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EXPERIMENTAL STUDY ON LANE CHANGE MANEUVERS WITH A MOTORCYCLE

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ABSTRACT

In this study, an innovative concept to measure the dynamic parameters of lane change maneuvers with motorcycles is presented and measurement results and conclusions are discussed An instrumented motorcycle is used for the experiments. Two independent measurement systems provide redundant data for obtaining precise readings of the vehicle position and the speed, for 3-axis accelerations and angular speeds, and more. Among these signals, the roll angle and the roll rate are especially important signals in this context.

Measurements were carried out on public roads in a city and on highways, to allow for a broad range of speeds. The time series of the numerous tests were examined and analyzed with respect to the aforementioned signals and their correlation. Because of a regression analysis, analytical expressions could be derived for the lane change duration depending on the offset, for the maximum roll rate depending on the manoeuver intensity and finally for the roll rate and the roll angle as a function of time.

Keywords: accident avoidance, evasion maneuver, lane change.

1. INTRODUCTION

Braking hard or executing an evasion maneuver, this are the two main options a motorcycle rider has, if he is in a dangerous traffic situation with other vehicles and needs to avoid an accident. Therefore, if the second option is chosen, an evasion maneuver must be mastered by a rider of a PTW (Powered Two-Wheeler). The limits of such highly dynamic maneuvers are mostly set by the driver's capabilities and have been addressed in several studies in the past, see the (incomplete) list of references.

Watanabe et al. in [1] were one of the first to investigate experimentally evasion maneuvers to avoid obstacle collisions, but did not include the aligning after the manoeuver. Early experimental studies of a full lane change are reported in [2] and [3]. Kuschefski [4] carried out a more recent and very comprehensive study, taking up the question already posed in [1], whether braking or swerving is more effective in accident avoidance.

Since then, new questions did arise and new measurement equipment became available. As for the new challenges, there is an increasing demand for rider models to be used in simulation environments, since the traffic system will change significantly in the future. With the advent of autonomously driving passenger cars, important questions concerning heterogeneous traffic systems have to be answered. For the control system of an autonomously steered vehicle, the behavior of a non-autonomously conducted vehicle like a motorcycle must be predictable. Therefore, validated PTW-rider models are needed in order to bring forward the modelling of the entire motorcycle-rider-system, see [5], [6], and [7].

Another reason for new studies on lane change manoeuvers is the minimal reduction (if at all) of motorcycle accidents in Austria and other countries during the last years, compared to the success gained for other vehicles. To develop effective measures to reduce the death toll on motorcycle riders, all aspects of motorcycle riding must be thoroughly investigated and understood. Especially when a vehicle accident with a motorcycle involved has to be analyzed, it is of utmost importance to have realistic data at hand concerning the abilities of an average motorcycle rider.

Last but not least, in the last years data loggers, sensors, GPS-receivers, on-board cameras have become smaller, cheaper,

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more precise and more robust. This makes it possible to equip a motorcycle with a measurement system of excellent quality. Consequently, measurements can be taken during "natural riding" in public traffic, which makes the need for special test tracks (partly) obsolete. This and the aforementioned reasons motivated the authors of this study to carry out a new series of lane change experiments, which makes use of newest measurement technology and which is based on tests on public roads and not on closed test tracks.

2. MEASUREMENT EQUIPMENT

The motorcycle available for this study was a KTM 1290 Super Adventure. This model is equipped with numerous on-board sensors, which are needed and used by the six rider assistance systems. To mention the most relevant control systems for this study: Combined-ABS (C_ABS), Traction Control (MTC), Stability Control (MSC), and Cruise Control (MCC). The on-board sensors needed for these functions comprise wheel speed sensors, a 5-axis inertia measurement unit (IMU), throttle position sensor, and more. All sensors communicate via a CAN-bus. Despite the extensive on-board measurement system installed on the standard model, additional instrumentation was added. Most important, position measurement was made possible by GPS-antennas and receivers, on-board cameras were mounted, and a steering angle sensor was attached to the front wheel system. Additional full 6-axis-IMUs were added for quality reasons and redundancy. A CAN-bus interface allowed the access to the vehicle sensors and two independent and powerful data loggers were used to record the many signals, see Figs. 1 and 2. Finally yet importantly, two trigger switches were installed on the handlebar, to precisely detect the onset of a steering action by the rider. In a future step of upgrading the measurement system, a steering moment sensor on the steering axis will give even better and more versatile signals about rider's force application to the handles

Figure 1: Motorcycle used in the experiments, annotated with additional measurment equipment.

