point Likert]

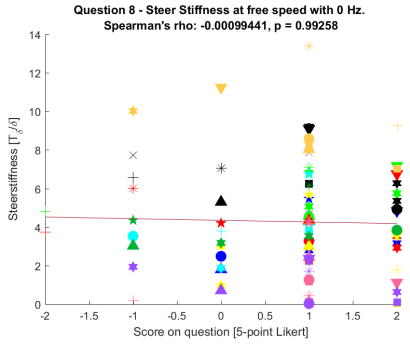

Question 7 - Largest Real Eigenvalue at 2ms-1.
Spearman's rho: 0.11159, p = 0.29507
Real Eigenvalue []
Score on question [5-point Likert]

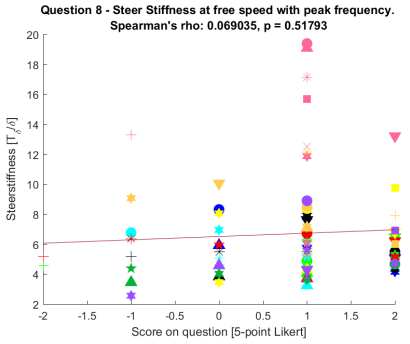

Question 7 - Largest Real Eigenvalue at free speed.
Spearman's rho: -0.0031098, p = 0.97679
Real Eigenvalue[]
Score on question [5-point Likert]

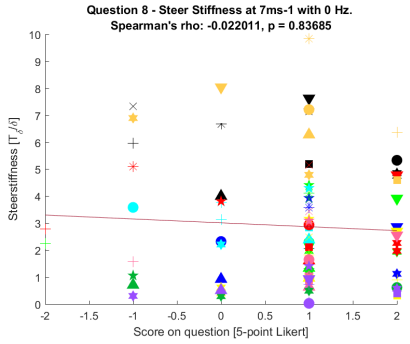

Question 7 - Largest Real Eigenvalue at 7ms-1.
Spearman's rho: -0.1829, p = 0.084441
Real Eigenvalue []
Score on question [5-point Likert]

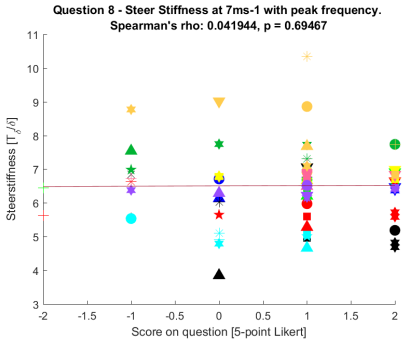

Question 8 - Steer Stiffness at 2ms-1 with 0 Hz.
Spearman's rho: -0.064269, p = 0.5473
Steerstiffness [T_δ/δ]
Score on question [5-point Likert]

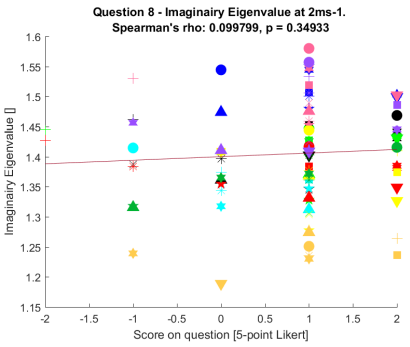

Question 8 - Steer Stiffness at 2ms-1 with peak frequency.
Spearman's rho: -0.065398, p = 0.54027
Steerstiffness [T_δ/δ]
Score on question [5-point Likert]

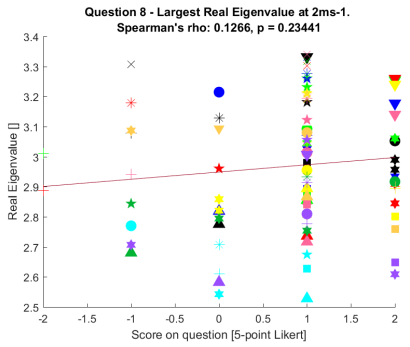

Question 8 - Steer Stiffness at free speed with 0 Hz.
Spearman's rho: -0.00099441, p = 0.99258
Steerstiffness [T_δ/δ]
Score on question [5-point Likert]

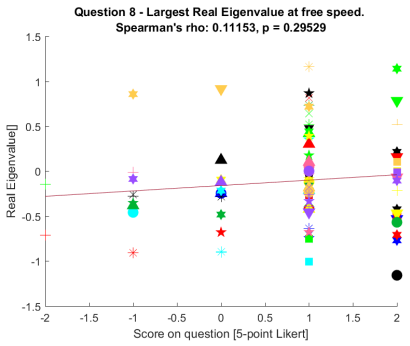

Question 8 - Steer Stiffness at free speed with peak frequency.
Spearman's rho: 0.069035, p = 0.51793
Steerstiffness [T_δ/δ]
Score on question [5-point Likert]

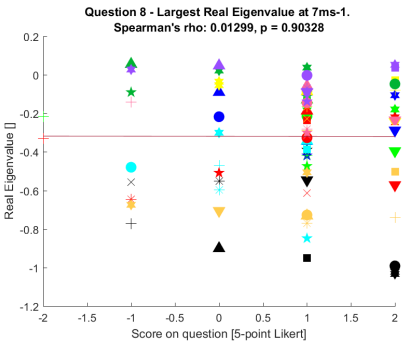

Question 8 - Steer Stiffness at 7ms-1 with 0 Hz.
Spearman's rho: -0.022011, p = 0.83685
Steerstiffness [T_δ/δ]
Score on question [5-point Likert]

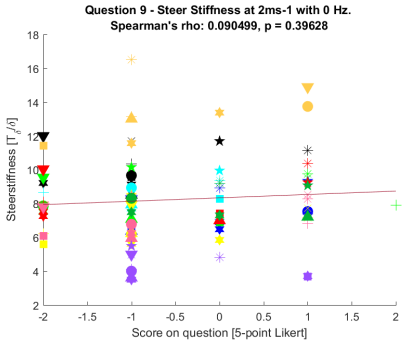

Question 8 - Steer Stiffness at 7ms-1 with peak frequency.
Spearman's rho: 0.041944, p = 0.69467
Steerstiffness [T_δ/δ]
Score on question [5-point Likert]

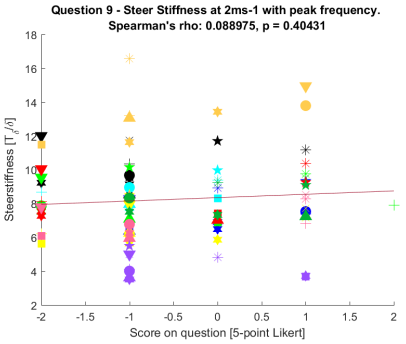

Question 8 - Imaginairy Eigenvalue at 2ms-1.
Spearman's rho: 0.099799, p = 0.34933
Imaginairy Eigenvalue []
Score on question [5-point Likert]

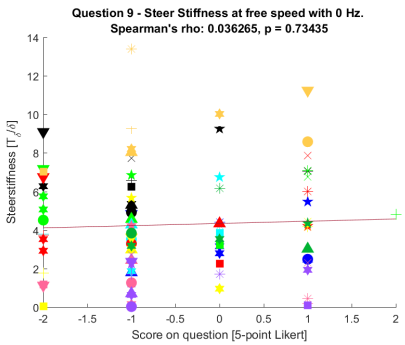

Question 8 - Largest Real Eigenvalue at 2ms-1.
Spearman's rho: 0.1266, p = 0.23441
Real Eigenvalue []
Score on question [5-point Likert]

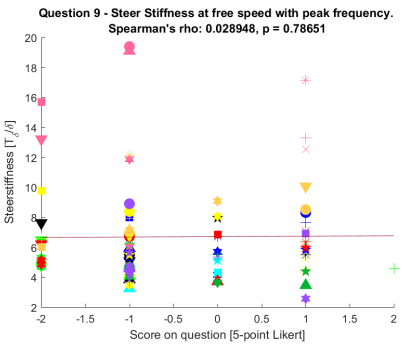

Question 8 - Largest Real Eigenvalue at free speed.
Spearman's rho: 0.11153, p = 0.29529
Real Eigenvalue[]
Score on question [5-point Likert]

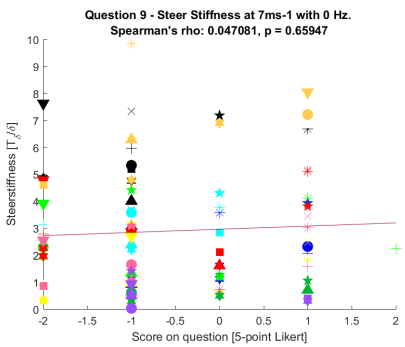

Question 8 - Largest Real Eigenvalue at 7ms-1.
Spearman's rho: 0.01299, p = 0.90328
Real Eigenvalue []
Score on question [5-point Likert]

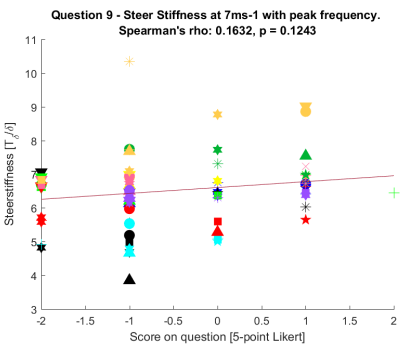

Question 9 - Steer Stiffness at 2ms-1 with 0 Hz.
Spearman's rho: 0.090499, p = 0.39628
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

