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Dynamic behaviour of cargo bikes: An approach for quantitative evaluation

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Abstract: People's desire for individuality and flexibility in inner-city traffic often leads to high emissions and a critical parking situation. The extensive use of private cars puts a strain on the entire transportation system. In order to counteract, this paper deals with quantifying driving behaviour in order to influence the product development of cargo bikes, which are designed to transport loads for short distances. The overall bicycle developments are based on user studies on riding behaviour and thus focus on higher acceptance. The aim is that the newly developed multi-lane cargo bikes will achieve the same driving behaviour as a conventional bicycle and increase public acceptance of sharing systems and usability of cargo bikes. A single-lane cargo bike is presented, which is used for the active recording of measured values. This enables the assessment of forces such as saddle forces, pedal forces and steering forces, as well as steering movement and velocity. Statistical methods can be used to draw conclusions about the driving behaviour of cargo bikes, which is significantly influenced by the load distribution. Cargo bikes present a valuable opportunity to reinforce sustainable mobility and supplant the automobile as a mode of transportation. In particular, if the transportation of heavy loads remains within the rider's control, a positive riding experience can be achieved, as is the case with conventional bicycles.

Keywords: Cargo bike, handling ability, driving behaviour, rainflow analysis, quantitative evaluation, steering angle

1 Introduction

SteigtUM is a public funded project. Electrical cargo bicycles, also known as cargo bikes or cargo e-bikes, have become very popular in the recent years. The data of sales of cargo e-bikes in Germany in year 2022, which are released by Zweirad-Industrie-Verband (2023), had a share of 7.5 % of all sold e-bikes with an overall growth of 37.5 % compared to the previous year.
The unconventional design, ergonomics, unusual steering mechanics or weight distribution of these cargo bikes often results in poor handling characteristics. Examples of this include poor steering behaviour, a large turning circle, an excessively high centre of gravity of the loads or the incorrect load arrangement, which result in inadequate driving characteristics. In many cases, these problems lead to poor acceptance. The dynamics of cargo bikes describes the movement of bikes due to the forces acting on them and is therefore a very complex subject. The interesting dynamics of cargo bike include balancing, steering, braking, acceleration, suspension activation and vibrations. Another important aspect is evaluation of different types of cargo bikes through test studies, to find out the best cargo bike concept and to identify factors that exert a significant influence on driving behaviour. There are many aspects to be aware of when developing a cargo bike with special regard to driving abilities, which will be used in a public sharing concept. First of all it must be safe to ride and easy to handle, so no one needs to learn riding the bike before usage. Therefore, it must be lightweight and self-explaining. It helps a lot, when the rider can make use of experience he already got from normal bicycles or other cargo bikes. When developing a new type of cargo bike, it is important to think about positioning the cargo and its effects on driving behaviour and handling abilities. When it comes to special requirements given from the research project SteigtUM, like multi-lane for autonomous driving capability, design and development gets more complex as well as the driving behaviour.

2 Bicycle Dynamics

Cargo bikes are a subtype of bicycles and are available with electric motors for pedal-assist. In general, they are vehicles with two wheels aligned in a single lane or three or more wheels - a multi-lane tricycle or quadricycle. All those vehicles are affected by the same physics expressed in bicycle dynamics. Wilson (2004) defines bicycle physics as power and speed, accelerating and braking, aerodynamics, rolling movements with tires and bearings. Furthermore, the geometry of the frame, materials and stresses, as well as mechanics for power transmission are connected to bicycle theory, which is important especially for development and design. The main aspect for describing the driving behaviour of such vehicles are the steering and balancing in objective means and the resulting safety and comfort feeling from the riders point of view.

2.1 Dynamic behaviour – steering and balancing

It has been demonstrated by researchers that the stability of a bicycle is a highly complex phenomenon to describe. Kooijman et al. (2011) demonstrated that it is possible to reduce the complexity of the dynamic system to a simplified version, where

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the gyroscopic effects of spinning wheels and the caster effect due to the trail of the steering wheel are excluded. Most of the influencing parameters can be described in formulas based on geometric relationships connected to mass and movement. Based on those relationships it would be possible to simulate a moving bicycle in a multibody-simulation investigating dynamic behaviour influenced by various parameters. In theory it is possible to compare different kind of vehicles by calculations and simulations, but it is very extensive in modelling and the results still have to be validated with experimental investigations.