In addition to the sensor systems, a double-camera on-board video system was installed on the left and on the right roll bar. The cameras point to the road ahead and show also the front wheel, see Fig 3. This feature was very important for the judgment of the achieved lane change offset, since a precise measurement of the lateral position was not possible. The GPS-signals did give rather good results, but could not reach the quality of position signals when using D-GPS. This feature needs a stationary antenna, which could not be used since the range of these signals is rather limited. However, the problem of measuring the lane change offset was overcome by the restriction to only two different offset distances, and will be explained in the next section.

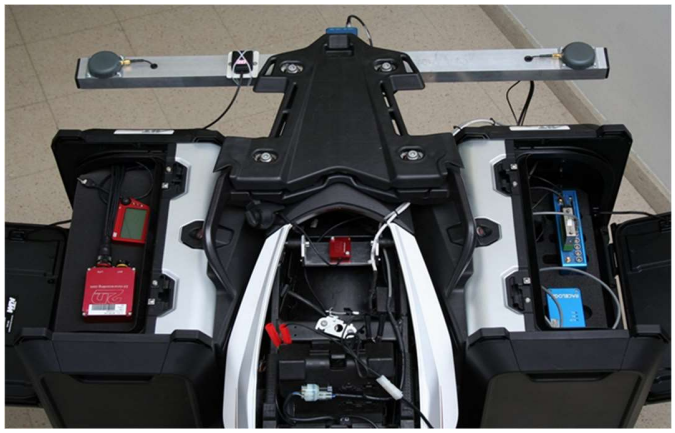
Figure 2: Rear end of the test-vehicle. Red /left- measurement system #1 (Debus&Diebold). Blue/right- measurment system #2 (Racelogic). Aluminum-bar at the very end carries the GPS-antennas for both systems.

Figure 3: Combined video of left and right on-board camera to judge on crossing a traffic line or a highway striping.

3. TEST DESIGN

One goal of this study was to gather lane change maneuver data at a broad range of speeds. For a speed range up to 50km/h a suitable private test track would have been available, but not for speeds of 100km/h or more. Therefore, all experiments were carried out in regular traffic! For low speed testing, days with weak traffic were chosen and road sections in the outskirts of Vienna were selected, see Figs. 3 and 4. The high speed testing was performed on a highway with a speed limit of 130km/h, see the aerial view of a section of this highway in Fig. 6.

Figure 5: Inner-city test on an easy to follow street with road surface markings (barrier line and lane separator line) that were used for lane change manoeuvers.

Figure 5: Street in the suburbs of Vienna as used in the lane change tests.

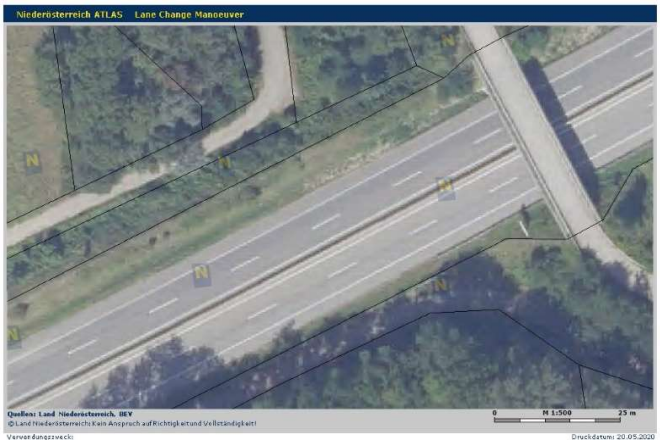

Figure 6: Aerial view of a high-speed highway with road surface markings (barrier line and lane separator line) as used in the tests.

Although the speed limit was higher, so far the maximum test speed was a little less than 120 km/h. Testing on a high speed highway was somewhat difficult, because other traffic must not be disturbed and the rider had to wait for situations with no other vehicles approaching the motorcycle from behind.