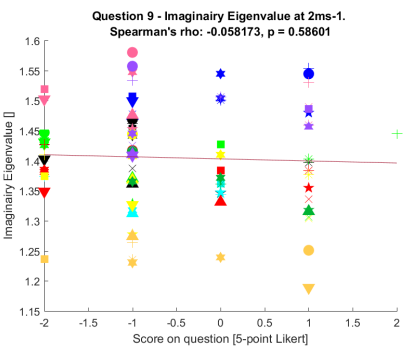

Question 9 - Steer Stiffness at 2ms-1 with peak frequency.
Spearman's rho: 0.088975, p = 0.40431
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

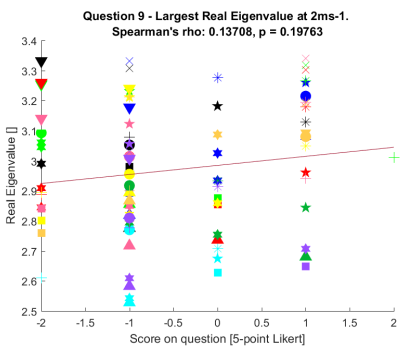

Question 9 - Steer Stiffness at free speed with 0 Hz.
Spearman's rho: 0.036265, p = 0.73435
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

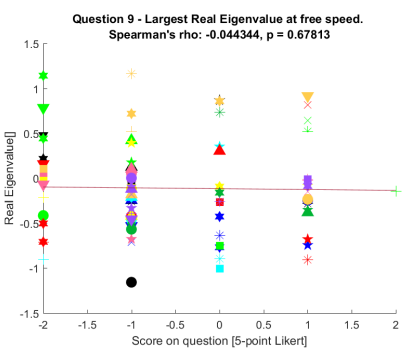

Question 9 - Steer Stiffness at free speed with peak frequency.
Spearman's rho: 0.028948, p = 0.78651
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

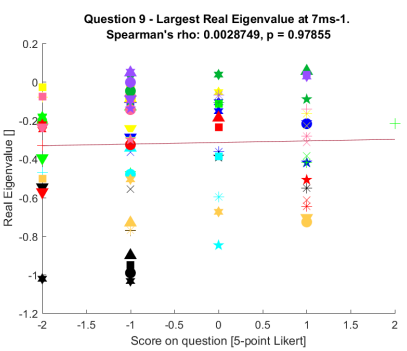

Question 9 - Steer Stiffness at 7ms-1 with 0 Hz.
Spearman's rho: 0.047081, p = 0.65947
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

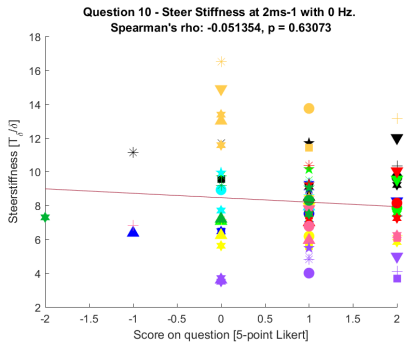

Question 9 - Steer Stiffness at 7ms-1 with peak frequency.
Spearman's rho: 0.1632, p = 0.1243
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

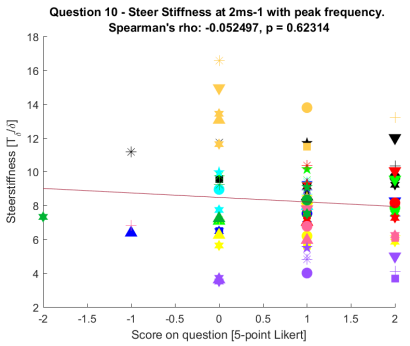

Question 9 - Imaginairy Eigenvalue at 2ms-1.
Spearman's rho: -0.058173, p = 0.58601
Imaginairy Eigenvalue []
Score on question [5-point Likert]

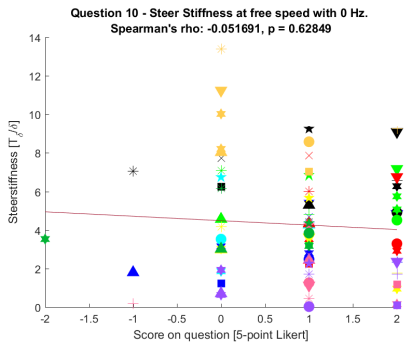

Question 9 - Largest Real Eigenvalue at 2ms-1.
Spearman's rho: 0.13708, p = 0.19763
Real Eigenvalue []
Score on question [5-point Likert]

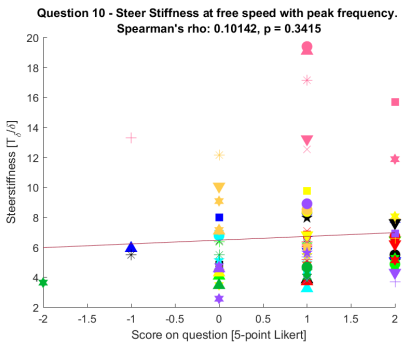

Question 9 - Largest Real Eigenvalue at free speed.
Spearman's rho: -0.044344, p = 0.67813
Real Eigenvalue[]
Score on question [5-point Likert]

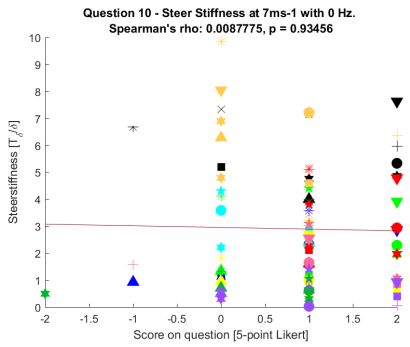

Question 9 - Largest Real Eigenvalue at 7ms-1.
Spearman's rho: 0.0028749, p = 0.97855
Real Eigenvalue []
Score on question [5-point Likert]

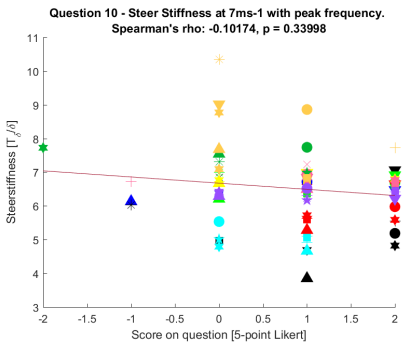

Question 10 - Steer Stiffness at 2ms-1 with 0 Hz.
Spearman's rho: -0.051354, p = 0.63073
Steerstiffness [T_δ/δ]
Score on question [5-point Likert]

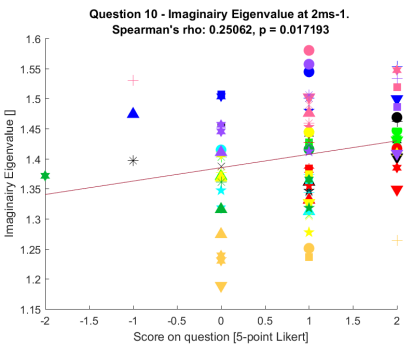

Question 10 - Steer Stiffness at 2ms-1 with peak frequency.
Spearman's rho: -0.052497, p = 0.62314
Steerstiffness [T_δ/δ]
Score on question [5-point Likert]

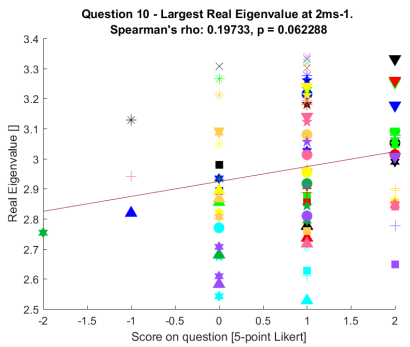

Question 10 - Steer Stiffness at free speed with 0 Hz.
Spearman's rho: -0.051691, p = 0.62849
Steerstiffness [T_δ/δ]
Score on question [5-point Likert]

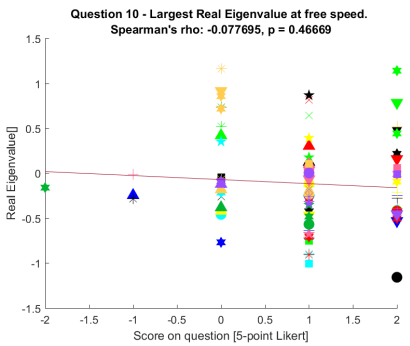

Question 10 - Steer Stiffness at free speed with peak frequency.
Spearman's rho: 0.10142, p = 0.3415
Steerstiffness [T_δ/δ]
Score on question [5-point Likert]

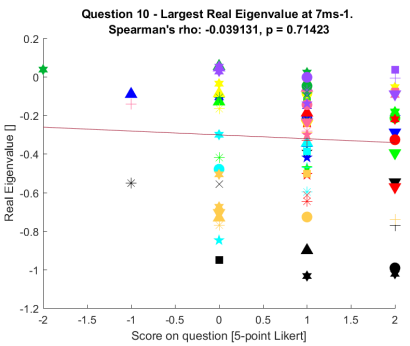

Question 10 - Steer Stiffness at 7ms-1 with 0 Hz.
Spearman's rho: 0.0087775, p = 0.93456
Steerstiffness [T_δ/δ]
Score on question [5-point Likert]