2.2 Influence on riders experience

Only while riding a bicycle, the cyclist on his own can provide information on how it is to ride the actual bicycle. To compare different models of bikes it is necessary to test the bikes in a short time interval and the cyclist needs the experience to draw the right conclusions from the feedback he got from the bike. To investigate new methods for quantifying the evaluation of different types of bicycles, it is important to understand how the rider's experience can be expressed and simplified. It is important to understand the expressions based on feelings of the cyclist, like safety, comfort, manoeuvrability, stability and ergonomics. One approach is to focus on the points of contact between the cyclist and the vehicle, where the cyclist receives direct feedback from the bike, which is then transformed into a subjective impression and experience.
There are three major aspects that have a significant impact on driving behaviour: the vehicle, the cyclist and the environment. Each of these aspects is characterised by a number of parameters that can vary. If we take a look at the vehicle itself the major parameters are the geometry connected to cargo capacity and the overall mass. The geometry of any bicycle is defined through its design of the frame connecting all major parts like wheels and steering and of course the contact points between cyclist and bicycle. Additionally, the intended use scenario is the base of the design. The concept of cargo bikes differs significantly with regard to payload distribution, i.e. the location and quantity of the cargo. The overall vehicle mass is determined by the design concept, the materials used and the features incorporated. The cyclist itself is also characterised by a number of variable parameters. Obvious characteristics such as height, mass and stature of the cyclist in relation to mass distribution are easy to measure. However, each rider possesses a unique level of experience. It is difficult to quantify how individuals adapt to novel or spontaneous circumstances, such as reaction time or balance. These data would require a psychological evaluation. Furthermore, the rider's expectations on how to handle a new type of bicycle may vary widely. Every cyclist has their own preferences when it comes to ergonomics. In conclusion those cyclist related parameters are hard to measure and evaluate. External circumstances increase the number of variable parameters further. In order to create realistic driving situations, it is necessary to ride outdoors on any type of test track. Some of the environmental influences such as weather conditions (wind, temperature, humidity) can not be controlled. This results in different surface properties. It is possible to influence other parameters with relative ease, such as the surface type (asphalt, cobblestone or gravel) and the presence of distractions from the surrounding environment, such as pedestrians or traffic. With so many factors influencing riding behaviour, it is very difficult to compare different bicycles. Things get even more complicated when the type of bike also varies.

3 Evaluation of different types of cargo bikes

At this time there are very much different cargo bikes available. Europe's largest fair for any kind of cycles EUROBIKE set a new benchmark for diversity of vehicles. Therefore it is necessary to get a short overview on the market and the main differences.

3.1 Types and concepts

Many of those different types can be categorized in concepts based on cargo positioning, capacity and number of wheels and their position. There are many different cargo bike concepts on the market distinguished by few main aspects that have the most influence on the appearance: The positioning of cargo and the rider, and the overall cargo capacity and mass of the vehicle. Other characteristics are the number and positions of wheels. Furthermore centre of mass and the weight distribution has a huge impact on appearance. Based on the categorisation for cargo bikes mentioned in Gressmann et al. (2019) four different types with the greatest possible differences in characteristics were chosen for further investigation and are shown in simplified manor in Fig. 1.