Another major problem with such lane change tests is the measurement of the lane change offset. This problem was circumvented by using the regular lane markings on the road surface, which were 3,5 m apart from each other. Test riders had to ride precisely on a marked lane and then change to the next lane to the left or to the right. Since the distance between the lanes was known from measurements, this procedure provided a precise road setup. Also half lane changes were performed. In that case the rider had to change from the invisible center line of a lane to the next marked line, which was not a problem for an experienced rider.

In the course of this study only two different riders were involved. They will be indicated later on by the shortcuts HE and SL. Rider HE was a 60 year old experienced motorcycle rider. His attitude in the test rides was that of a very cautious rider, who would ride with a large safety margin. Rider SL was a young fellow with significant riding experience, especially also in racing. His attitude was more of a sporty rider, who accepts a higher risk level and enjoys speedy riding. Of course, also this rider did not even come close to his personal limits and riding abilities.

4. MEASUREMENTS

All in all a number of 167 lane change maneuvers were performed and recorded. The number of inner-city tests at low speeds (< 60 km/h) was 110, the other 57 tests were executed on highways at higher speeds. The number of full lane changes was 120 and that of half width lane changes was 43. A few were neither half nor full and therefore excluded from the study.

Figure 7 shows a frequency distribution of the speeds driven at the maneuvers. Most maneuvers were performed between 45 and 55 km/h. The maximum speed was 118km/h, the minimum speed 26km/h, with an average of 67 km/h. Several frequency maxima can easily be identified and correlate with the different test locations. Due to the speed limit within the city limits of 50km/h there is a frequency maximum at/near this speed. Outside of the city border test could be performed at higher speeds, leading to another peak at 80km/h.

On the highway, predominantly 100km/h was used as the test speed and a few at 120 km/h. Especially during the high-speed tests it turned out that the cruise control feature of the motorcycle was very useful. The rider could set the test speed and had no longer to concentrate on the throttle but could observe the traffic behind and could pay attention to the execution of the lane change manoeuver. Therefore, it was possible to sample quite many tests at the same speed.

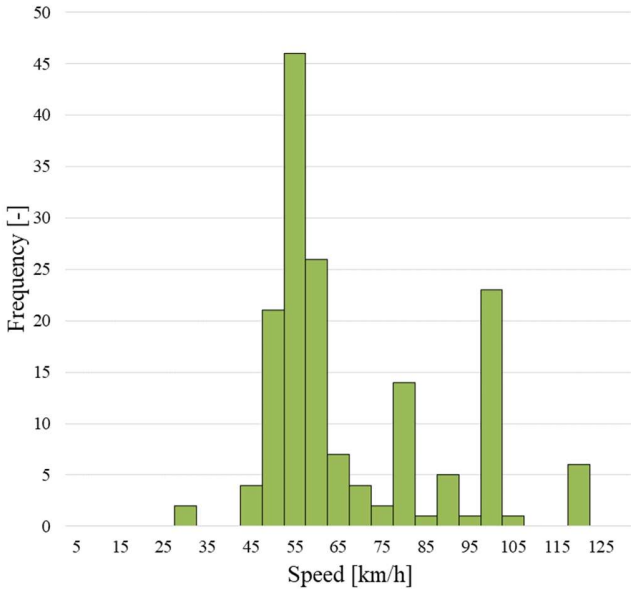

Figure 7: Histogram of vehicle speed during lane change maneouvers

The following Figures 8-11 show typical time series of the roll angle and the roll rate, to give an impression of the shape of these raw data functions. Examples are given for manoeuvers at low-speed and high-speed riding, and also for a "slowly" and a "quickly" executed lane change. The driving speed is a measured parameter and therefore easy to quantify. Whether a manoeuver is executed "slow/lazy" or "fast/aggressive/ambitious" is not directly measurable. The reason for this statement can be seen in the following figures. While the onset of a lane change manoeuver can be identified more or less explicit from the roll signals and the trigger switch, the end of it is by far less clear. The reason for this observation is the attempt of the rider to align the motorcycle with the reference line after the lane change. This involves an oscillatory approach to the final position on the reference line. It is clear that a rider cannot perform this steering control process for every lane change in a perfect manner, especially in public (realistic) traffic. Therefore, the duration of such a lane change, as the most self-evident parameter to decide on "slow or fast", is not really useful. Moreover, an unknown correlation with the riding speed had also to be considered. This led to the creation of a new parameter termed "intensity of the lane change manoeuver", which describes the *ambition* or the *aggressivity* (to use related nouns) when performing the manoeuver. In the next Chapter 5 a definition will be given for this newly introduced parameter.

