Untersuchung der Existenz einer Schräglagenschwelle bei Motorradfahrern*innen

Investigation of the existence of a leaning threshold among motorcyclists

Raphael Pleß, Sebastian Will, Alexandra Neukum

Würzburger Institut für Verkehrswissenschaften (WIVW GmbH),
Veitshöchheim, Germany

Florian Scherer

TU Darmstadt Fachgebiet Fahrzeugtechnik (FZD),
Darmstadt, Germany

Zusammenfassung

Schwere Motorradunfälle in Kurvensituationen und ohne Einfluss anderer Verkehrsteilnehmer sind in der Statistik auffällig häufig. Aus Rekonstruktionen dieser Unfälle ist bekannt, dass das maximal mögliche Schräglagenpotential nicht ausgenutzt wurde. Bestandteil des durch die Bundesanstalt für Straßenwesen (BASt) geförderten Forschungsprojekts „Schräglagenangst" (Projekt FE 82.0710/2018) ist daher die Untersuchung, ob eine Schräglagenschwelle Fahrende daran hindert, dieses Potential auszunutzen. Das Auftreten einer solchen Schräglagenschwelle wird dabei insbesondere in Situationen erwartet, welche vom Fahrenden als gefährlich wahrgenommen werden – selbst, wenn oftmals keine reale Gefährdung (z.B. nahende Kollision oder Reibwertsprung) existiert.

Zur Untersuchung der Existenz einer Schräglagenschwelle werden zwei Versuchsreihen durchgeführt. Zum einen dient eine Realfahrstudie zur Erfassung alltäglich gefahrener Schräglagen. Zum anderen werden auf abgesperrtem Testgelände subjektiv kritische, jedoch real unkritische („pseudokritische") Fahrmanöver provoziert. Diese zwingen die Fahrenden z.B. zum unvorhergesehenen Ausweichen oder Anpassen von Geschwindigkeit oder Rollwinkel. Die in beiden Untersuchungen erfassten Messdaten werden mit Subjektivbewertungen der Probanden verglichen. Ein hierzu entwickelter Fragebogen ermöglicht zudem Aussagen zur interindividuellen Risikobereitschaft und dem Komfortbereich der Fahrenden hinsichtlich der gefahrenen Schräglagen.

Eine kollektive Schräglagenschwelle wird nicht beobachtet. Die individuellen Schräglagenschwellen variieren stark in ihren Maxima. Ein Vergleich der im Straßenverkehr gemessenen Rollwinkelverläufe mit theoretischen Verläufen unter Annahme quasistationärer Fahrt ermöglicht eine Clusterbildung, welche gute Übereinstimmung mit den subjektiv erfassten Schräglagenangstbewertungen der Probanden zeigt. In den künstlichen Fahraufgaben auf abgesperrtem Gelände treten je nach Fahrertyp charakteristische Einbrüche in der Rollrate beim Erreichen einer bestimmten Schräglage auf, was für ein situationsabhängiges Verharren in der Rollwinkelaufbauphase spricht. Zudem werden teils unnötig starke Reaktionen auf das Auftreten pseudokritischer Situationen in Form von Brems- oder Lenkeingriffen bei den Probanden beobachtet. Weder ein Unter- noch ein Überschreiten der persönlichen Schräglagenschwelle ist in den Fahrversuchen zu beobachten. Dies führt zu der Annahme, dass insbesondere Fahrtrainings mit starkem Bezug zu Voraussicht, Gefahrenwahrnehmung und dem Steigern der individuellen Schräglagenschwelle eine Besserung des Unfallgeschehens bewirken können.

Die vorgestellte Methodik zur Kombination von Subjektiv- und Objektivdaten aus verschiedenen Erhebungsquellen zur Untersuchung einer Schräglagenschwelle bei Motorradfahrenden zeigt sich insbesondere in Kombination mit neuen Messmethoden (siehe: „Stanglmayr, M. et al.: *Towards Safer Rides: Measuring Motorcycle Dynamics with Smartphones*"), sowie innerhalb des Projektes prototypisch entwickelter, stationärer Messtechnik, tauglich zur Erfassung einer größeren Datenbasis. Diese könnte zukünftig genauere Aussagen zur Existenz einer Schräglagenangst ermöglichen.

Abstract

Severe motorcycle accidents in cornering situations and without the influence of other road users are conspicuously frequent in the statistics. From reconstructions of these accidents it is known that the maximum possible lean angle potential was not exploited. As part of the BASt research project "Corner-Fear" (project FE 82.0710/2018), it is therefore being investigated whether a lean angle threshold prevents riders from exploiting this potential. The occurrence of such a lean angle threshold is expected especially in situations which are perceived as dangerous by the rider - even if often no real danger exists (e.g. approaching collision or µ-jump).

To investigate the existence of a lean angle threshold, two test series are carried out. On the one hand, a naturalistic riding study is used to record roll angles used in everyday riding. On the other hand, subjectively critical, but really uncritical ("pseudo-critical") riding maneuvers are performed on a closed-off test area. These force the riders to e.g. perform unexpected evasion maneuvers or adjust speed or roll angle. The measured data recorded in both investigations are compared with subjective evaluations of the study participants. In addition, the questionnaire developed for this purpose enables statements to be made on the inter-individual willingness to take risks and the comfort range of the rider with regard to their typical use of lean angles.

A collective leaning threshold is not observed. The individual leaning thresholds vary greatly in their maxima. A comparison of the roll angle date measured in road traffic with theoretical curves assuming quasi-stationary riding allows a cluster formation, which shows good agreement with the subjectively assessed fear of lean angles of the participants. In the pseudo-critical riding maneuvers on closed-off terrain, characteristic drops in the roll rate occur when a certain angle is reached, depending of the rider type, which speaks for a situation-dependent persistence in the roll angle build-up phase. In addition, sometimes unnecessarily strong reactions in the form of braking or steering interventions to the occurrence of pseudo-critical situations are observed among some study participants. This leads to the assumption that especially rider trainings with a strong reference to foresight, risk perception and increasing the individual lean angle threshold can improve the occurrence of accidents.

The presented methodology for the combination of subjective and objective data from different survey sources for the investigation of a lean angle threshold of motorcyclists is particularly suitable for the acquisition of a larger database in combination with new measuring methods (see: „Stanglmayr, M. et al.: *Towards Safer Rides: Measuring Motorcycle Dynamics with Smartphones*“), as well as within the project prototypically developed stationary measuring technology. In the future, this could enable more precise statements to be made about the existence of cornering fear.

Investigation of the existence of a leaning threshold among motorcyclists

1 Introduction

In honoration of one of the most renown researchers in the field of motorcyclists' behavior, Professor Bernt Spiegel, we motivate this paper by citing from his book "The Upper Half of the Motorcycle"[1]

> *"Man is […] not "built" to ride motorcycles, but at least he is "pre-adapted" for riding a two-wheeler. That is, he has been adapted in advance (by evolutionary changes) to his original habitat – most notably, starting to walk upright on two legs – and this* ***pre-adaption*** *comes in very handy when he gets on a two-wheeler. Over the course of his evolution, man has had to develop intricate, genetically transmitted behavior programs which have made possible an ever more perfected two-legged existence, and which prepare him well for riding a motorcycle. The programs that give him the ability to balance appear as smaller components or building blocks integrated into the program for motorcycle riding. If man had not, over the past millions of years, already been dealing with the biomechanical challenges of an extremely high center of mass, combined with a very small footprint, neither bicycles nor motorcycles would exist in their current form.*
>
> *Similar explanations apply to lean angle and tire stickiness.* ***Owing to millions of years of experience walking on various surfaces, the available static friction (stiction) under his feet spontaneously leaps into his conscious attention and becomes clearly and directly evident.*** *[…] Man can take the ancient building blocks of behavior affecting sensory and motor activities and incorporate them into the programs that he is acquiring today. In this way, once he has attained perfect command of a high-level program (such as riding a motorcycle), the motorcyclist can extend the so-called evidence experience all the way into the contact patch of the tires.*
>
> *With regard to lean angle, there is another useful pre-adaption, or ancient program stub, that can be used as a building block.* ***As a fast runner, man is already fully able to handle lean angle but only to about 20 degrees.*** *It is exactly the same lean angle that arise everywhere from fast locomotion, where relatively natural conditions exist with respect to stiction (that is, no knobbies, spikes, fixed track surfaces, etc.) As soon as a person has more or less learned to ride a two-wheeler, he will immediately make use of the "naturally" available 20 degrees of lean angle, but he will not go beyond those 20 degrees. This has applied for millions of years to all fast runners – horses, dogs, ostriches. Beyond 20 degrees, on a natural surface, the danger of losing traction increases quickly.*
>
> *In order to exceed the 20 degrees, particular technical conditions are not the only requirement. Another key requirement is a long period of continuous practice. This is the time that is needed to* ***build up a new behavior-controlling program that allows the pre-set limits (based on our genetic heritage) to be exceeded.****"*

Motorcylists belong to the most vulnerable road users. Due to their specific riding dynamics and the preferably curvy, rural roads they ride on, the severity of their accidents is exceptionally high. In 2014, Bauer[2] showed that 45% of the killed motorcyclists in his sample have crashed while cornering without any obvious external cause. Apparently, these accidents all follow an equal pattern:

---

[1] Spiegel, B.: *The Upper Halt of the Motorcycle,* p.35-36

[2] Bauer, K. et al.: *Retrospective analysis of fatal motorcycle accidents*

The rider tangentially exits the turn as he might not feel confident with his actual velocity and roll angle or due to badly executed braking until he eventually hits opposing traffic or other hard objects (e.g. trees, posts, signs). Only 30% of those riders tried to reduce the velocity that they have subjectively perceived as too high, while the other 70% didn't show any reaction before exiting their line. As anticipated by Prof. Bernt Spiegel, the study shows that no rider exceeded the threshold of 20 degrees of roll angle. It is also shown, that none of the accidents would have happened if the rider increased the roll angle to 35 degrees or even less.