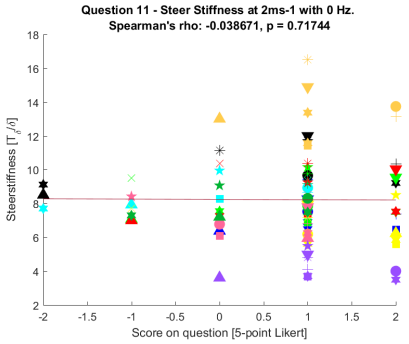

Question 10 - Steer Stiffness at 7ms-1 with peak frequency.
Spearman's rho: -0.10174, p = 0.33998
Steerstiffness [T_δ/δ]
Score on question [5-point Likert]

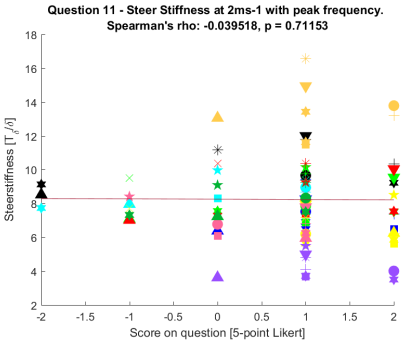

Question 10 - Imaginairy Eigenvalue at 2ms-1.
Spearman's rho: 0.25062, p = 0.017193
Imaginairy Eigenvalue []
Score on question [5-point Likert]

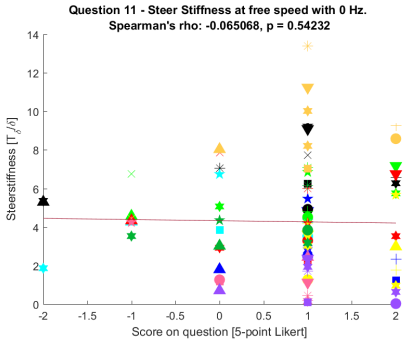

Question 10 - Largest Real Eigenvalue at 2ms-1.
Spearman's rho: 0.19733, p = 0.062288
Real Eigenvalue []
Score on question [5-point Likert]

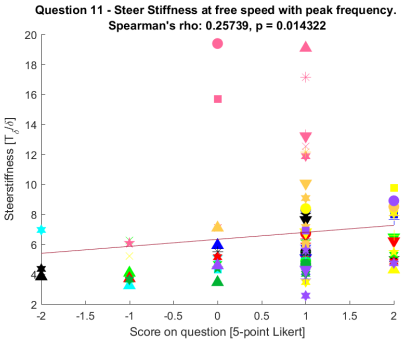

Question 10 - Largest Real Eigenvalue at free speed.
Spearman's rho: -0.077695, p = 0.46669
Real Eigenvalue[]
Score on question [5-point Likert]

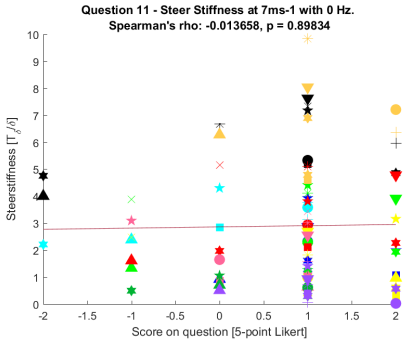

Question 10 - Largest Real Eigenvalue at 7ms-1.
Spearman's rho: -0.039131, p = 0.71423
Real Eigenvalue []
Score on question [5-point Likert]

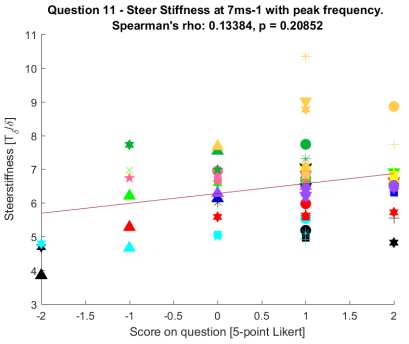

Question 11 - Steer Stiffness at 2ms-1 with 0 Hz.
Spearman's rho: -0.038671, p = 0.71744
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

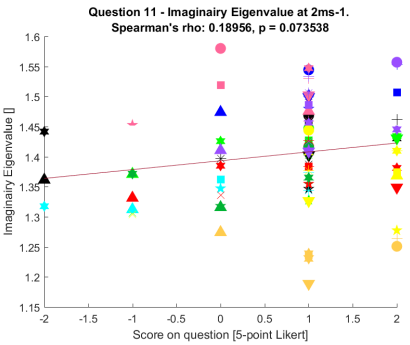

Question 11 - Steer Stiffness at 2ms-1 with peak frequency.
Spearman's rho: -0.039518, p = 0.71153
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

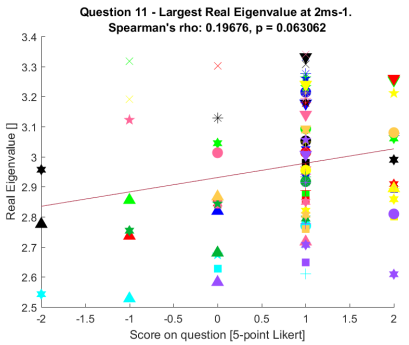

Question 11 - Steer Stiffness at free speed with 0 Hz.
Spearman's rho: -0.065068, p = 0.54232
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

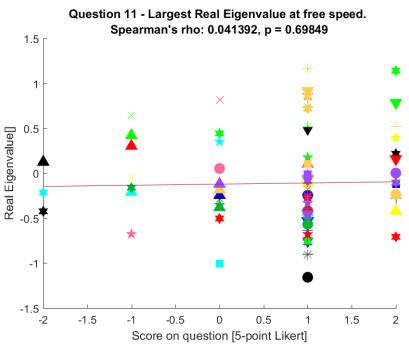

Question 11 - Steer Stiffness at free speed with peak frequency.
Spearman's rho: 0.25739, p = 0.014322
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

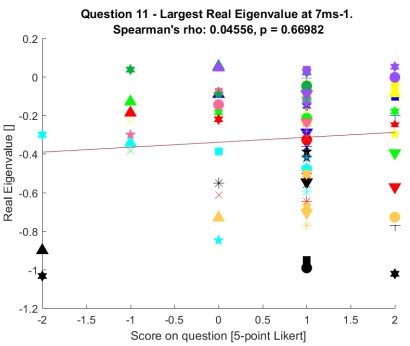

Question 11 - Steer Stiffness at 7ms-1 with 0 Hz.
Spearman's rho: -0.013658, p = 0.89834
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

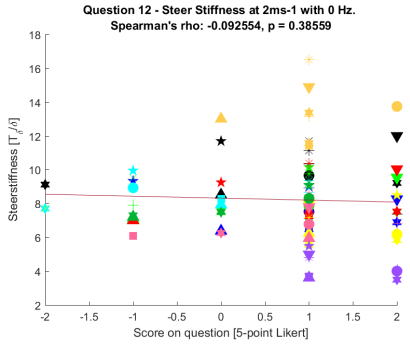

Question 11 - Steer Stiffness at 7ms-1 with peak frequency.
Spearman's rho: 0.13384, p = 0.20852
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

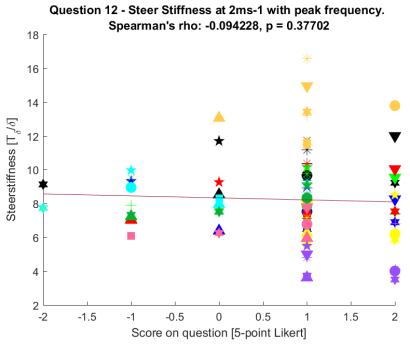

Question 11 - Imaginairy Eigenvalue at 2ms-1.
Spearman's rho: 0.18956, p = 0.073538
Imaginairy Eigenvalue []
Score on question [5-point Likert]

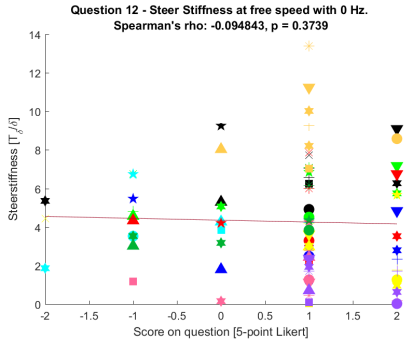

Question 11 - Largest Real Eigenvalue at 2ms-1.
Spearman's rho: 0.19676, p = 0.063062
Real Eigenvalue []
Score on question [5-point Likert]

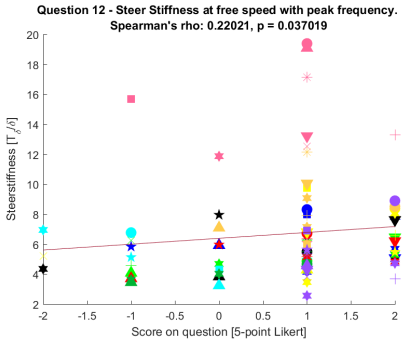

Question 11 - Largest Real Eigenvalue at free speed.
Spearman's rho: 0.041392, p = 0.69849
Real Eigenvalue[]
Score on question [5-point Likert]