Figure 8 shows time series of roll rate and roll angle of a lane change manoeuver with high intensity. The maximum roll angle reaches 26,5 deg and the roll rate is 76 deg/s. The duration of the lane change is approximately 3 sec. The shape of both functions is characteristic for a lane change manoeuver as executed in this test series. Initially, roll angle and roll rate increase rapidly. Of course the angle follows the rate with a time lag. When the initial turn is passed, both signals become negative and reach a second peak due to the necessary counter steering. The following final section of the signals often show an oscillatory behavior. In this example this phenomenon is less pronounced, the rider reaches rather quickly the final state of the manoeuver and continues riding straight and upright.

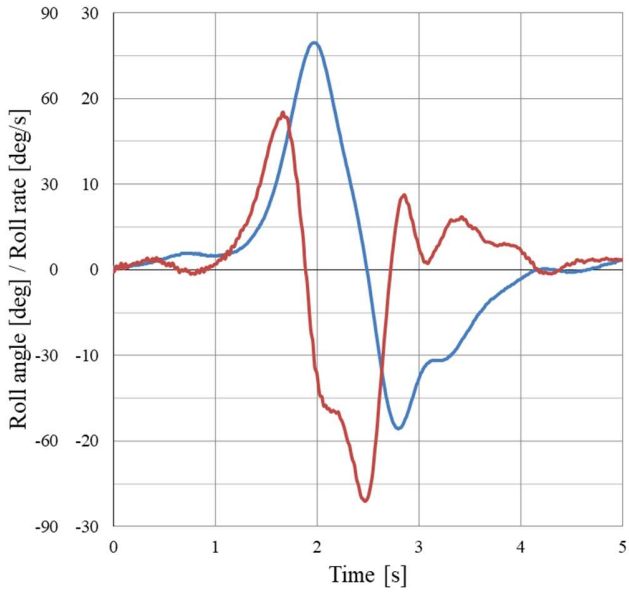

Figure 8: Time series of roll angle (blue) and roll rate (red) of a high intensity lane change manoeuver at 79km/h (49mph)

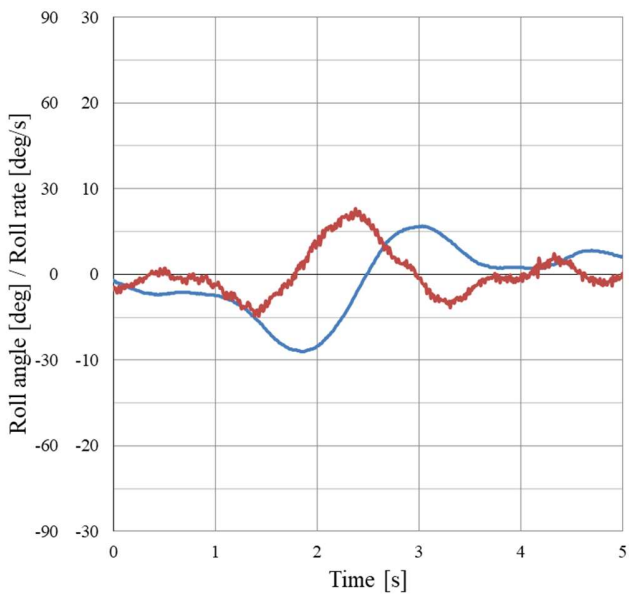

Figure 9: Time series of roll angle (blue) and roll rate (red) of low intensity lane change manoeuver at 58 km/h (36mph)

In contrast, Figure 9 shows a low intensity lane change. The maximum roll angle is less than 10 deg, the maximum roll rate reached is below 30 deg/s. However, the duration of this lane

change is somewhat but not significantly longer than the one before. This example shows quite good that end and sometimes also the beginning of a manoeuver is not clearly defined. It is also worth to note that in both examples, the first peak of roll angle, but the second peak of the roll rate is the highest.