Even not so modern motorcycles (both in terms of chassis and tires) are easily capable of performing lean angles way above 35 degrees as long as the friction coefficient between tire and road exceeds not more than μ = 0,7. Therefore, the reason for such crashes must rather be sought in the rider's than his vehicle's performance or environmental factors. This leads towards three main questions:

- Can we find relevant data to support the thesis of the existence of a common roll angle threshold among a broad number of motorcyclists?
- Is this threshold omnipresent or rather only immanent in critical scenarios?
- Are there subjective or objective measurements correlating to a possibly individual threshold value?

To the knowledge of the authors, almost no representative study is published, dealing with statistical distributions of roll angles of everyday riders in everyday riding and – possibly even more important – during critical events. Investigating potential limitations in rider's lean angle performances requires a vast effort in data collection. This is especially true for data of critical events, as there is no simple and ethical way of exposing study participants to real critical situations.

This paper concentrates on the data acquisition methods used to investigate the abovementioned questions and shows first results of a pilot study. It is split in four following chapters: Firstly, we discuss different approaches to acquire the data needed to support – or falsify – the thesis that a roll angle threshold value exists. In chapter 3 we describe a method to collect such data without needing equipped motorcycles that has been prototypically tested in this study. Chapter 4 discusses the possibility of testing "pseudo critical maneuvers" on a closed track. Finally, we show first results from a participant study that was performed within the project BASt FE 82.0710/2018 "Schräglagenangst" ("Cornering Fear"). The paper will then end with chapter 6, a summary and outlook.

2 Data acquisition

Following Bernt Spiegel's hypothesis, only training enables us to ride a motorcycle with roll angles exceeding 20 degrees. However, measurements show, that even beginners may quickly be confident with riding at higher values of roll angle, sometimes even up to 40 degrees under normal conditions[3]. At the same time, the abovementioned accident reconstructions obviously point towards such low values as 20 degrees. Therefore, we assume, that such a threshold might not manifest in everyday riding, but rather in critical events, or – more specific – such events that are perceived as critical by the rider, even if they aren't from a technical point of view. As the rider loses his trust and comfort during maneuvering, e.g. due to an unexpected change in curvature, oncoming traffic or other disturbances and distractions, he might fall back to an "emergency mode", or in terms of Bernt Spiegel a "program" that he can access under any circumstances, whenever supposed emergencies force him to rely on it.

[3] Magiera, N. et al.: *An Approach for Automatic Riding Skill Identification*

Luckily for any study participant of an on-road experiment, such critical events are rather rare. Thus, if we want to investigate them, we have different options:

1) Increase the individual duration of observation and wait for rarely happening critical events.
2) Concentrate the observation to where statistics show an aggregation of critical events.
3) Provoke critically perceived events in a safe environment without real danger.

Obviously, these options differ in the achievable data volume, data quality and efficiency.

The first method relies on many measurements of many riders over a long period of time. In this study, we prototypically use an equipped motorcycle for on road testing with N=24 participants. However, it is rather inefficient to provide expensive high-fidelity measurement equipment or even a fully instrumented vehicle to every study participant. Stanglmayr[4] therefore developed the smartphone application *MotoLogger*, that allows to collect data from a broad range of voluntary users in everyday riding. This technology was used for additional N=15 participants of on road testing in this study.

The second method decreases the individual measurement duration and therefore increases efficiency by concentrating the data acquisition locally e.g. towards accident hotspots. As this is only possible by observing everyday riders on their own (unequipped) motorcycles, a tool is needed that allows to observe e.g. the rider's trajectory, velocity, lean angle, etc. externally. While such a technology lacks of precision compared to onboard measurement equipment, it promises to observe the most natural behavior of riders on their own accustomed vehicles in their natural habitat. In comparison to the first method, it is easy to collect detailed information about road- and environmental conditions. On the contrary, only little to none information about the individual rider can be collected.

The third method excels in data quality levels regarding the environment and rider information as well as vehicle dynamics. On a closed track, single study participants can perform tests with a high-fidelity measurement motorcycle allowing for the largest amount and highest quality of data per rider/experiment. At the same time, it is the most "unnatural" environment for study participants and needs the highest invest regarding the measurement equipment, test-track and personnel. With proper design of the riding task it is even possible to generate a perception of criticality without risking real danger, as shown in chapter 4.

Table 1 shows empirical ratings of the different data acquisition methods.

Table 1: Rating of different data acquisition methods

Method	**Data Quality**			**Possible number of participants**	**Individual observation duration**	**Naturalistic behavior**	**Cost per observation**
	Vehicle	**Environ-ment**	**Rider**				
Widely spread lowcost measurements	Low	Low	Medium	Very High	Very Long	High	Low
Stationary measurements	Low	High	Very Low	High	Very Short	Very High	Medium
Closed track experiments	High	Very High	Very High	Very Low	Medium	Low	Very High

[4] Stanglmayr M. et al.: *Measuring Motorcycle Dynamics with Smartphones*

While Stanglmayr[4] describes in detail, how a low-cost measurement system can be set up, the following chapter of this paper presents the concept of a stationary measurement technique that might be used for testing on public roads in the future.

3 Stationary Measurement Technique

Investigations of specific accident hotspots and the measurement of trajectories, roll angles, etc. of passing riders in such hotspots has been the interest of several researchers in the recent years, e.g. Winkelbauer [5,6]. However, gathering continuous measurements of the rider or vehicle states has not yet been implemented successfully and therefore only discrete states were analyzed. (e.g. the roll angle estimated from a single picture, made in perpendicular projection of the motorcycle, or its lane position on such a picture.)

One goal of the project at hand was to develop a prototype measurement technology that allows automated, continuous measurements of at least velocity, roll angle and path of a motorcycle entering, passing and leaving a turn in typical rural corners.

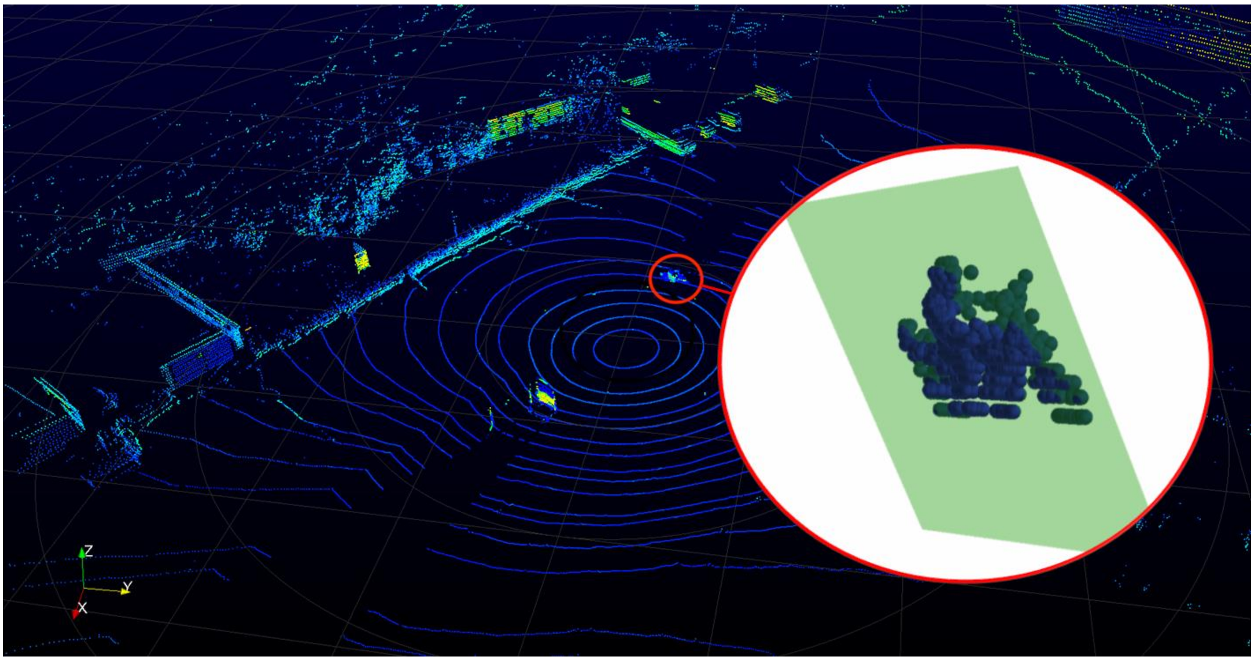

Figure 1: Exemplary point cloud resulting from a LIDAR measurement

A first approach to compare different stationary measurement systems is provided by the work of Häffner[7]. Herein different concepts like RADAR or LIDAR, as well as mono- and stereo camera systems are prototypically built up and tested for their suitability for the use in road traffic.

The advantage of the direct measurability of vehicle speeds with RADAR sensors is opposed to the problem of the bad assignability of single measuring points to the corresponding point on the vehicle. The use of LIDAR sensor technology, on the other hand, offers the great advantage of a data protection compliant measurement (Figure 1), but the error in determining the roll angle is large due to the lack of information about the plane of symmetry of the vehicle. Together with the high price of the sensors utilizing this measurement technology, the decision is made against using LIDAR for this purpose.