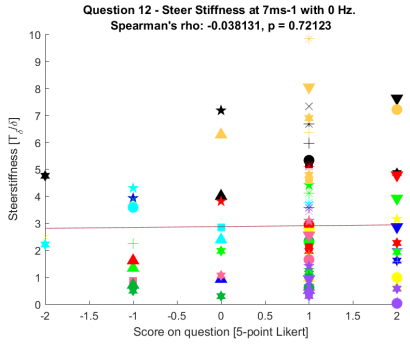

Question 11 - Largest Real Eigenvalue at 7ms-1.
Spearman's rho: 0.04556, p = 0.66982
Real Eigenvalue []
Score on question [5-point Likert]

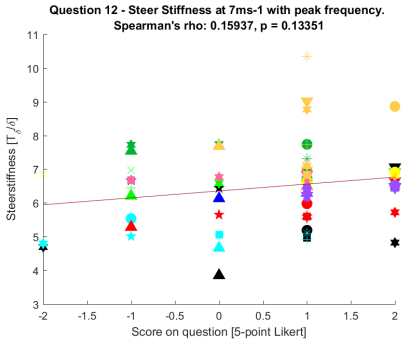

Question 12 - Steer Stiffness at 2ms-1 with 0 Hz.
Spearman's rho: -0.092554, p = 0.38559
Steerstiffness [T_δ/δ]
Score on question [5-point Likert]

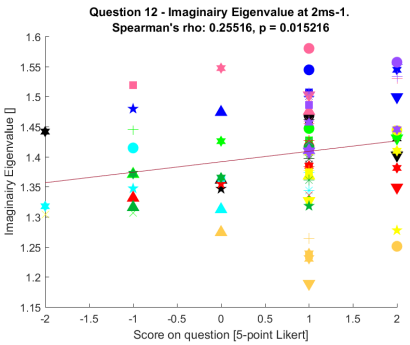

Question 12 - Steer Stiffness at 2ms-1 with peak frequency.
Spearman's rho: -0.094228, p = 0.37702
Steerstiffness [T_δ/δ]
Score on question [5-point Likert]

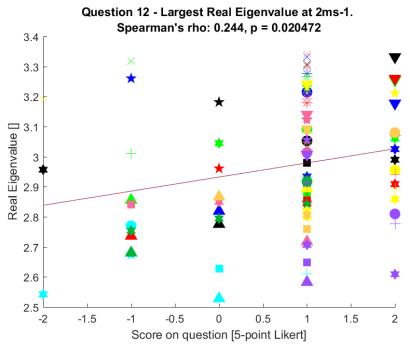

Question 12 - Steer Stiffness at free speed with 0 Hz.
Spearman's rho: -0.094843, p = 0.3739
Steerstiffness [T_δ/δ]
Score on question [5-point Likert]

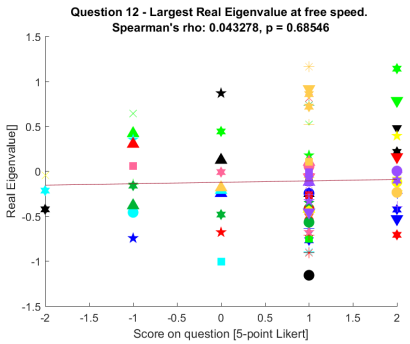

Question 12 - Steer Stiffness at free speed with peak frequency.
Spearman's rho: 0.22021, p = 0.037019
Steerstiffness [T_δ/δ]
Score on question [5-point Likert]

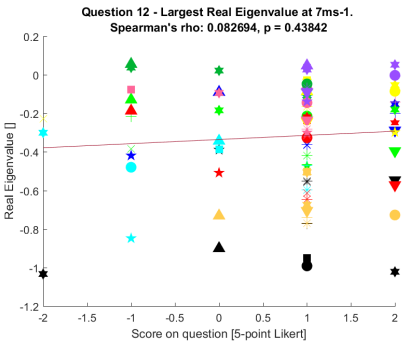

Question 12 - Steer Stiffness at 7ms-1 with 0 Hz.
Spearman's rho: -0.038131, p = 0.72123
Steerstiffness [T_δ/δ]
Score on question [5-point Likert]

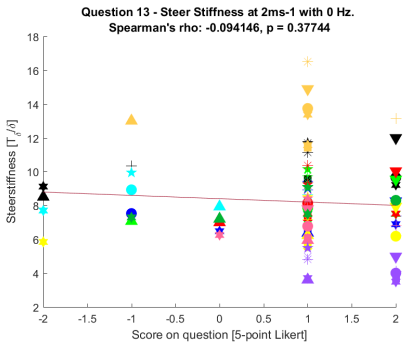

Question 12 - Steer Stiffness at 7ms-1 with peak frequency.
Spearman's rho: 0.15937, p = 0.13351
Steerstiffness [T_δ/δ]
Score on question [5-point Likert]

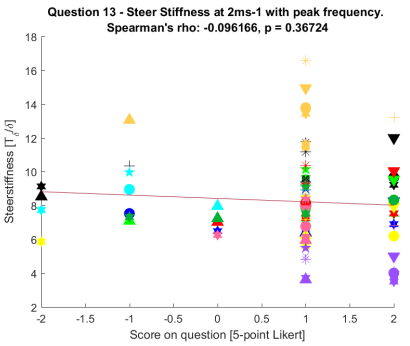

Question 12 - Imaginairy Eigenvalue at 2ms-1.
Spearman's rho: 0.25516, p = 0.015216
Imaginairy Eigenvalue []
Score on question [5-point Likert]

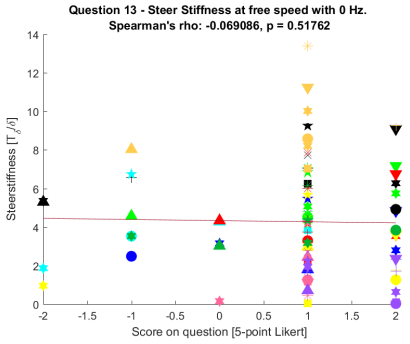

Question 12 - Largest Real Eigenvalue at 2ms-1.
Spearman's rho: 0.244, p = 0.020472
Real Eigenvalue []
Score on question [5-point Likert]

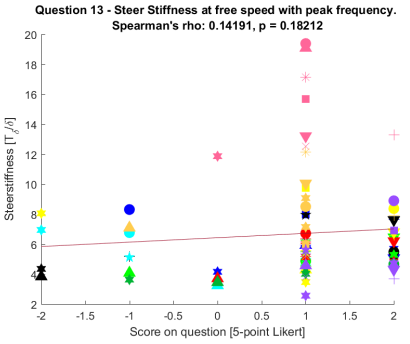

Question 12 - Largest Real Eigenvalue at free speed.
Spearman's rho: 0.043278, p = 0.68546
Real Eigenvalue[]
Score on question [5-point Likert]

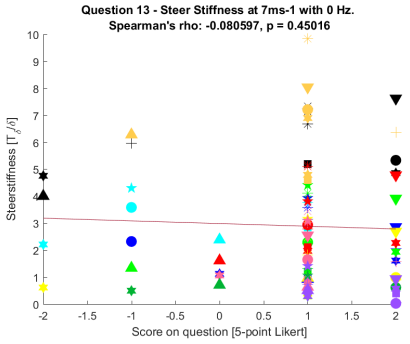

Question 12 - Largest Real Eigenvalue at 7ms-1.
Spearman's rho: 0.082694, p = 0.43842
Real Eigenvalue []
Score on question [5-point Likert]

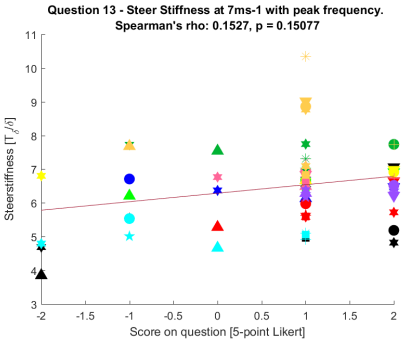

Question 13 - Steer Stiffness at 2ms-1 with 0 Hz.
Spearman's rho: -0.094146, p = 0.37744
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

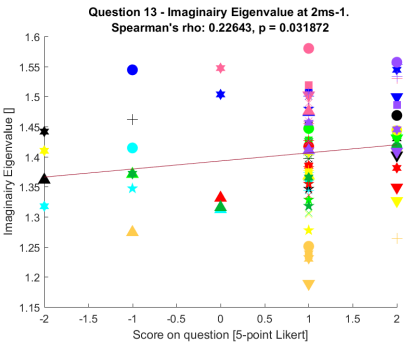

Question 13 - Steer Stiffness at 2ms-1 with peak frequency.
Spearman's rho: -0.096166, p = 0.36724
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

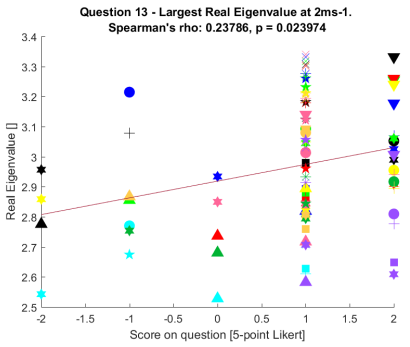

Question 13 - Steer Stiffness at free speed with 0 Hz.
Spearman's rho: -0.069086, p = 0.51762
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