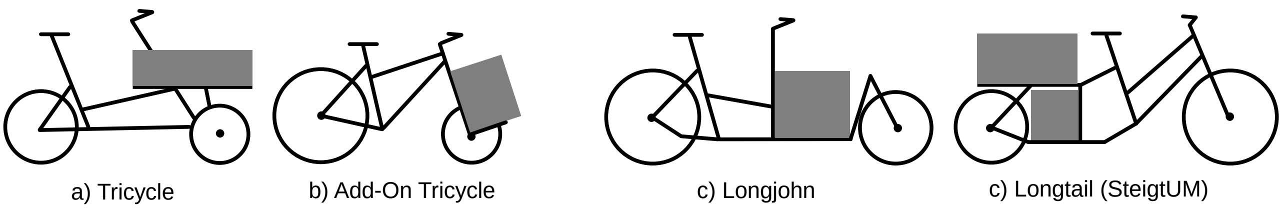

Fig. 1: Different concepts of cargo bikes

Two of the concepts, type a) and b), can be designated to multi track cycles with two wheels in the front and one wheel behind the cyclist. Both tricycles are featuring a tilting mechanism for better dynamic driving behaviour. They differ a lot in their maximum payload. Model a) is designed to transport approximately 80 kg with a volume of 210 litres (Chike (2024)), whereas the concept b) is limited to a much smaller capacity of 25 kg with a volume of 70 litres (Trego (2024)). The two other concepts are typical two wheeled cargo bikes, where for the frontloader or longjohn type c) the cargo can be positioned on a lower platform in front of the rider. An example for the longjohn is the Douze V2 longtail in a very compact configuration with a capacity of approximateley 120 litres and 50 kg. The prototype concept designed and engineered within the research project SteigtUM is intended to combine the benefits of an usual longtail cargo bike with the idea to split up the cargo area to a low level position for small and heavy cargo and a second position for bulky lightweight cargo on a rack above the rear wheel with an overall capacity of 50 kg and 100 litres of available storage space.

3.2 Test study results and conclusion for engineering

The four cargo bikes, where each represents a type of cargo concept from Fig. 1, have been investigated in a large scale field study at Technische Universität Bergakademie Freiberg (TUBAF) under the lead of our project partners from Technische Universität Chemnitz (TUC). On a small oval shaped course with some obstacles forcing intended driving situations like small turns, slalom or bumpy road, 20 people tried out all cargo bikes with several states of payload. The psychological accompanying study included interviews and questionnaires before and after test rides. The results of this test showed that there are very big differences between all the different types of cargo bikes with regard to handling characteristics and dynamic behaviour, especially when the cargo bike is loaded with 50 kg of cargo Kreißig et al. (2021). The study showed that the prototype concept developed by the Institut für Maschinenelemente, Konstruktion und Fertigung (IMKF) at TUBAF, was the best rated model and was most easy to control and steer, even with maximum cargo loaded. The conclusion for further development from this study was that a cargo bike for public sharing should be a longtail concept and needs to be lightweight for good handling abilities. Similarities to a normal bicycle helps a lot to make learning process obsolete. A good payload distribution has a minor impact on handling and driving behaviour. Feedback from this study were used to develop production status of the cargo bike for the sharing concept.

4 Experimental evaluation and measurements

In order to obtain representative data to compare different types of bicycles and to use them for future developments, a large-scale field test needs to be set up, as Kreißig et al. (2021) did in their experiment with a number of 20 voluntary participants. This takes up a lot of time and human resources on the part of the researchers, as well as on the part of the users in a field study. Another approach to evaluate the user experience, which needs to be simpler in theory and implementation, especially for cargo bikes, is to equip the research bike with simple measurement technology and collect data to investigate the influence of different parameters on handling and driving behaviour in a short-term experiment.

4.1 Approach and expectations

To keep the variables low in number, it is necessary to get a theoretical look at the movement on the cargo bike. The obvious aspects of movement can easily be tracked with the steering angle and velocity over time or distance. So, you can determine a straight forward path as seen in Fig. 2. As the steering angle increases a cornering process is initiated. While keeping the angle constant a constant radius is driven. Decreasing the angle means bending back into a straight forward condition. While in theory the graph can look smooth reality could show differences. The low smooth frequency with high amplitudes of the cornering process can be overlapped by a higher frequency with low amplitudes referred e.g. to balancing impacts like shown in Fig. 2 right side.

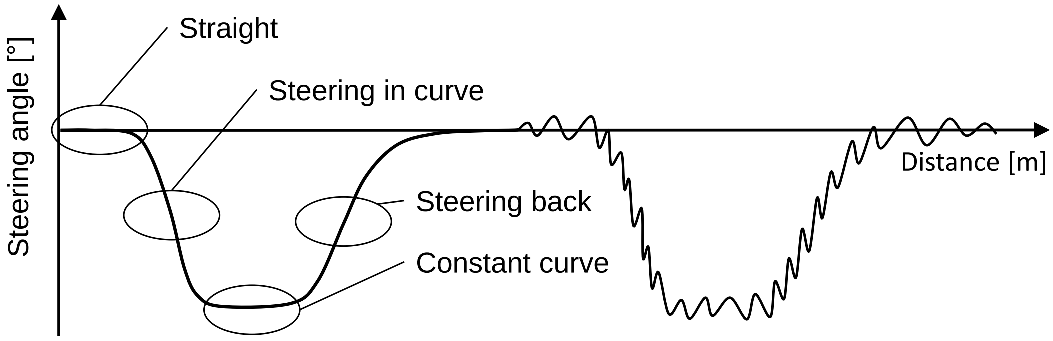

Fig. 2: Steering angle over time in theory (left) and with overlapped higher frequencies (right)