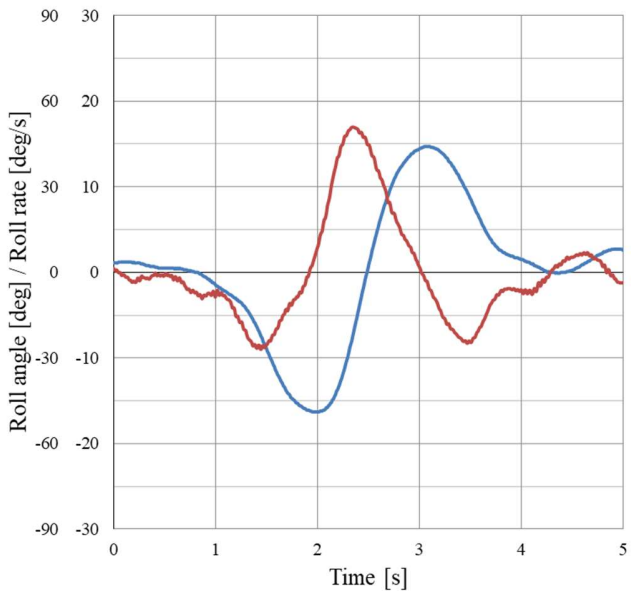

Figure 10: Time series of roll angle (blue) and roll rate (red) of high speed lane change manoeuver at 97 km/h (60mph)

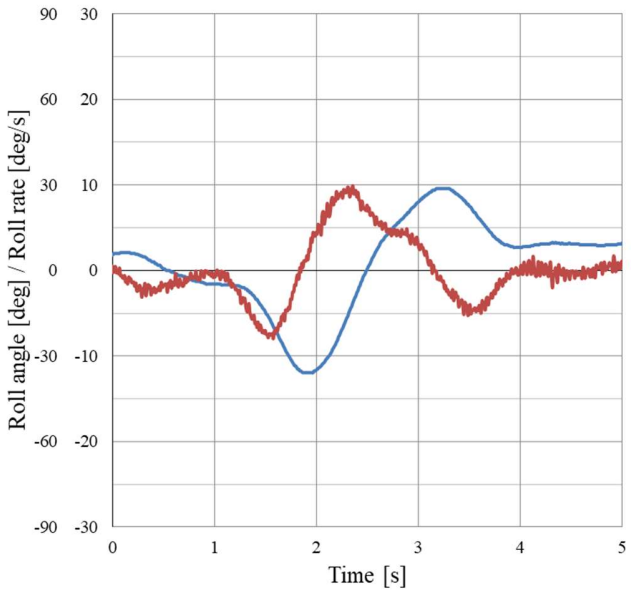

Figure 11: Time series of roll angle (blue) and roll rate (red) of a low speed lane change manoeuver at 52 km/h (32 mph)

For comparison, the Figs. 10 and 11 show a high speed (97km/h) and a low speed (52km/h) lane change maneuver, respectively. The lane change signals in Fig. 10 have reversed signs, since the manoeuver was executed in the opposite direction. Although there is quite some similarity with Fig. 8, the sharpness of the peaks is less pronounced and suggests a manoeuver of less intensity. The manoeuver shown in Fig.11 was executed at almost half of the speed but by the same rider and the same attitude as the previous test. Nevertheless, the peak values are lower compared to Fig.10, but higher in comparison to Fig.9. The most interesting outcome of the test at the two largely different speeds is the duration of the manoeuver. One can easily see that both tests at 97km/h and at 52km/h take nearly the same time, namely approximately 3 sec. For completeness, it must be mentioned that all four tests were full lane change tests with a lane width of 3.5 Meters.

5. DATA ANALYSIS

As already mentioned in Chapter 2, the test vehicle was equipped with a large number of sensors, and most of the dynamic measurement variables were even recorded multiply. The redundant signals were used primarily to cross-check signals and improve the quality of signals further processed.