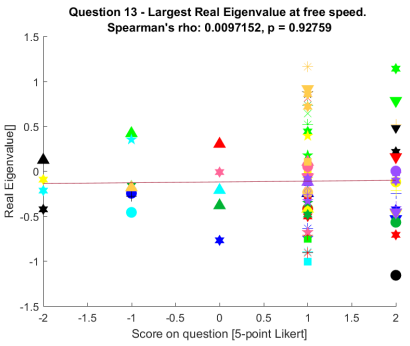

Question 13 - Steer Stiffness at free speed with peak frequency.
Spearman's rho: 0.14191, p = 0.18212
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

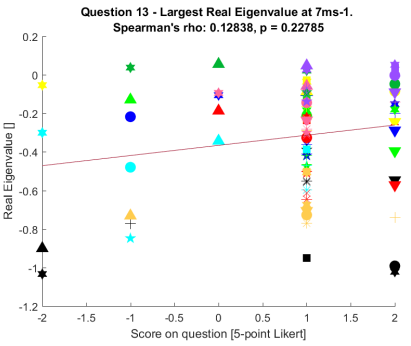

Question 13 - Steer Stiffness at 7ms-1 with 0 Hz.
Spearman's rho: -0.080597, p = 0.45016
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

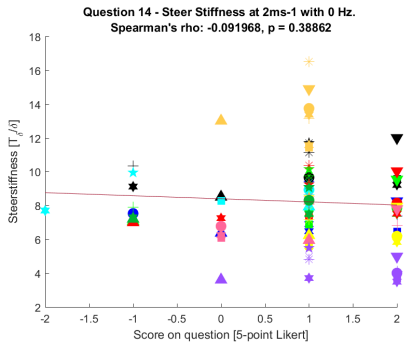

Question 13 - Steer Stiffness at 7ms-1 with peak frequency.
Spearman's rho: 0.1527, p = 0.15077
Steerstiffness [T_o/δ]
Score on question [5-point Likert]

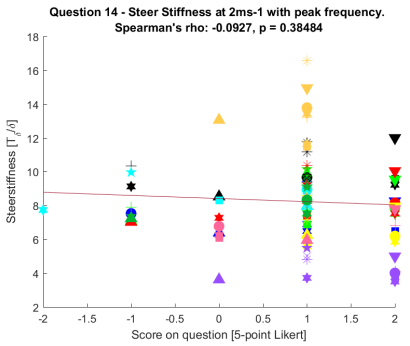

Question 13 - Imaginairy Eigenvalue at 2ms-1.
Spearman's rho: 0.22643, p = 0.031872
Imaginairy Eigenvalue []
Score on question [5-point Likert]

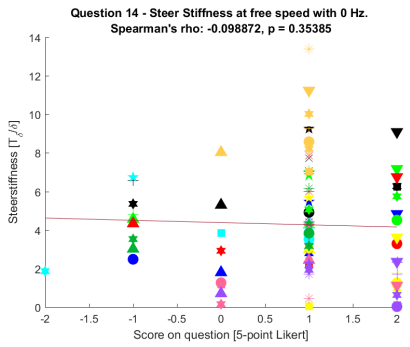

Question 13 - Largest Real Eigenvalue at 2ms-1.
Spearman's rho: 0.23786, p = 0.023974
Real Eigenvalue []
Score on question [5-point Likert]

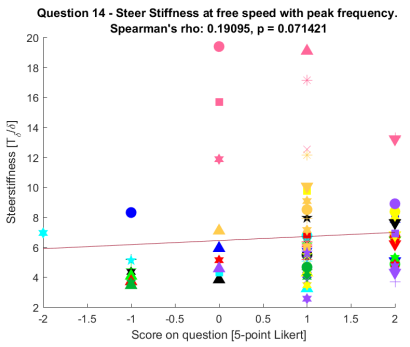

Question 13 - Largest Real Eigenvalue at free speed.
Spearman's rho: 0.0097152, p = 0.92759
Real Eigenvalue[]
Score on question [5-point Likert]

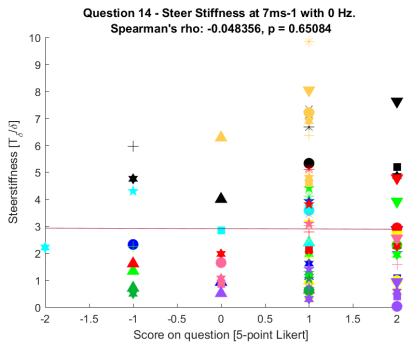

Question 13 - Largest Real Eigenvalue at 7ms-1.
Spearman's rho: 0.12838, p = 0.22785
Real Eigenvalue []
Score on question [5-point Likert]

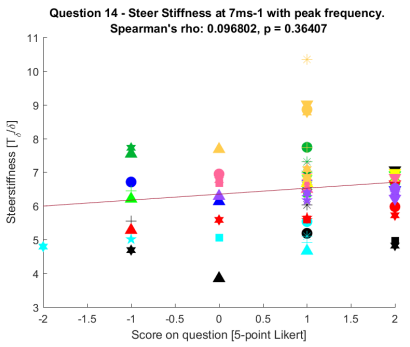

Question 14 - Steer Stiffness at 2ms-1 with 0 Hz.
Spearman's rho: -0.091968, p = 0.38862
Steerstiffness [T_δ/δ]
Score on question [5-point Likert]

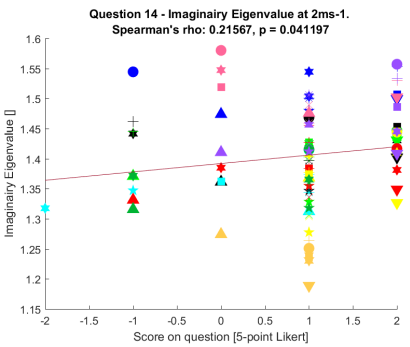

Question 14 - Steer Stiffness at 2ms-1 with peak frequency.
Spearman's rho: -0.0927, p = 0.38484
Steerstiffness [T_δ/δ]
Score on question [5-point Likert]

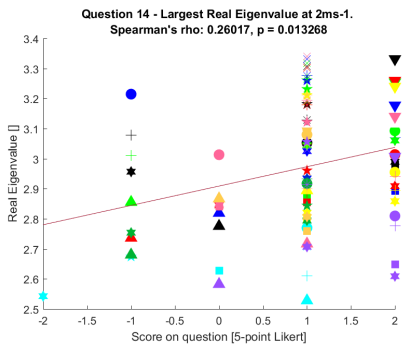

Question 14 - Steer Stiffness at free speed with 0 Hz.
Spearman's rho: -0.098872, p = 0.35385
Steerstiffness [T_δ/δ]
Score on question [5-point Likert]

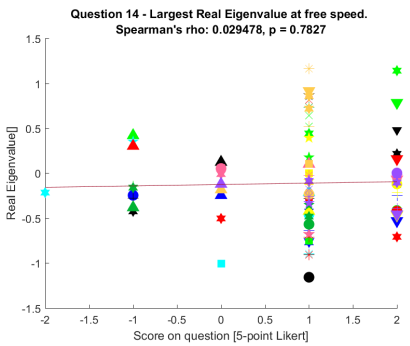

Question 14 - Steer Stiffness at free speed with peak frequency.
Spearman's rho: 0.19095, p = 0.071421
Steerstiffness [T_δ/δ]
Score on question [5-point Likert]

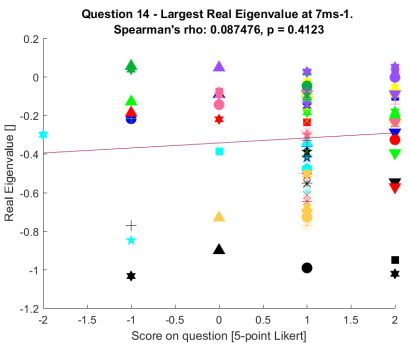

Question 14 - Steer Stiffness at 7ms-1 with 0 Hz.
Spearman's rho: -0.048356, p = 0.65084
Steerstiffness [T_δ/δ]
Score on question [5-point Likert]


Question 14 - Steer Stiffness at 7ms-1 with peak frequency.
Spearman's rho: 0.096802, p = 0.36407
Steerstiffness [T_δ/δ]
Score on question [5-point Likert]


Question 14 - Imaginairy Eigenvalue at 2ms-1.
Spearman's rho: 0.21567, p = 0.041197
Imaginairy Eigenvalue []
Score on question [5-point Likert]

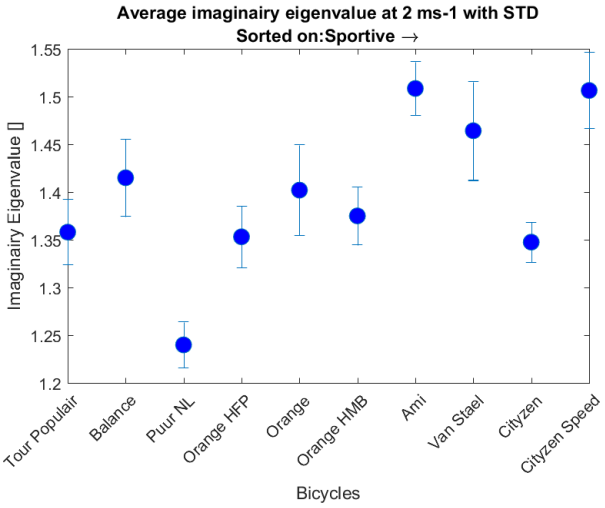

Question 14 - Largest Real Eigenvalue at 2ms-1.
Spearman's rho: 0.26017, p = 0.013268
Real Eigenvalue []
Score on question [5-point Likert]