Based on theoretical considerations research hypotheses can be established:

- The cargo has influence on driving behaviour:
  - Positive influence due to beneficial positioning of the cargo (IMKF concept)
  - Small negative influence due to good mass distribution (compared to other cargo bike concepts)
- The driver has influence on the driving behaviour:
  - Body size, -mass and stature (influence of centre of mass)
  - Cycling position (ergonomics)
- (Un)safe driving behaviour is measurably recognisable:
  - Stable straight forward path
  - Special situations: Emergency brake manoeuvre, slalom, slowly cornering, . . .
- Learning and adaption effects are identifiable (repeated tests. . .).
- A preferred direction of cornering is recognizable.

4.2 Experimental concept

Based on the hypotheses made up from theory, experiments were set up to investigate evaluation methods for driving behaviour. With simple preliminary tests measurement equipment was implemented and configured.

4.2.1 Measurement equipment

The test vehicle for this experiment is the series type frame of the CityPed built up as a single lane cargo bike with two 20” wheels. To track data of the movement while cycling a speed sensor is implemented in the front wheel. Additionally, a cadence sensor is situated at the crank to measure the rider’s rotation speed when pedalling. The measurement of steering is realized with a steering angle sensor connected to the head tube of the frame and the steering tube of the handlebar assembly. Furthermore, several force sensors based on strain gauges are implemented, located at the contact points between cyclist and bicycle. The cyclists force exerted onto the saddle can be measured with a single strain gauge at the backside of the seatpost. At the right side of the handlebar are two sensors perpendicular arranged to each other, to differentiate between horizontal and vertical forces. Another strain gauge is implemented in a force measuring pedal, which was developed by the IMKF. All sensors are designed for easy attachment, so it is possible to change all the measurement equipment to any other bike. Fig. 3 shows the cargo bicycle used in the experiments. In addition to the positions of the sensors, the figure shows the distribution of the available cargo space. The upper containment is made from expanded polypropylene (EPP) and has a capacity of approximately 80 litres. A small amount is required for the peripheral measurement equipment, like amplifiers, power supply, AD-converter and laptop. The remaining space is used for up to 30 kg of payload. The lower platform can hold up to 20 kg in a sturdy box fixed with a tensioning strap.