---

[5] Winkelbauer, M.: *Riding Left Hand Corners*

[6] Winkelbauer, M. et al.: *Lean Angles and Lane Positions of Motorcyclists*

[7] Häffner, N.: *Entwurf einer stationären Messtechnik zur Bewertung des Kurvenfahrverhaltens*

Due to the disadvantages mentioned above and the advantage of mono and stereo camera systems in terms of acquisition costs, as well as the possibility of carrying out detailed, automated evaluations of the image material using machine learning algorithms, this technology is used as the basis of the following development.

3.1 License Plate Tracking

As firstly implemented by Anton[8], the system used in this study utilizes mono-camera signals, preferably from an array of cameras lined up along the perimeter of a curve for measuring the roll angle. Therefore, a motorcycle's license plate is identified by modern image processing methods followed by an evaluation of its orientation.

The problem of estimating the position and orientation of an object from image information has existed for many years and is a core problem of machine vision. Basically, the three-dimensional position of an object in world coordinates must be determined from two-dimensional image information in pixel coordinates.

A special case of position estimation is the prediction of the relative position of a planar object. It is called "Plane-based Pose Estimation (PPE)", which is also used in camera calibration, where the position of a flat chessboard has to be estimated in relation to the camera. In calibration, it is used to estimate the extrinsic values of the camera.

One possibility to determine the position is to exploit point correspondences and is called the PnP problem. PnP stands for Perspective-n-Points, where n represents the number of points from which the orientation of the object is to be estimated. In the case of the license plate, four model points describing the plate are assigned to the four projected vertices in the image plane.

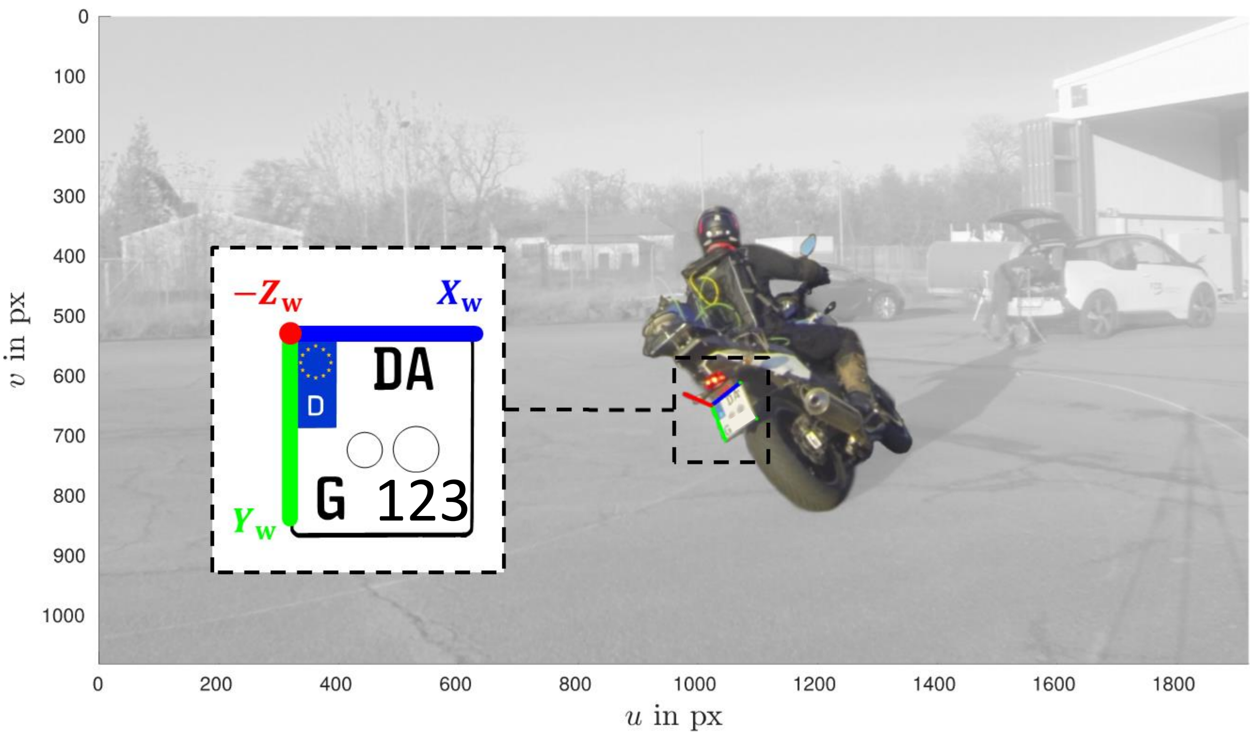

Figure 2: Recognized coordinate system of the license plate from the machine learning algorithm

[8] Anton,M.: *Untersuchung und Bewertung stationärer Messtechnikkonzepte*

The algorithm used is called Infinitesimal Plane-based Pose Estimation (IPPE), after Collins[9]. The underlying idea of IPPE is that some locations on the surface can be estimated more accurately than others. This point is sought and used to determine the position of the surface. Collins and Bartoli have found that the center point within the four model points is the most suitable for this purpose, as it is the point on which the influence of noisy point correspondences is the lowest.

The calculation is carried out using a first-order partial differential equation. The analytical approach makes IPPE particularly fast compared to other PnP methods based on numerical solution algorithms. Collins also shows that the IPPE algorithm provides better results than common PnP methods and is faster.

The IPPE algorithm is implemented in OpenCV. The result of the algorithm is three rotation and three translation values that describe the rotation and translation of the camera coordinate system into the world coordinate system. Figure 2 shows an example of the corresponding coordinate system as it is transferred to a license plate recognized in the image.

Figure 3 shows a comparison between the raw data acquired with the newly developed system with high fidelity IMU signals. It can be seen, that already the magnitude of the roll angle is determined quite well. High frequency deviations might be compensated in the future e.g. by adding appropriate filtering or by increasing the number of cameras along the perimeter.

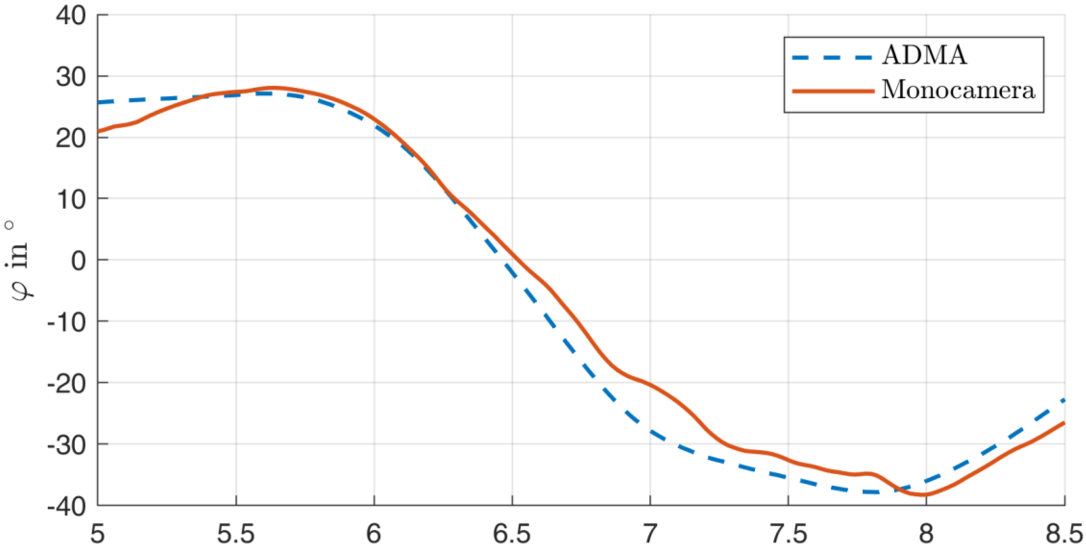

Figure 3: Comparison of a Mono-Camera roll angle estimation with ADMA measurements

During the presented study, the technology was only used in a closed, controlled environment. One reason for this is about legally being able to perform such automated measurements on public roads. Once, these issues are dealt with, we expect this technology to be able to generate highly relevant data for the investigation of critical events.

4 Pseudo-Critical Maneuvers

As discussed in chapter 1, experiments on a closed track might be able to help understanding a potentially existing roll angle threshold. Such testing with an equipped motorcycle in artificial scenarios bears the risk of not showing the naturalistic behavior of the study participants, as it is by all means not commonplace for them. They have to get used to both the environment and test vehicle and must follow specific paths and instructions. Also, they might tend to be overly cautious as they most certainly

[9] Collins, T.; Bartoli, A.: *Infinitesimal plane-based pose estimation*

expect something to happen at some point. Despite all of this, we don't see any alternative solution enabling us to expose motorcyclists to scenarios that they might experience as dangerous. As the reactions of a motorcyclist to an unexpected event may vary extremely (from braking to accelerating, from rush evasion maneuvers to no reaction at all) it is mandatory that each experiment is designed in a way that

- There is always enough evasion space available in every direction behind the event
- There are no hard obstacles around that might be hit by the rider or cause him to crash
- The risk of riding through any configuration of the experiment must not exceed the risk of riding on a typical road by means of visibility, friction, distraction, etc.

A full list of design parameters and demands for such an experiment design can be found in Walther[10]. All maneuvers performed in the study have been tested by professionals and each criticality was subjectively rated by them. As an objective criterion for criticality, the friction coefficient needed to perform each maneuver was evaluated, by measuring the motorcycle's acceleration in all three dimensions. If the subjective criticality was rated high while the friction demand did not exceed a critical value and if all abovementioned demands were fulfilled, the scenario was rated as "pseudo critical". The following maneuvers were performed in this study:

- Multiple rides through a U-turn with constant radius, with the radius changing after several runs, without informing the rider.
- Riding through a corner, after some passes, the corner's exit is rebuilt to steadily increase its curvature.
- Riding through a corner with obstructed view, after some passes, a soft obstacle is placed on the trajectory.