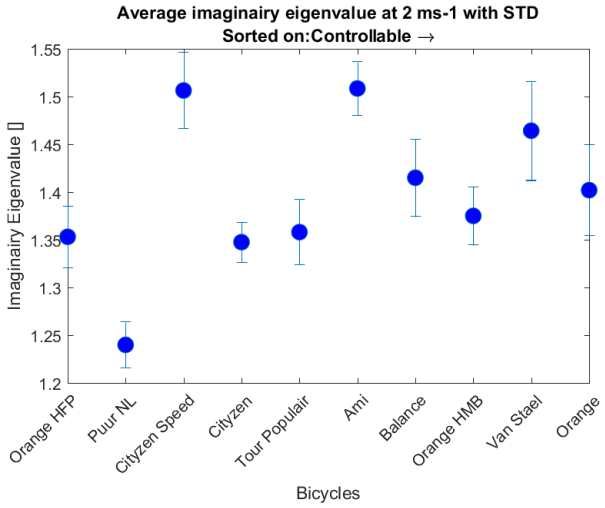

Question 14 - Largest Real Eigenvalue at free speed.
Spearman's rho: 0.029478, p = 0.7827
Real Eigenvalue[]
Score on question [5-point Likert]

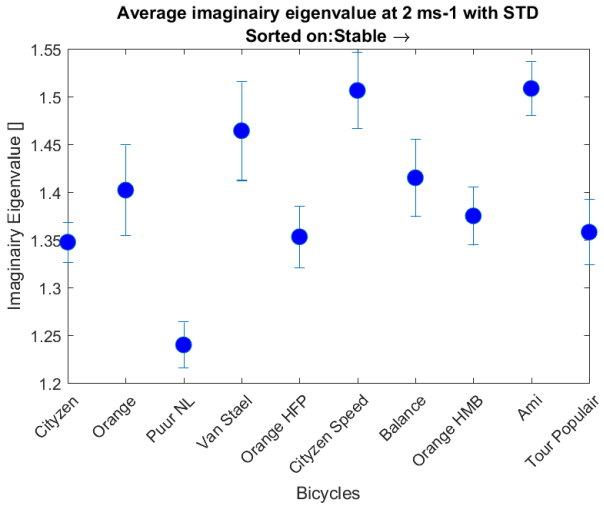

Question 14 - Largest Real Eigenvalue at 7ms-1.
Spearman's rho: 0.087476, p = 0.4123
Real Eigenvalue []
Score on question [5-point Likert]

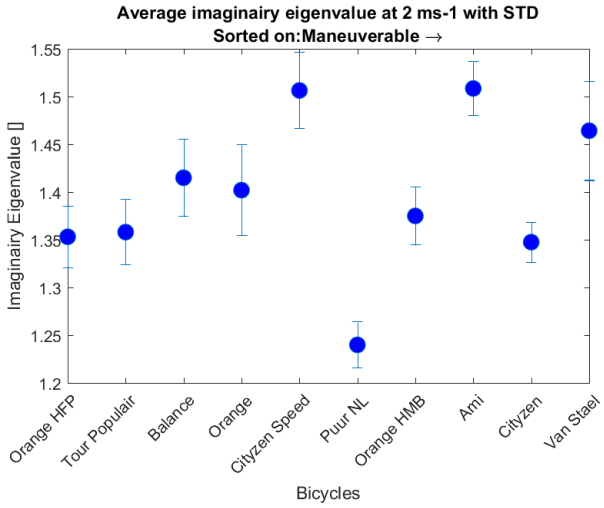
Bicycle Ranking per Correlation

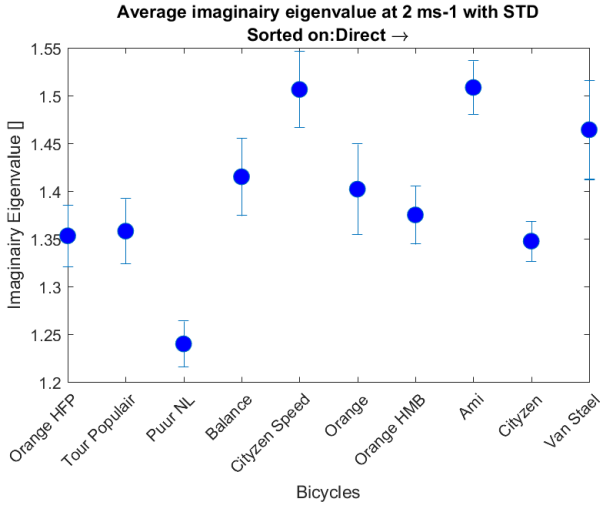
The bicycles are sorted from a low to high score on the handling qualities for the significant correlations with an objective bars. The values are averaged and the STD value is displayed as well. A perfect correlation should show an increasing (or decreasing when negative) average value form left to right. Because the bicycles are not positioned on the x-axis by value but by rank, the trend line does not have to be straight. It might have some steps.

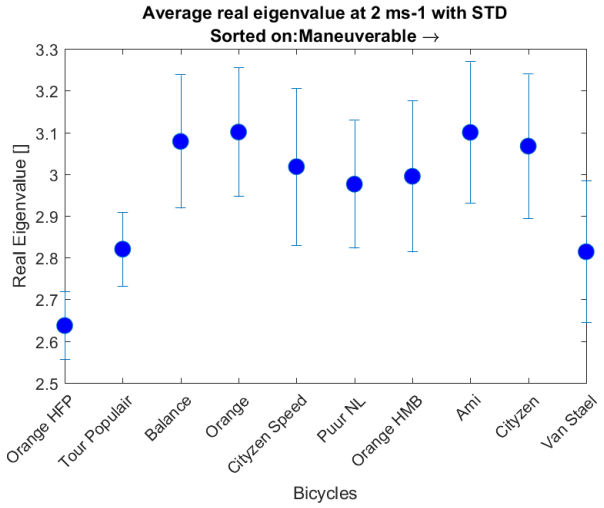


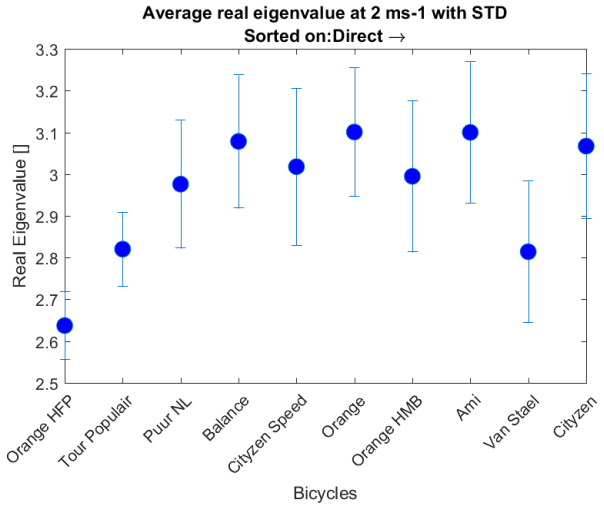


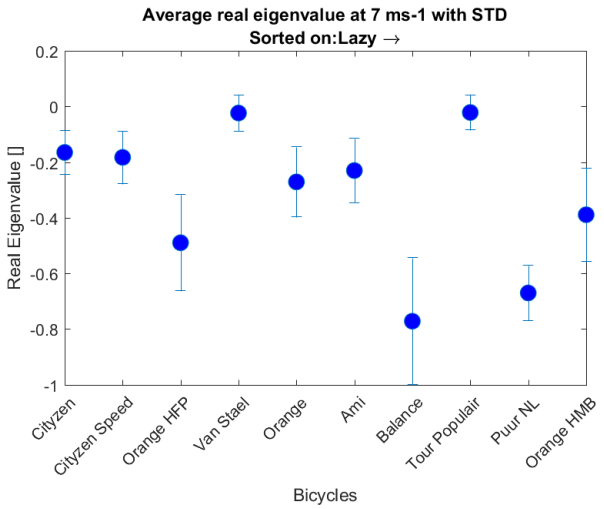

Average imaginairy eigenvalue at 2 ms-1 with STD
Sorted on:Stable →
Imaginairy Eigenvalue []
1.55
1.5
1.45
1.4
1.35
1.3
1.25
1.2
Cityzen
Orange
Puur NL
Van Stael
Orange HFP
Cityzen Speed
Balance
Orange HMB
Ami
Tour Populair
Bicycles

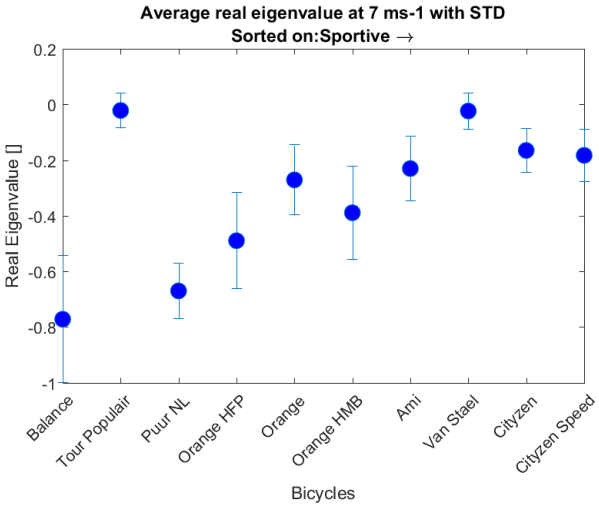

Average imaginairy eigenvalue at 2 ms-1 with STD
Sorted on:Maneuverable →
Imaginairy Eigenvalue []
1.55
1.5
1.45
1.4
1.35
1.3
1.25
1.2
Orange HFP
Tour Populair
Balance
Orange
Cityzen Speed
Puur NL
Orange HMB
Ami
Cityzen
Van Stael
Bicycles