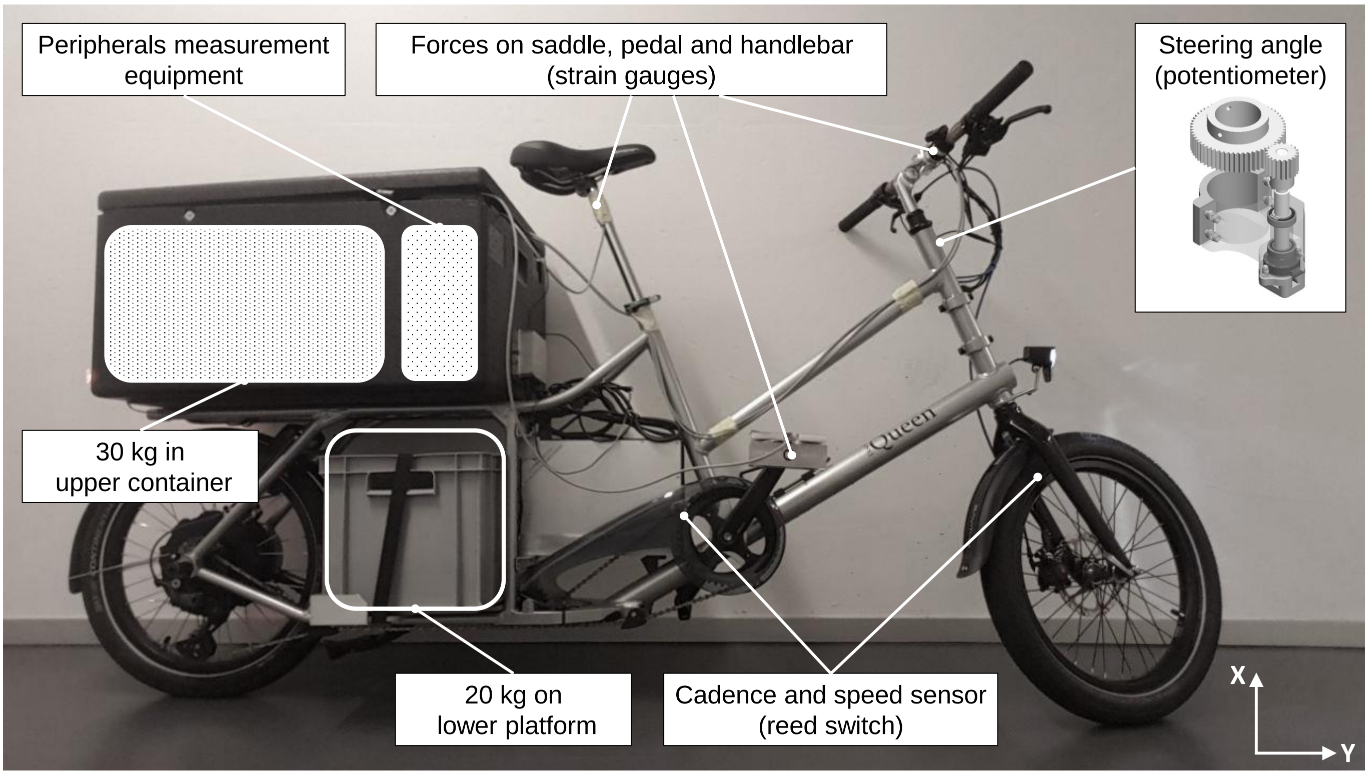

Fig. 3: Research cargo bike with position of sensors and payload distribution

4.2.2 Test track and procedure

The test track for this experiment was a simple oval course with focus on repetition of movements. It was specially prepared to enable a very simple driving situation of cornering and driving straight forward. The symmetric oval on asphalt surface had two straight forward parts of 16 metres and a curve radius of 6,5 m. Each test subject had to go for 10 laps following the given path. After five laps, the subject had to perform a stop-and-go manoeuvre at the start area. The course was completed by every cyclist in clockwise and counter clockwise direction. For each direction three different payload situations were investigated: Without additional cargo, with 20 kg situated only at the lower platform and with full payload, where 20 kg are mounted to the lower platform and 30 kg were put in the upper cargo box. Every cyclist was allowed to adjust only the seatpost height to enable an ergonomic position. All other vehicle parameters like gear, motor support and tyre pressure were not changed. The experiments were made with the same environmental conditions, sunny and dry asphalt. In total 4 different cyclist have produced data with a wide diversity of parameters like body size, mass and experience. The individual properties of the test subjects are shown in Tab. A.1.

4.3 Methods for analysis

The measured raw data can be presented in two different diagrams for preliminary evaluation and recognizing significant differences between two subjects in the same driving situation. The reaction forces of the handlebar and saddle are drawn over time in one diagram. Steering angle and velocity are plotted over time in the movement diagram. The raw data of forces shows significant points in the experiment, where the test subject starts and stops the movement and the repetitive cornering situations. Figure 4 shows the raw data of forces for comparing two different test subjects to each other. The excerpts are taken from the entire measurement data of forces of the two cyclists and consists of multiple rounds of the test track in counter clockwise direction with only 20 kg payload at the lower platform.