4.1 Results of the track test

The experiments have been performed by N=10 participants with different experience in terms of mileage and daily use. Firstly, no collective leaning threshold could be observed. During the U-turn maneuvers with no dictated speed (all participants were allowed to freely choose a velocity they saw fit for performing the turn), all participants except one showed a median of more than 30 degrees of roll angle both going left and right during the U-turn maneuvers. This part of the track tests was used to determine the personal comfort roll angle range.

As shown in Figure 4, some riders approach different roll angle maxima depending on the direction of the curve, whereas others ride through left and right-hand curves in a very similar way, such as rider number 2. A very large difference between the two curve directions is particularly noticeable for rider number 5. A possible explanation is a recent accident of this rider in a left-hand corner.

[10] Walther, L.: *Entwurf Pseudokritischer Testmanöver für den Motorradfahrversuch*

In addition, there are differences in the absolute, maximum roll angle per turn, as well as the variance of this feature, respectively the interquartile distance. The interquartile distance indicates how evenly the rider passes through the same curve each time. A large inter-quartile distance typically indicates a more inconsistent riding style, whereas a small bar indicates that a similar maximum roll angle is ridden again and again from the first pass to the last. This can often be found for more experienced riders, such as rider number 8, who is the participant in the study with the longest experience. In addition, there are clearly different comfort roll angles, as can be seen between riders 4 and 6.

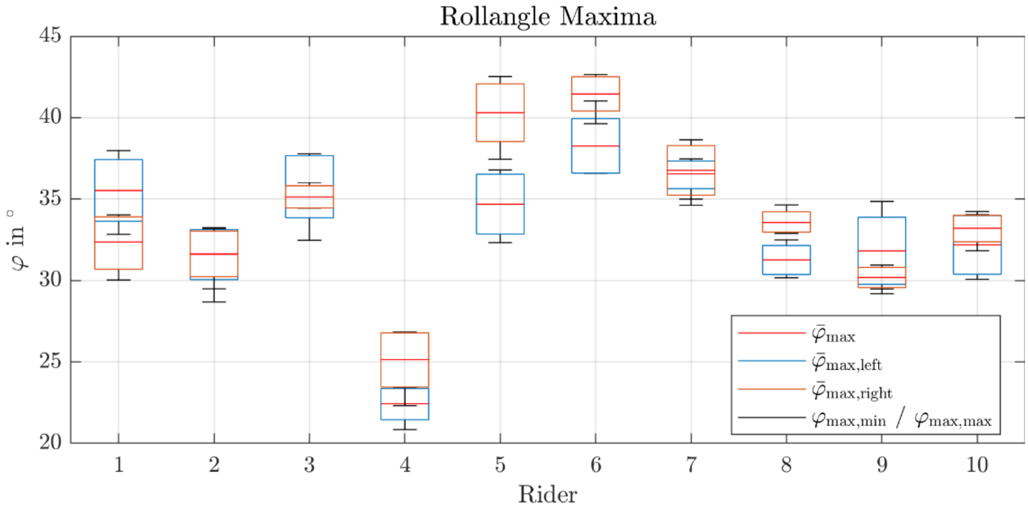

Figure 4: Roll angle distribution in closed track experiment

In order to investigate the existence of a lean angle threshold in potentially critical situations, the reactions of the riders during the pseudo-critical maneuver were compared with the data from the normal riding situations. The most frequent reaction is the reduction of the velocity, both by changing the throttle position and partly by brake interventions. It is interesting to note that all three female test subjects showed similar reactions and intervened more moderately than the male test subjects. For example, in none of the maneuvers a braking intervention was carried out by the female riders, in contrast to the male subjects. Here, however, the small sample size and thus lacking statistical relevance must be pointed out.

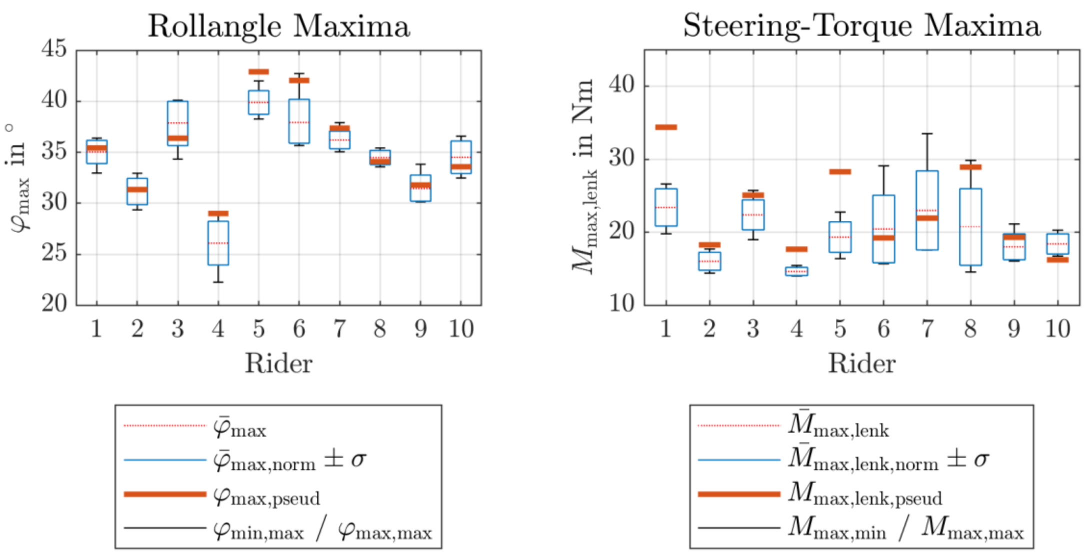

Figure 5: Maximum roll angle and steering torque during pseudocritical maneuver

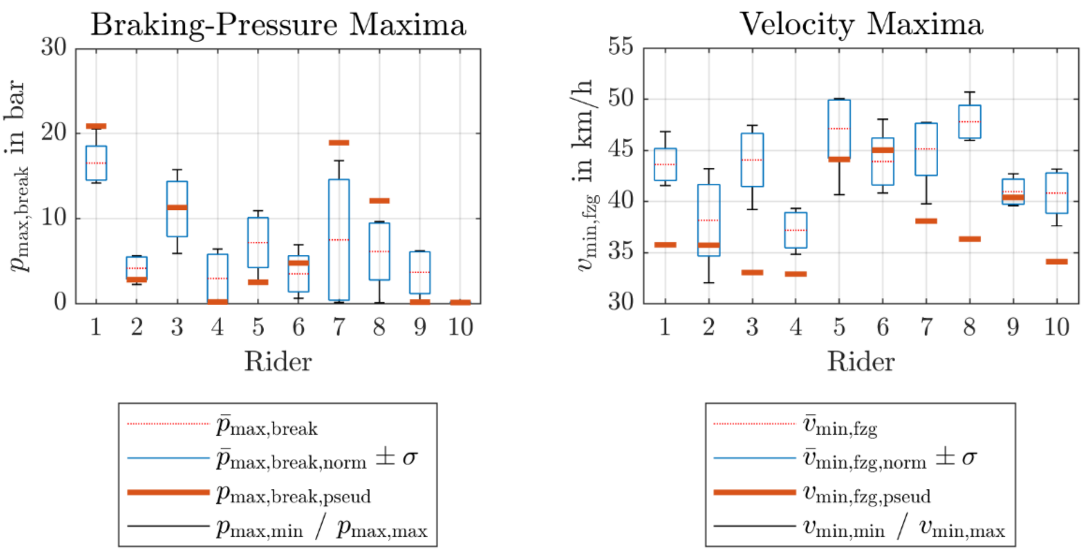

Figure 6:Maximum brake pressure and steering Torque during pseudocritical maneuver

The interventions of all riders are shown exemplarily in Figures 5 and 6, where the distribution of the maximum roll angle or braking pressure respectively are plotted in blue boxes during the cornering without an event and in orange during the pseudo-critical obstacle avoidance maneuver. It should be emphasized that during the entire curve including the pseudo-critical maneuver no less inclined roll angle maxima than during normal maneuvers can be observed. There is a clear difference in the maximum steering torque during the pseudocritical maneuver. Here, high deflections can be observed. Likewise, all the riders reduced speed significantly. This happened partly in parallel with a brake intervention, which also makes the change in the steering torque due to the brake steering torque to be compensated plausible.

The changed behavior also becomes visible when the roll angle distribution of the vehicles is plotted using a cumulative distribution function, like shown in Figure 7. Here a clear change to the otherwise very even distribution of the roll angle becomes visible. In addition, a kink in the distribution at a roll angle of 20 degrees is noticeable during the pseudo-critical maneuver.