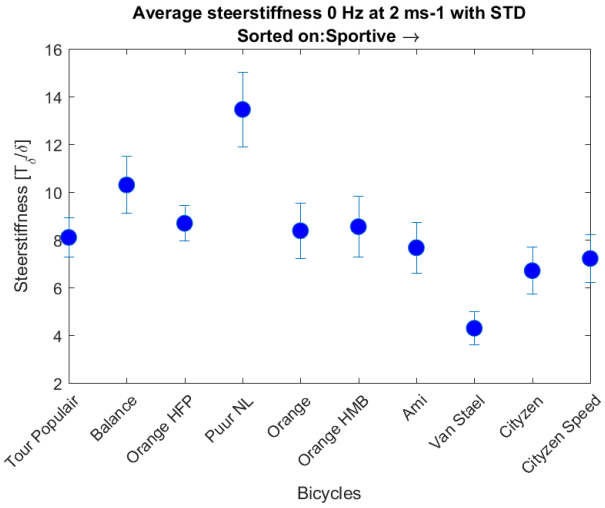

Average imaginairy eigenvalue at 2 ms-1 with STD
Sorted on:Direct →
Imaginairy Eigenvalue []
1.55
1.5
1.45
1.4
1.35
1.3
1.25
1.2
Orange HFP
Tour Populair
Puur NL
Balance
Cityzen Speed
Orange
Orange HMB
Ami
Cityzen
Van Stael
Bicycles

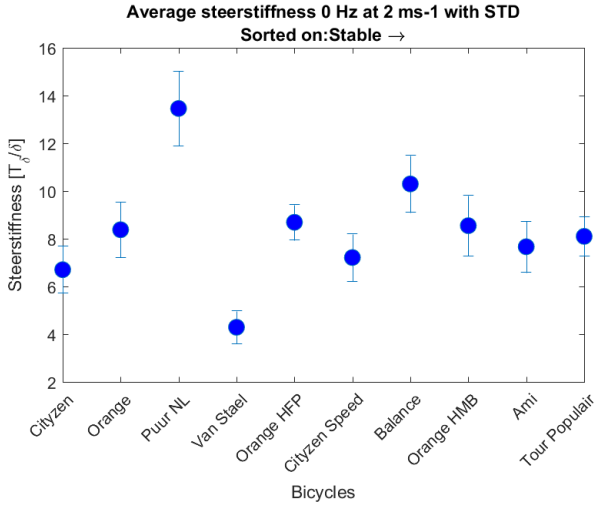

Average real eigenvalue at 2 ms-1 with STD
Sorted on:Maneuverable →
Real Eigenvalue []
3.3
3.2
3.1
3
2.9
2.8
2.7
2.6
2.5
Orange HFP
Tour Populair
Balance
Orange
Cityzen Speed
Puur NL
Orange HMB
Ami
Cityzen
Van Stael
Bicycles

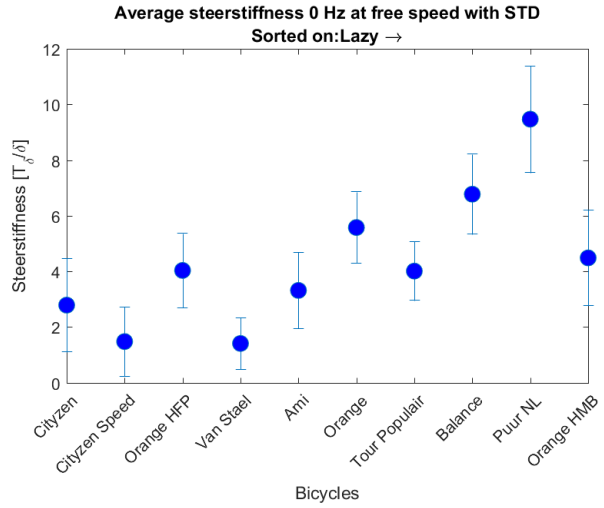

Average real eigenvalue at 2 ms-1 with STD
Sorted on:Direct →
Real Eigenvalue []
3.3
3.2
3.1
3
2.9
2.8
2.7
2.6
2.5
Orange HFP
Tour Populair
Puur NL
Balance
Cityzen Speed
Orange
Orange HMB
Ami
Van Stael
Cityzen
Bicycles

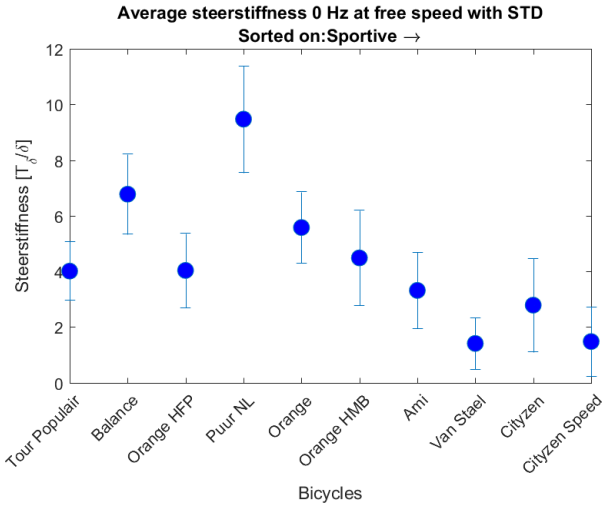

Average real eigenvalue at 7 ms-1 with STD
Sorted on:Lazy →
Real Eigenvalue []
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
Cityzen
Cityzen Speed
Orange HFP
Van Stael
Orange
Ami
Balance
Tour Populair
Puur NL
Orange HMB
Bicycles

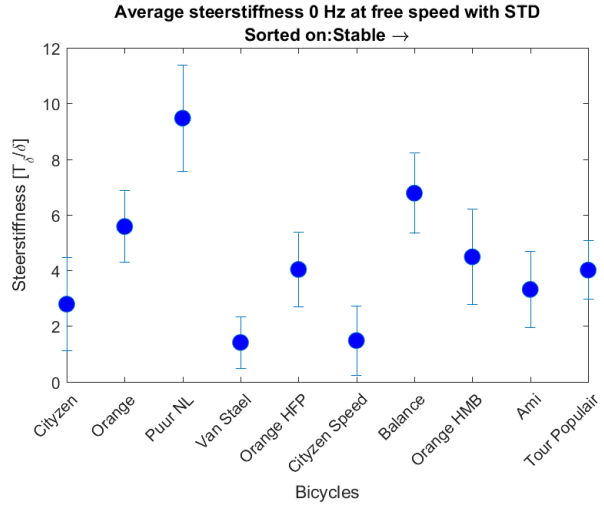

Average real eigenvalue at 7 ms-1 with STD
Sorted on:Sportive →
Real Eigenvalue []
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
Balance
Tour Populair
Puur NL
Orange HFP
Orange
Orange HMB
Ami
Van Stael
Cityzen
Cityzen Speed
Bicycles

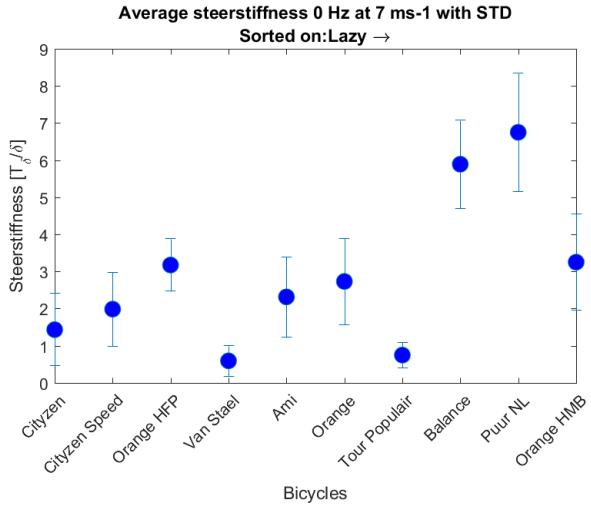

Average steerstiffness 0 Hz at 2 ms-1 with STD
Sorted on:Sportive →
Steerstiffness [T_δ/δ]
16
14
12
10
8
6
4
2
Tour Populair
Balance
Orange HFP
Puur NL
Orange
Orange HMB
Ami
Van Stael
Cityzen
Cityzen Speed
Bicycles