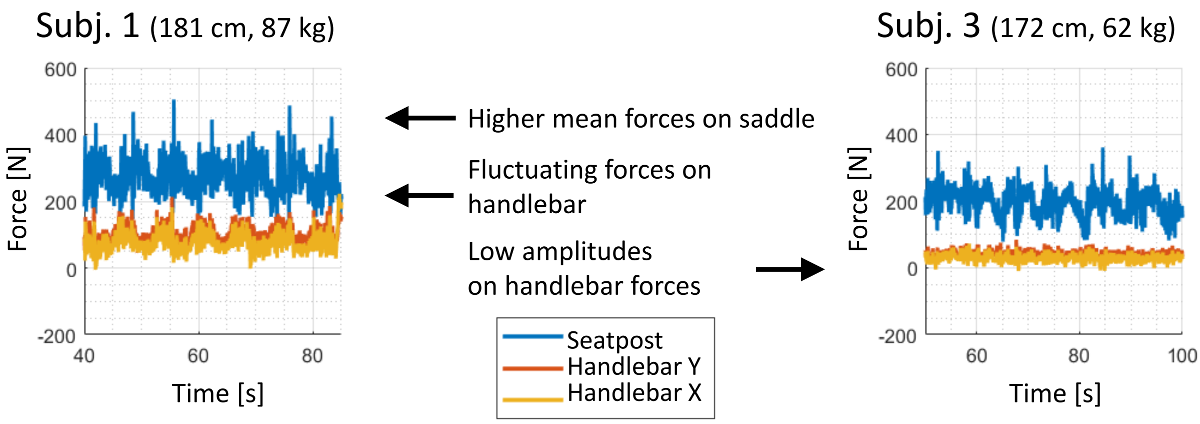

Fig. 4: Raw force data of two test subjects, payload 20 kg on lower platform, counter clockwise direction

The cyclist's mass is represented by the mean value of the sum of all forces measured at the contact points between cyclist and bicycle. Even without the measured data of the pedal force a significant relationship between mass and force is noticeable. In comparison between test subject 1 and 3 the measured raw forces show an average higher force exerted on the saddle and handlebar for subject 1. This is obvious, because test subject 1 is taller and heavier than test subject 3. Another recognizable detail are the amplitudes of the measurement signal. Subject 1 tends to be a more active cyclist with high force amplitudes, where the low amplitudes on the handlebar of subject 3 shows a more passive cycling style.

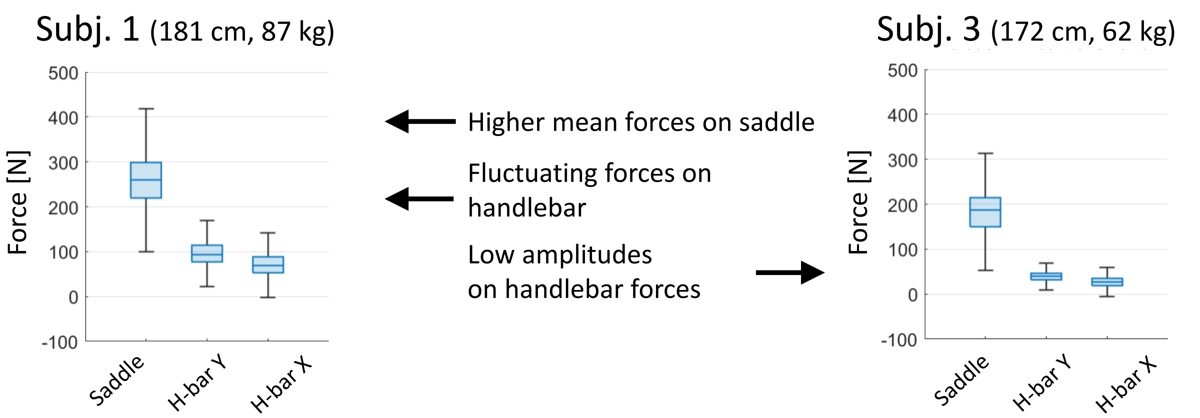

Fig. 5: Boxplots of forces of two test subjects, payload 20 kg on lower platform, counter clockwise direction

To make the measurements of forces comparable over the whole test course, each raw data signal is evaluated in a boxplot with the mean value and 25% and 75%-quantiles. The outliers were not considered. Figure 5 shows the boxplots of forces for comparing test subject 1 and 3. It is evident that the mean values are significantly higher for cyclist 1. Furthermore, the deviation from the mean value is generally higher for cyclist 1, especially for the forces on the handlebar due to more active cycling.
The signals for velocity and steering angle are both plotted together in one diagram, to find correlations between steering and velocity. Figure 6 shows significant excerpts from the same test subjects as before. The start and stop sections are measured, but not included in analysis, because the focus of this experiment is set primarily on cycling constant at repetitive conditions. The plot of steering angle over time represents the steering action of the cyclist following the designated path of the experimental test track. The data consist of two superimposed oscillating wave patterns. The major oscillation is at a low frequency with high amplitudes representing the steering action to change the direction of the cargo bike to follow the test track. An angle of 0° is a straight forward movement. When driving a curve, the cyclist has to push at the corresponding side of the handlebar inducing a steering force, which results in an increasing steering angle. The Angle stays at its maximum value for driving a constant radius of the curve and goes back to 0° to go straight forward again. This low frequency oscillation with high amplitudes is superimposed with a high

frequency oscillation with small amplitudes. This phenomenon can be explained especially by the balancing manoeuvres of the cyclist. The velocity graphs are very different for each test subject and the different driving situations.