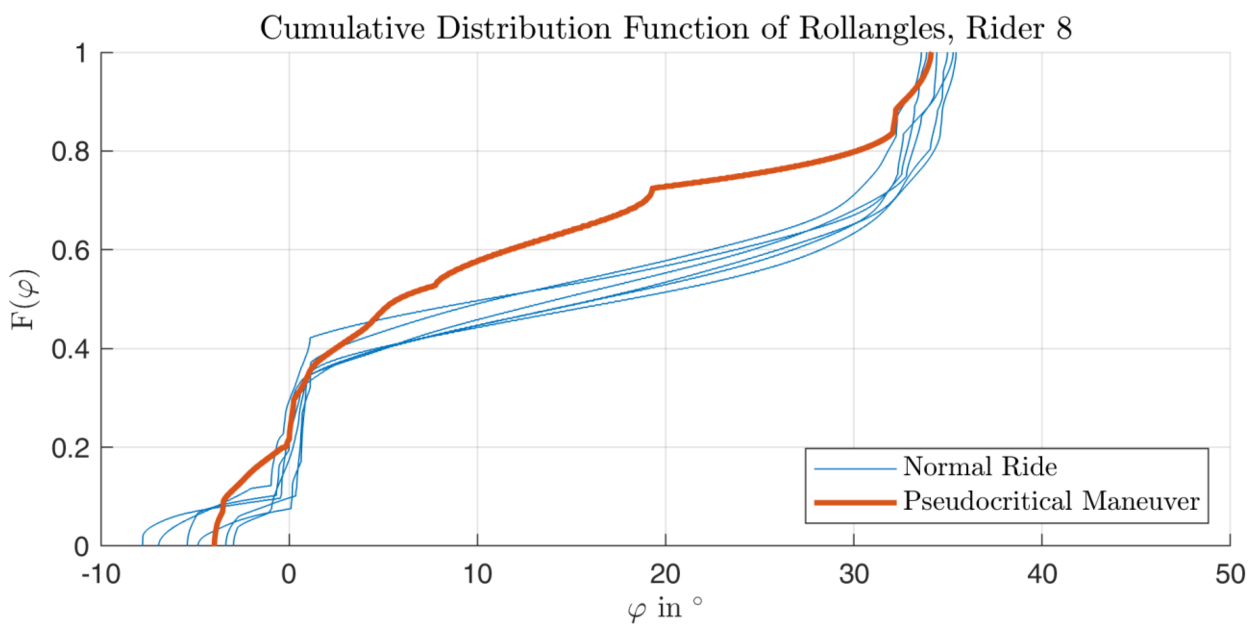

Figure 7: Empirical Cumulative Distribution Function of the Roll angles during cornering

This indicates that the rider remains in this position for a short time. This stopping point with subsequent correction during the roll angle build-up is possibly a useful characteristic value for the investigation of leaning thresholds. A similar behavior can be observed at 8 out of 10 riders.

To get a better understanding of the happening during such an event it is recommended to have a look at the phase diagram of roll angle and roll rates as shown in Figure 8. In comparison to the blue depicted courses of a roll-in and roll-out movement in the right-hand curve without pseudo-critical maneuver, the course of a suddenly appearing obstacle looks very different. The course of such a passage of the pseudo-critical maneuver is marked by arrows in Figure 8.

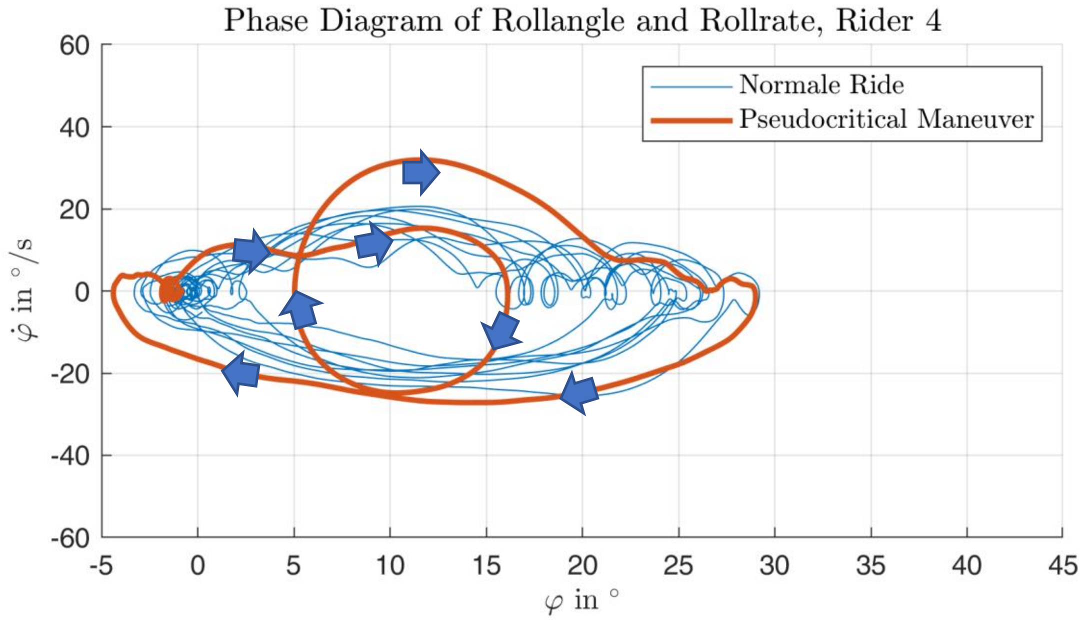

Figure 8: Obstacle & obstructed view

Especially the roll angle build-up to the personal comfort roll angle (positive roll angle in a right-hand bend) is carried out with major stops and restarts of the roll motion. This can be observed through points where the roll rate decreases strongly or approaches zero. 9 of 10 riders, showed a similar behavior. This allows a first interpretation of the existence of a kind of situation-dependent lean angle threshold. The reactions to a pseudo-critical maneuver are not directly related to the personal comfort zone or the way the rider handles in normal situations and again speaks for a situation-dependent threshold. An undershooting below the personal lean angle threshold directly after a pseudo-critical maneuver is not observed in any situation, but vice versa. Thus, the hypothesis of the existence of a situation-dependent lean angle threshold cannot be clearly proven by the investigations.

5 On-road testing

From the previous chapter, it can be seen, that the artificially designed scenarios and the limited number of study participants can only serve for few, descriptive results. Concerning the questions stated in chapter 1 and considering the small number of samples, we can only conclude the following:

- There seems to be no common roll angle threshold among the participants.
- Even during (pseudo-)critical events, each rider manages to reach his (individual) threshold value.
- The small sample number does not allow for correlations between the threshold values and other subjective / objective characteristic values.

Trying to find generalizable results necessitates a larger number of samples. Therefore, an on-road participant study was performed that is described in the following chapter.

5.1 Study design

The aim of the study is to evaluate the usability of low-cost measurement technology and to find evidence for the potential existence of a common roll angle threshold, i.e. analyze the roll angle distributions among a larger sample number during typical rural rides.

Courses

The two-part study was executed in parallel. In the first part, N=15 participants were riding on a specified course (led by satellite navigation) south of Dresden, using the abovementioned smartphone measurement technology on their private motorcycles. In the second part, N=23 participants were riding on a specified course north of Würzburg, using an equipped measurement motorcycle (KTM 790 Duke). Both routes were designed to show typical characteristics of an everyday motorcyclist's route, including curvy roads, inclination, better and worse asphalt quality, etc.

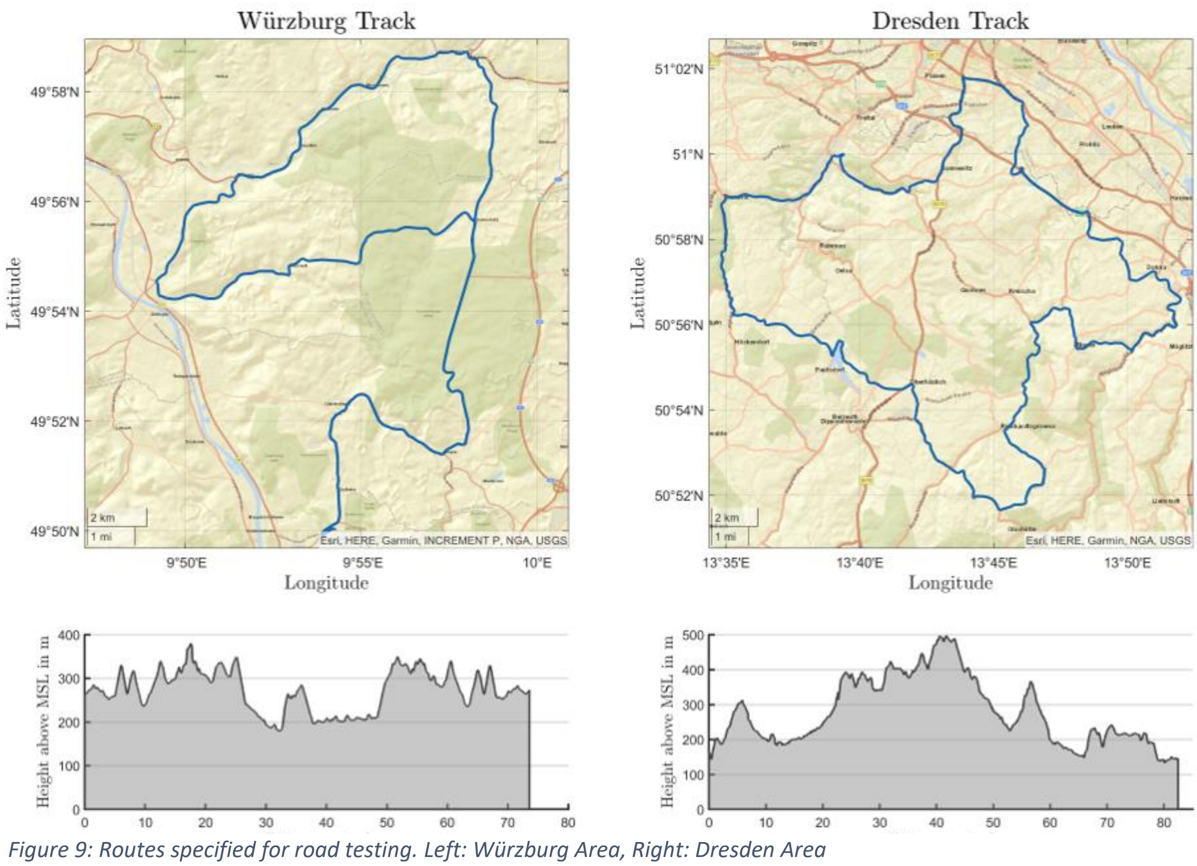

Figure 9: Routes specified for road testing. Left: Würzburg Area, Right: Dresden Area

A length of 83 km or 74 km respectively resulted in a duration of 80-100 minutes, depending on traffic and rider's speed. All participants were told – but not controlled – to stay within the public speed limits and to just ride "normal".