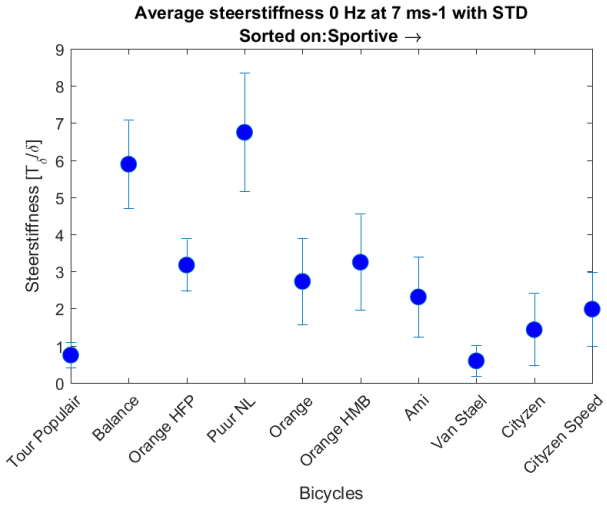

Average steerstiffness 0 Hz at 2 ms-1 with STD
Sorted on:Stable →
Steerstiffness [T_δ/δ]
16
14
12
10
8
6
4
2
Cityzen
Orange
Puur NL
Van Stael
Orange HFP
Cityzen Speed
Balance
Orange HMB
Ami
Tour Populair
Bicycles

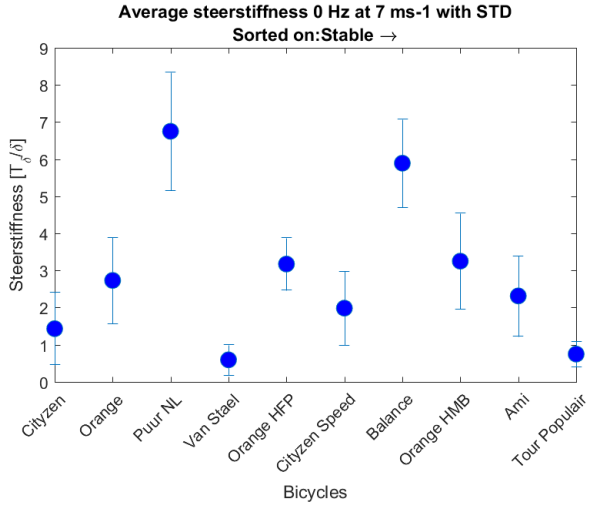

Average steerstiffness 0 Hz at free speed with STD
Sorted on:Lazy →
Steerstiffness [T_δ/δ]
0
2
4
6
8
10
12
Cityzen
Cityzen Speed
Orange HFP
Van Stael
Ami
Orange
Tour Populair
Balance
Puur NL
Orange HMB
Bicycles

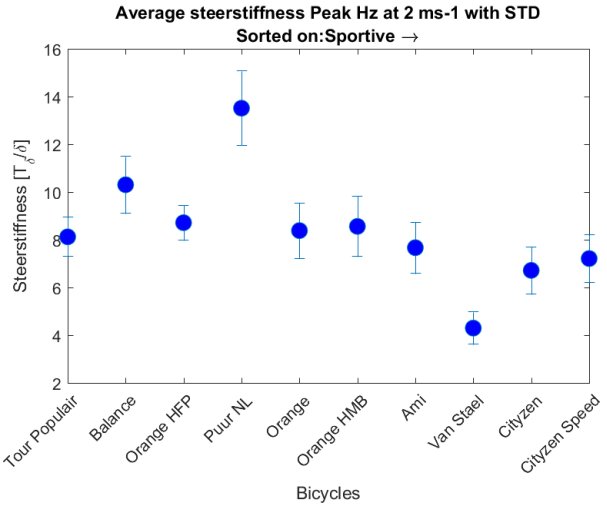

Average steerstiffness 0 Hz at free speed with STD
Sorted on:Sportive →
Steerstiffness [T_δ/δ]
0
2
4
6
8
10
12
Tour Populair
Balance
Orange HFP
Puur NL
Orange
Orange HMB
Ami
Van Stael
Cityzen
Cityzen Speed
Bicycles

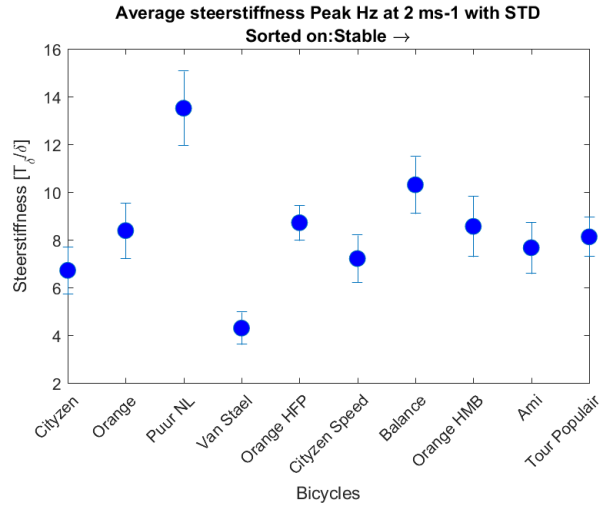

Average steerstiffness 0 Hz at free speed with STD
Sorted on:Stable →
Steerstiffness [T_δ/δ]
0
2
4
6
8
10
12
Cityzen
Orange
Puur NL
Van Stael
Orange HFP
Cityzen Speed
Balance
Orange HMB
Ami
Tour Populair
Bicycles

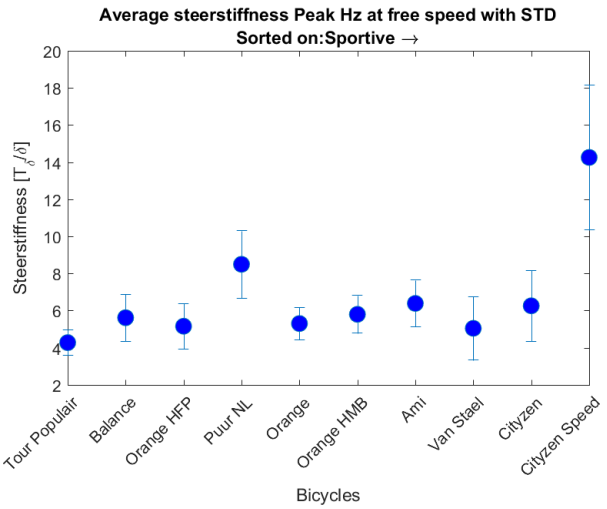

Average steerstiffness 0 Hz at 7 ms-1 with STD
Sorted on:Lazy →
Steerstiffness [T_δ/δ]
0
1
2
3
4
5
6
7
8
9
Cityzen
Cityzen Speed
Orange HFP
Van Stael
Ami
Orange
Tour Populair
Balance
Puur NL
Orange HMB
Bicycles

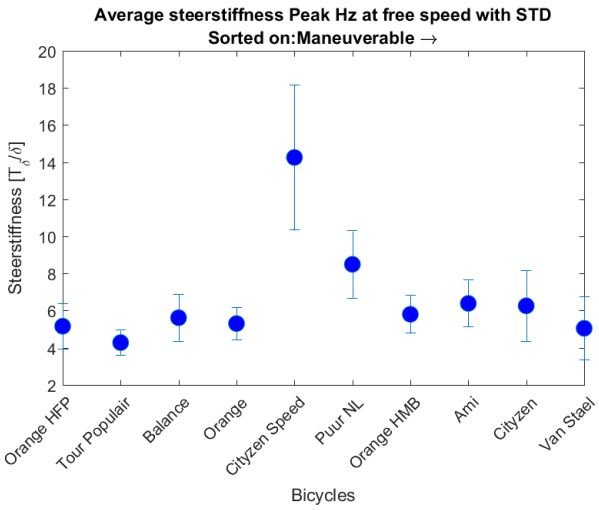

Average steerstiffness 0 Hz at 7 ms-1 with STD
Sorted on:Sportive →
Steerstiffness [T_δ/δ]
0
1
2
3
4
5
6
7
8
9
Tour Populair
Balance
Orange HFP
Puur NL
Orange
Orange HMB
Ami
Van Stael
Cityzen
Cityzen Speed
Bicycles


Average steerstiffness 0 Hz at 7 ms-1 with STD
Sorted on:Stable →
Steerstiffness [T_δ/δ]
0
1
2
3
4
5
6
7
8
9
Cityzen
Orange
Puur NL
Van Stael
Orange HFP
Cityzen Speed
Balance
Orange HMB
Ami
Tour Populair
Bicycles


Average steerstiffness Peak Hz at 2 ms-1 with STD
Sorted on:Sportive →
Steerstiffness [T_δ/δ]
16
14
12
10
8
6
4
2
Tour Populair
Balance
Orange HFP
Puur NL
Orange
Orange HMB
Ami
Van Stael
Cityzen
Cityzen Speed
Bicycles


Average steerstiffness Peak Hz at 2 ms-1 with STD
Sorted on:Stable →
Steerstiffness [T_δ/δ]
16
14
12
10
8
6
4
2
Cityzen
Orange
Puur NL
Van Stael
Orange HFP
Cityzen Speed
Balance
Orange HMB
Ami
Tour Populair
Bicycles


Average steerstiffness Peak Hz at free speed with STD
Sorted on:Sportive →
Steerstiffness [T_δ/δ]
20
18
16
14
12
10
8
6
4
2
Tour Populair
Balance
Orange HFP
Puur NL
Orange
Orange HMB
Ami
Van Stael
Cityzen
Cityzen Speed
Bicycles


Average steerstiffness Peak Hz at free speed with STD
Sorted on:Maneuverable →
Steerstiffness [T_δ/δ]
20
18
16
14
12
10
8
6
4
2
Orange HFP
Tour Populair
Balance
Orange
Cityzen Speed
Puur NL
Orange HMB
Ami
Cityzen
Van Stael
Bicycles