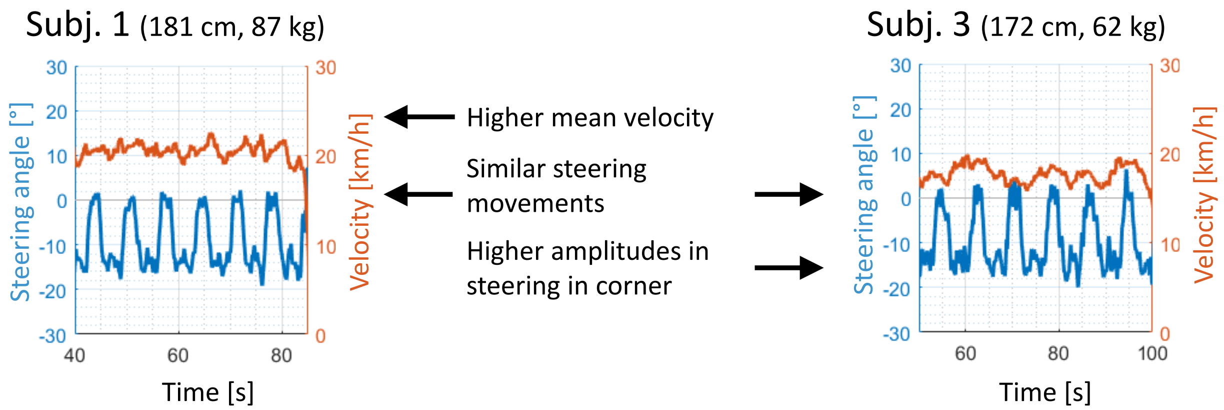

Fig. 6: Raw data of steering angle and velocity of two test subjects, payload 20 kg on lower platform, counter clockwise direction

In comparison of Subject 1 and 3 (Fig. 6) a clear difference in average velocity and variation is recognizable. This can be analysed with a boxplot (see Fig. 7). The graph of the steering angle of every test subject looks similar. An approach to differentiate this data and make it comparable, the statistic algorithm of rainflow counting was used. Figure 7 shows the result of the rainflow counting algorithm on the data of the same experiment from before.

There are three remarkable sections in this diagram, as already described in the raw data of steering. (1) is the straight forward movement around 0°, (2) is the constant cornering motion and (3) is the high valued steering motion, when entering and leaving a curve. The amplitude is an indicator whether the steering motion is intended to change the bicycles direction (higher angles, area 1) or for stability purpose (small valued amplitudes), which are represented in area (2) and (3). Data points which are not in this areas probably come from stop and start motion, where a low number of big steering movements were noticed during the experiments. In direct comparison there are major differences between subject 1 – an experienced cyclist - and subject 3 – an inexperienced cyclist. Focusing on the counts of oscillations in the histogram (Fig. 7) for straight forward and constant curve movement the experienced test subject 1 shows a higher number and less spread of steering angles. This means that test subject 1 has overall less scattering in data points, which lead to the assumption that test subject 1 shows a safer driving behaviour than test subject 3 for this investigated driving situation. Another indicator for unsafe driving of test subject 3 is the total count of oscillations, which is higher. Furthermore subject 1 had an overall higher velocity with lower mean value of the steering angles for area (1). This suggests a correlation between velocity and steering angles for driving repetitive curves.