Rider Panel

In preparation to the road testing, all participants were asked to fill in a questionnaire.

Firstly, it included questions about personal details (gender, age, etc.) and their motorcycle use (year-mileage, type of bike, typical use, etc.).

Secondly, 24 items of the questionnaire were aiming to define a rider-type. These Items were rated on a 5 score scale (1-does not appy → 5-does fully apply) and exemplarily included:

- *"I try to ride my bike as economical as possible"*
- *"I brake late and deliberately into turns"*
- *"If possible, I use the opposing lane to ride more dynamically"*

Factorial testing of all given answers then allowed to cluster the items into three representative groups: *sportive, defensive* and *constant*. We assigned every participant into that group, where his mean rating was highest, as depicted in Figure 10:

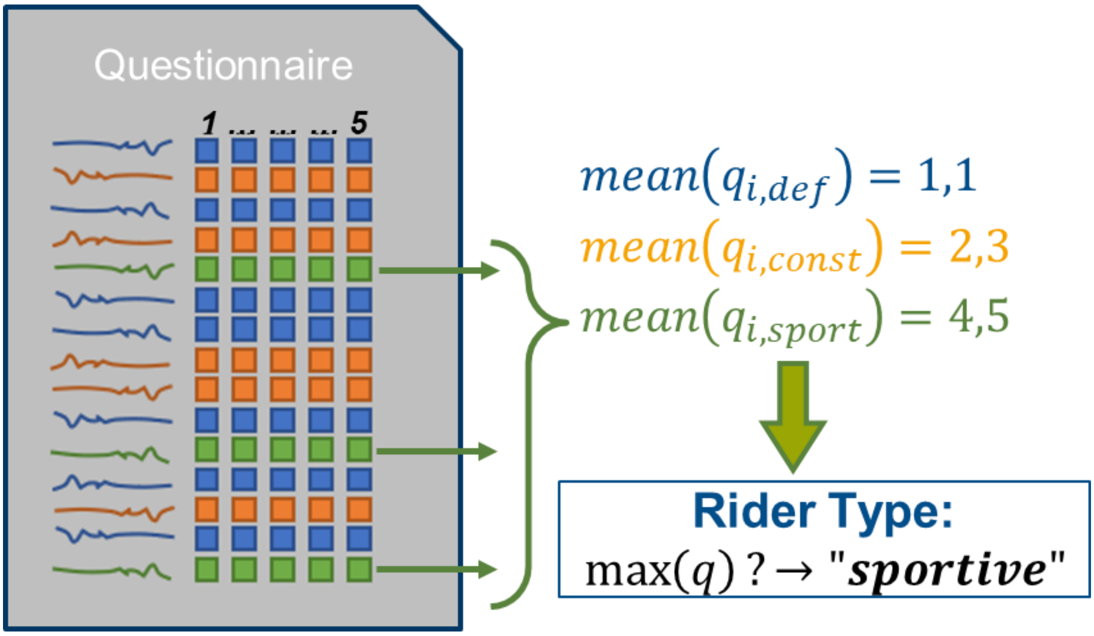

Figure 10: Assigning the rider type

Thirdly, the questionnaire included five items aiming to identify the cornering fear of the participants:

- "I have concerns to exceed a certain lean angle, even though my motorcycle would be capable of it"
- "I feel insecure as soon as I reach a certain lean angle"
- "I am afraid to lose control over my motorcycle while cornering"
- "I try to avoid riding with high lean angles"
- "I think, high lean angles are perilous"

All ratings of these five items were summed up, resulting in a combined "cornering-fear-indication" with values between 5 and 25 for each study participant.

5.2 Data evaluation

In total, more than 13.000 single corners were recorded, including timelines of GPS data and inertial measurements and – on the equipped motorcycle – additional timelines of multiple vehicle states (e.g. throttle, brake pressures, wheel speeds, etc.). In order to generate usable characteristic values for this number of cornering events, an automated data evaluation process is implemented. Firstly, the rider's trajectory is segmented, based on its curvature. As a simple method, we split the data at every sign change of the measured curvature and erase every interval, where the course angle change is less than 10 degrees.

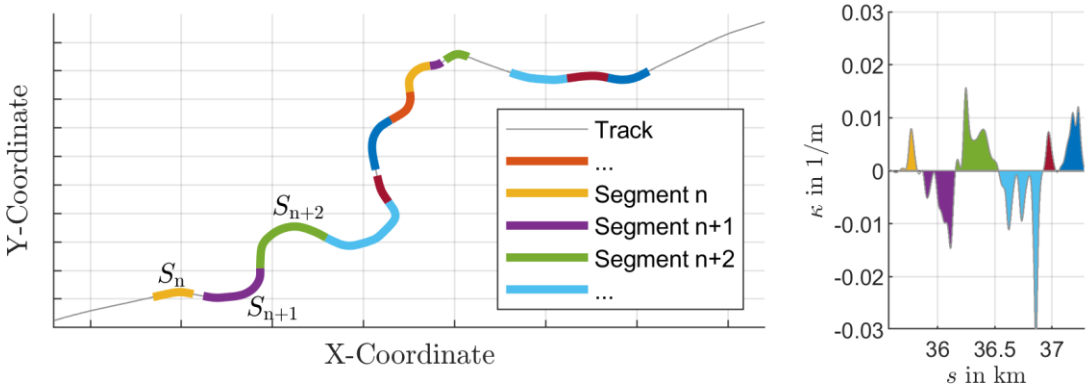

Figure 11: Track segmentation

While this method proves to be quite robust and simple to use, it is often not capable of discriminating between e.g. a single left turn or a multiple left turn, as can be seen in the bright blue segment in Figure 11. For each segment, a set of characteristic values is acquired that includes the maximum curvature, the maximum roll angle, the minimal velocity and other statistical values (means, deviations, etc.) also from further dynamic values (roll rates, longitudinal acceleration, etc.)

The next Figure shows the curvature distribution of the measured sample. It can be seen, that left and right corners occur at almost equal frequency. Furthermore, it shows, that the Dresden route contains a higher number of tighter turns compared to the Würzburg route.

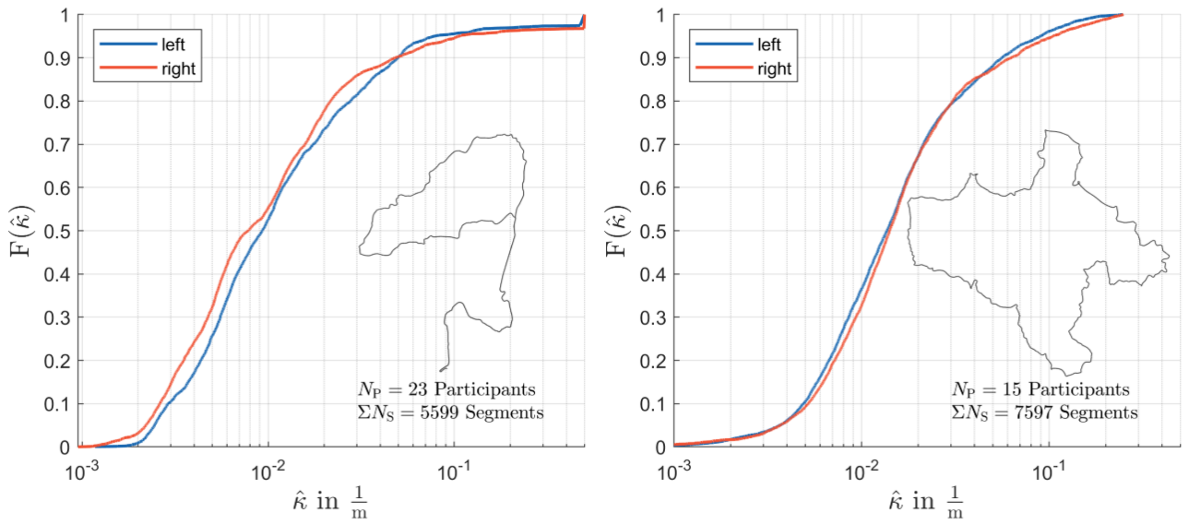

Figure 12: Frequency distribution of minimal curvatures per segment

5.3 Results

At first, we look at the frequency distribution of the maximum roll angles in left and right turns. Figure 13 shows the Würzburg and Dresden (dashed) samples of left (red) and right (blue) corners. The empirical cumulative distribution plot shows, which percentage of the total sample lies within a certain range of the characteristic value – here: the maximum of the absolute roll angle $|\hat{\varphi}|$.