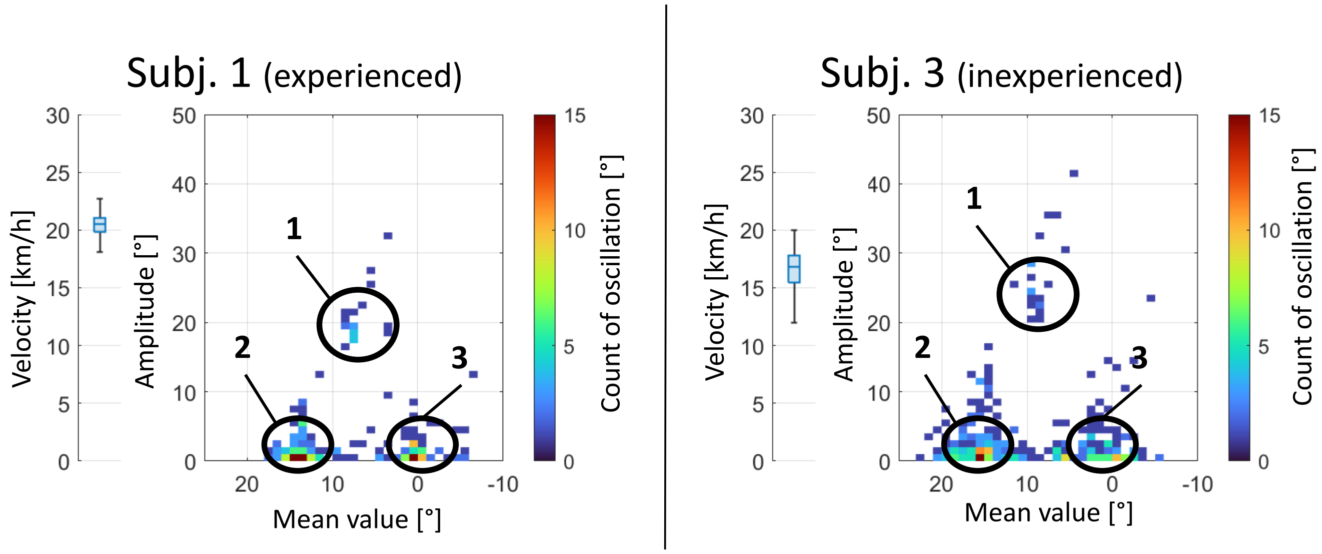

Fig. 7: Rainflow histogram for comparison of steering angle and boxplots of velocity

4.4 Conclusion

An approach for quantifying and evaluating driving behaviour has been developed and tested. Referring to the hypothesis based on theoretical considerations, analysis has shown that on a specified test track a driving situation is reproducible and can be used to compare different cyclists with each other. From analysing the corresponding rainflow diagrams the driver influence, unsafe cycling and the influence of cargo can be verified. So far, less recognizable is the cyclists preference of turning direction and learning effects. Furthermore, it is evident that the measurement technology and test track design is sufficient to produce significant data with low effort in human resources. With the developed methods it is possible to work out the differences in driving behaviour with interpreting boxplots of forces and rainflow diagrams of steering angles and correlate them to the cyclist to make an evaluation. It is necessary to further develop the evaluation method to get single or multiple specified values, which describe the driving behaviour based on steering angle and force measurements and which are easier to compare.

5 Outlook

For the acceptance of sharing systems and the switch from private cars to bicycles, it is important that cargo bikes in particular are easy and safe to ride, as they have great potential to replace cars for everyday transport tasks over short distances. This requires cargo bikes that are adapted to the needs of infrequent use by individuals. Driving behaviour plays a key role in the development of such micromobiles. The methods presented here for measuring and evaluating dynamic driving behaviour show that individual factors influence the driving behaviour and can be systematically investigated and evaluated.
So far, only simple driving manoeuvres have been investigated in order to develop the method and assess its suitability for comparing driving characteristics. Further research in this area will analyse different, even more complex driving situations. With further development of the measurement method and analysis, different cargo bike concepts could also be investigated. By evaluating existing cargo bike concepts in certain riding situations, conclusions can be drawn for the development of new cargo bikes so that they are particularly safe and easy to control, thus, contribute to the acceptance of the mobility transition.

Acknowledgement and funding information

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Appendix

In Tab. A.1 individual personal data of all test subjects for the experiments in the oval course are summarized. The experience level describes the previous knowledge and experience with cargo bikes and cargo e-bikes according to the test subject's own assessment.

Tab. A.1: Personal characteristics of the test drivers on the oval course

Subject No.	Gender	Age in years	Height in cm	Mass in kg	Level of experience
1	male	33	181	87	experienced
2	female	28	169	68	experienced
3	female	31	172	62	inexperienced
4	male	44	195	95	inexperienced

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