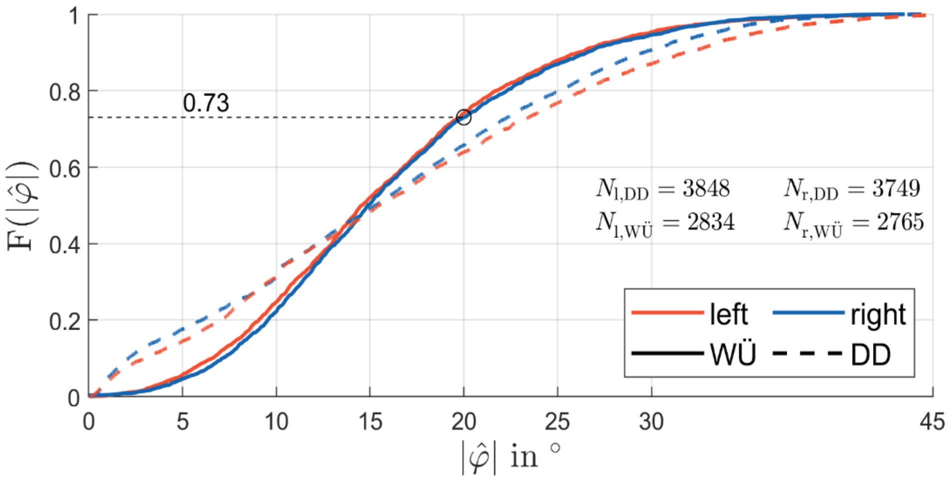

Figure 13: CDF-Plot of roll angle maximum

It can be seen that in 73% of the Würzburg sample and about 65% of the Dresden sample a roll angle of 20 degrees is not exceeded. This data includes all riders and all segments and therefore it is obvious, that also large amounts of lower roll angle maxima are observed. Nevertheless, it shows that at least one fourth to one third of the whole dataset exceeds the 20 degrees limit value that has been anticipated by Bernt Spiegel.

We continue the analysis with more individual data. As stated previously, the roll angle threshold – if existent – doesn't seem to be a common value for all riders but has individual differences. Figure 14 shows the distribution of the roll angle maxima of each study participant by means of a boxplot. The boxes are sorted by their median value. Additional information is given by coloration of the data.

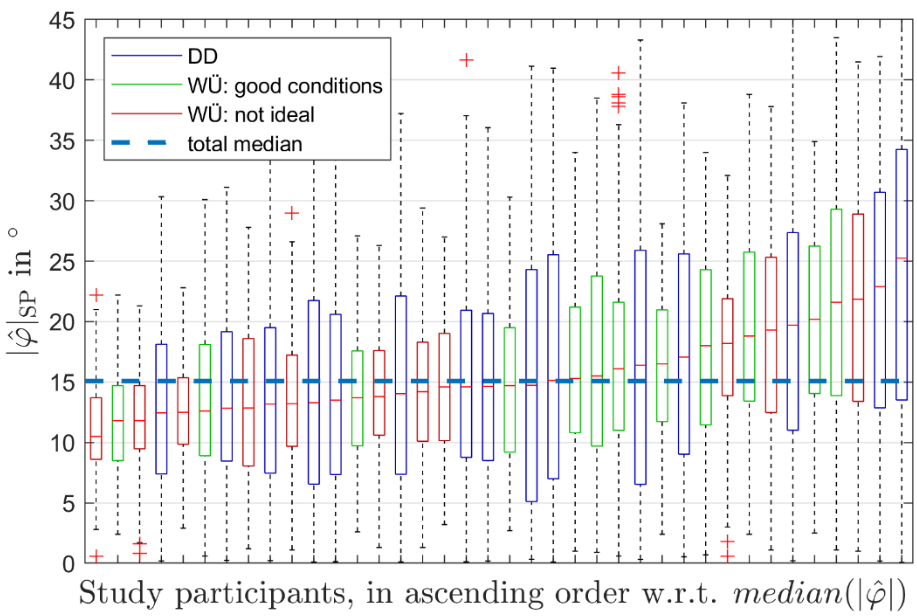

Figure 14: Roll angle distribution of each participant

Influence of environmental Conditions

The blue boxes of Figure 14 have been measured in the Dresden sample, all of them at perfect weather conditions. The red and green boxes result from the Würzburg sample, red indicating not ideal weather conditions. The data shows, that not ideal environmental conditions cause an accumulation of data at lower roll angles as expected. However, we also observe very low values without environmental conditions being an issue as well as very high values at bad environmental conditions.

If we compare the 95 percentile of the attained roll angles with the abovementioned cornering fear rating and discriminate between the environmental conditions, we find in Figure 15, that riders with low indications of cornering fear are able to retain more of their roll angle potential as conditions become worse, while such riders with high indications towards cornering fear lose much more of their roll angle potential.

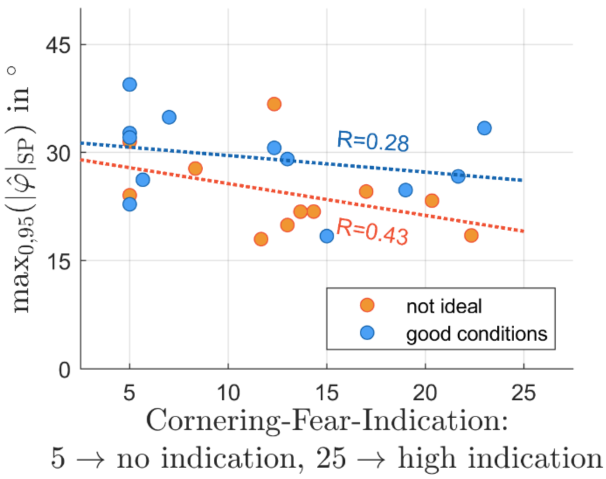

Figure 15: Decreasing roll angle potential under different environmental conditions

As this comparison is only possible with the Würzburg sample, the sample size for each condition becomes quite low and the linear regression may only be seen as a vague trend.

Comparison to cornering-fear-indication

To analyze the connection between the subjective cornering fear ratings of the questionnaire and the individually attained roll angles, we pick just those segments from our dataset that enable – or might even encourage – the study participants to ride at higher lean angles. Therefore, we filter the data for such segments, where the mean velocity was above 50 km/h and the course angle differed more than 90 degrees between entering and leaving the segment.

As this method decreases the sample size, we combine all samples with equal fear ratings (in steps of 5) into single boxes in Figure 16. Each sample point that is an element to a certain box is depicted in the same color. I.e. the box of the Dresden sample with a subjective Rating of about 15 contains all yellow scattered data points that have been collected from multiple study participants with fear ratings between 12.5 and 17.4. While this method results in different numbers of samples per box, it is well suited to show trends emerging from the data.

It can be seen, that in both participant groups the subjectively rated indications to cornering fear correlate well with the observed roll angles during on-road riding.

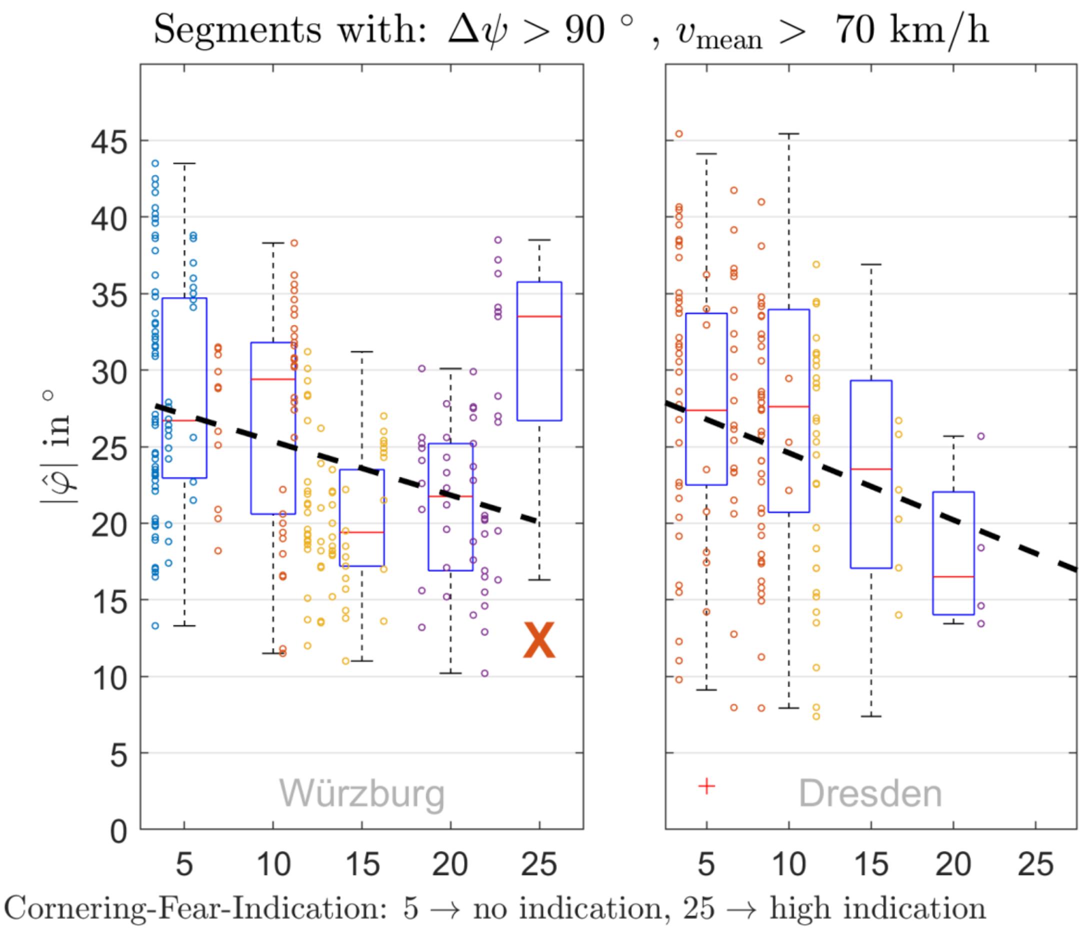

Figure 16: Roll angle maxima over subjective cornering fear ratings

Only one study participant of the Würzburg sample clearly stands out from this trend. With the highest cornering-fear-indication among all study participants, he is the sole member of the box marked with the red “x”, with no other participant contributing to the same box (i.e. having a subjective rating of more than 22,4).

While he is – according to his answers of the questionnaire – the most fearsome study participant, he is counter-intuitively also attaining very high roll angle values. Assuming that he is not purposely giving false answers, this might have two reasons. Either he underestimates his roll angles and attains these high values anyway – despite his concerns to exceed certain lean angles, him being insecure at high lean angles, his fear of losing control while cornering, his avoidance of high lean angles and perceiving high lean angles as perilous. Or he may be aware of his high roll angles but attains them anyway for reasons of thrill and excitement. A last hypothesis might be that he was falsely answering the questionnaire in order to be judged as an especially cautious and calm rider.

To further investigate the connection between the cornering-fear-indication and measured vehicle dynamics, multiple characteristic values have been equally assessed. All typical values like roll rates, velocities, etc. show equal behavior and correlation to the cornering-fear-indication values. Also, we find correlation in our data linking higher age to lower roll angles and higher yearly mileage to higher roll angles.

Steady-State-Deviation

The analysis of roll angle maxima, or similar values for roll rates, velocities, etc. cannot further explain the strange behavior observed with rider "x". Assumed, that he really suffers from great cornering fear, we develop the hypothesis, that this fear might not manifest in the absence of high roll angles but that the roll angles – while eventually reaching high values – are approached rather timidly and cautiously. To further investigate this hypothesis, we compare, how each rider approaches a specific turn. As a baseline, we use the timeline of a theoretic, steady state roll angle that can be calculated from the given curvature κ and velocity v following the equation

$$\varphi_{th} = \arctan\left(\frac{\kappa v^2}{g}\right)$$

This is the roll angle, that a motorcycle would need to build up if the speed and curvature would stay constant. For changing speed and curvature, this amount of roll angle ensures equilibrium between vertical and lateral accelerations at any point in time while neglecting dynamic state transitions. φ_{th} can therefore be seen as the smoothest possible way to ride over a defined trajectory with a defined velocity. It can be calculated for each segment of the dataset. As a single characteristic value, we define the root-mean-square (RMS) of the difference between the actual roll angle and the steady state estimation of the roll angle. This method is depicted in the middle plot of Figure 17.

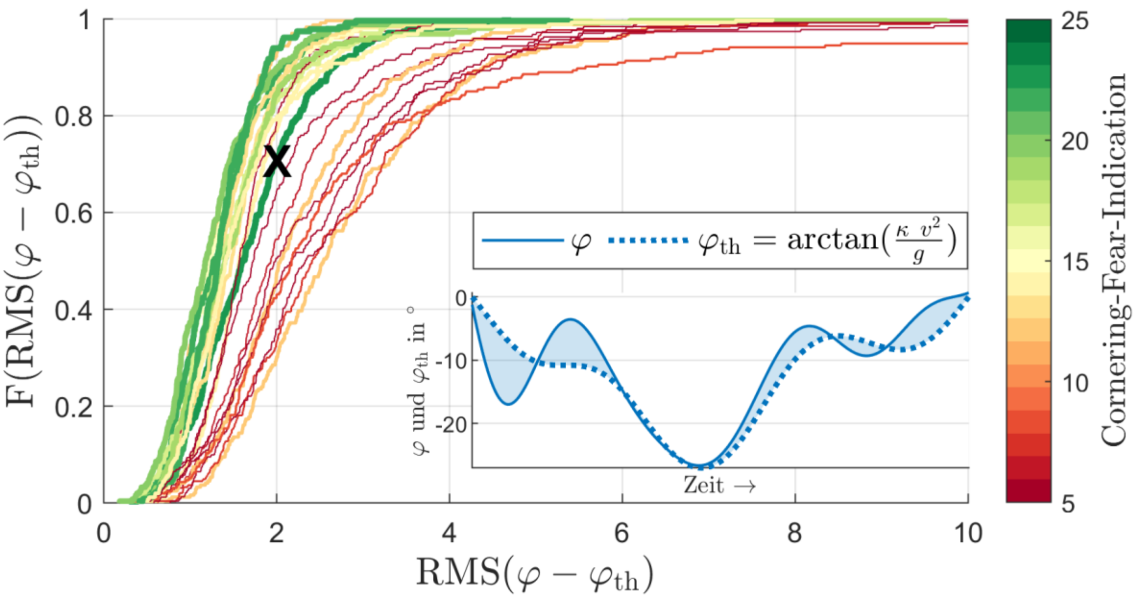

Figure 17: CDF Plot of the RMS of the Steady-State-Deviation

Low RMS values stand for a smooth rolling dynamic. The actual roll angle then tends to match the steady state assumption very well. High RMS values stand for rather dynamic rides. E.g. a rider might utilize body motion a lot or riding a rather edged trajectory.

From the dataset we find one RMS value per every segment. The CDF-plot in Figure 17 shows one line per rider with the color and thickness of the lines discriminating between each's subjective cornering fear rating. Thin, red lines are those riders with small ratings, while thick, green lines point towards higher fear ratings.

Evidently, the steady-state-deviation allows to build two clusters. One cluster with the participants that are less subject to cornering fear and generate higher steady-state-deviations and one cluster with those participants whose subjective ratings indicate towards high amounts of cornering fear.

Again, rider "x" (thick, darkest green line in the middle of the set of curves) plays a special role, as he basically separates the two clusters of either red or green lines from another. It shows, that he really is riding rather smoothly compared to the other riders that are achieving high roll angles and are less subject to cornering fear. It might be worth noting, that following the rider type definition in section 5.1 he is assigned to the small group of "constant" riders.

Summary

The on-road participant study generated huge amounts of data. For now, a simple segmentation method was applied and typical characteristic values were analyzed. They were able to show individual differences in how much roll angle is attained in everyday riding. The newly developed steady-state-deviation value also showed, that not only the individually observed maximum roll angles are of interest, but the way how this maximum is attained.

6 Conclusion and Outlook

The study at hand shows the high potential of the analysis of large naturalistic datasets for the investigation of riders' cornering behavior. The use of modern smartphone technology can produce convincing results even compared to those acquired with an instrumented measurement motorcycle, but is accessible to a much broader range of riders. A promising addition to vehicle bound measurements are stationary measurements. These might in the future allow to gather continuous data at accident hotspots or any other location to understand the cornering behavior of motorcyclists during critical events even if no direct measurements of the motorcycle dynamics are available.

While the data collected in this study doesn't show evidence for the existence of a common roll angle threshold, it does however find individual limits that correlate well to personal subjective ratings on items relating to cornering fear. This might e.g. allow to identify riders with a higher risk of becoming a casualty due to under-exploitation of roll angle potential. Also, it was shown, that the maximally achieved roll angle alone does not allow for a characterization of the rider. Therefore, future research should not further concentrate on the existence of a collective threshold value but rather on the robustness of and confidence in the individually attained roll angles. It doesn't help if a – trained or untrained – rider is capable of riding with 45 degrees of roll angle, as long as he does it without confidence in his capabilities and is capable to robustly maintain such values even in possibly critical events.

Disclaimer

Diesem Beitrag liegt das im Auftrag des Bundesministeriums für Verkehr und digitale Infrastruktur, vertreten durch die Bundesanstalt für Straßenwesen, unter FE 82.0710/2018 laufende Forschungsprojekt zugrunde.

Die Verantwortung für den Inhalt liegt allein beim Autor.

This report is based on the research project carried out at the request of the Federal Ministry of Transport and Digital Infrastructure, represented by the Federal Highway Research Institute, under research project No. 82.0710/2018.

The author is solely responsible for the content.

Bibliography

Anton, M.: *Untersuchung und Bewertung stationärer Messtechnikkonzepte hinsichtlich der erreichbaren Datenqualität zur Messung des Kurvenverhaltens von Motorradfahrern in Gefahrensituationen*, Masterthesis, TU Darmstadt (2020)

Bauer, K.; Peldschus, S.; Schick, S.: *Retrospective analysis of fatal motorcycle accidents and derivation of protective measures in complex braking maneuvers*, Proceedings of the 10th International Motorcycle Conference 2014, Institute for Motorcycle Safety e. V. (2014)

Collins, T.; Bartoli, A.: *Infinitesimal plane-based pose estimation*, International journal of computer vision, Vol. 109, S. 252–286 (2014)

Häffner, N.: *Entwurf einer stationären Messtechnik zur Bewertung des Kurvenfahrverhaltens von Motorradfahrern im Realverkehr*, Masterthesis, TU Darmstadt (2019)

Magiera, N.; Winner, H.; Janssen, H.; Heckmann, M.: *An Approach for Automatic Riding Skill Identification – Overview about the Methodology and first Results*, Proceedings of the 11th International Motorcycle Conference 2016, Institute for Motorcycle Safety e. V. (2016)

Spiegel, B.: *The Upper Half of the Motorcycle: On the Unity of Rider and Machine*, Motorbooks (2019)

Stanglmayr, M.; Bäumler, M.; Büttner, K.; Prokop, G.: Towards Safer Rides: Measuring Motorcycle Dynamics with Smartphones Proceedings of the 13th International Motorcycle Conference 2020, Institute for Motorcycle Safety e. V. (2020)

Walther, L.: *Entwurf Pseudokritischer Testmanöver für den Motorradfahrversuch*, Masterthesis, TU Darmstadt (2019)

Winkelbauer, M.: *Riding Left Hand Corners: Facts and Measures*, Proceedings of the 10th International Motorcycle Conference 2014, Institute for Motorcycle Safety e. V. (2014)

Winkelbauer, M.; Krack P.; Lamp, D.: *Lean Angles and Lane Positions of Motorcyclists*, Proceedings of the 12th International Motorcycle Conference 2018, Institute for Motorcycle Safety e. V. (2018)