For the data analysis of the lane change maneuvers six consolidated dynamic states of the main frame were available: 3-axis longitudinal accelerations and 3-axis rotational speeds, plus the integrated variables longitudinal speeds and rotational angles. In addition to that signals, GPS-coordinates, steering angle and wheel speeds could be analyzed. In a first step of the data analysis, all relevant signals were screened to look for the most significant ones. Not surprisingly, it turned out that the lane change manoeuver is almost fully captured by the signal about the roll axis, i.e. roll angle and angular roll velocity. Other signals like the lateral acceleration or velocity can be used as supplement. Since the lateral offset of the manoeuvers was set by the test design, there was no need to calculate the lateral position in this study. Further work will also include the lateral travel to be calculated and analyzed from the measured signals.

The data analysis was primarily based on the time series of the roll angle and the roll rate. Each data record of a test was scanned for characteristic features. The most significant events were the zero crossing of the roll angle and the maxima of the roll rate. A time shift was executed on the unscaled (raw) time series such that the first zero crossing of the roll angle (in the course of the manoeuver) was set to time zero. All other signals were also synchronized accordingly.

This procedure was applied to all valid time series. Then time series could be plotted over each other. See Fig.12 for the synchronized roll angle of all measurements. In this diagram, one can see that all plots have a similar shape and that the duration of the maneuvers does not differ much.

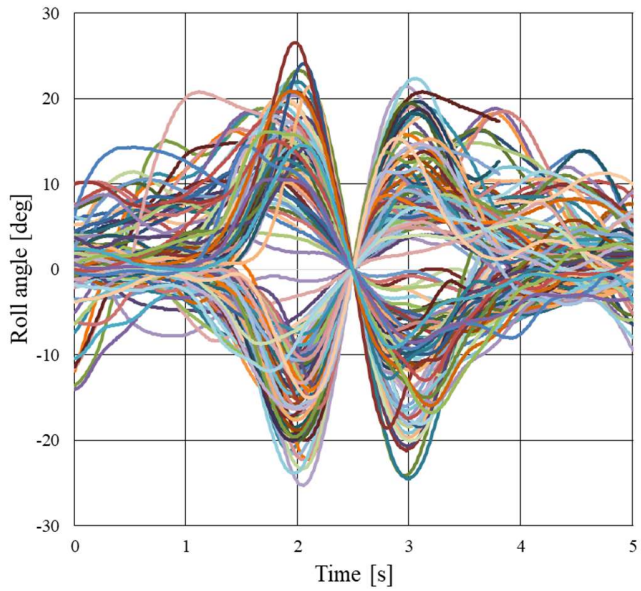

Figure 12:Time series of roll angles of all measured lane change maneuvers, synchronized by the zero crossing of the roll angle approximately in the middle of the lane change.

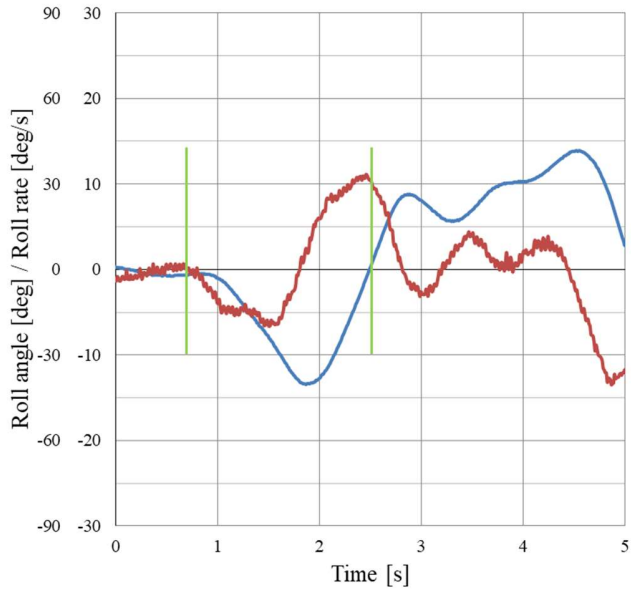

Figure 13: Estimation of duration of lane change manoeuver

The time needed for a lane change maneuver (duration) was calculated by the following procedure. Since the increase of the roll angle is hard to detect, instead the increase of the roll rate was used as the indicator for a beginning maneuver. Next, the zero crossing of the roll angle was searched and located. The time span between these two events was determined as the half lane change duration. Since the "lead-out" of a lane change maneuver is frequently fuzzy and mostly lacks of significant events, see Figs. 9 and 13, the half lane change duration was doubled and defined as the lane change maneuver time. This, of course, is a somewhat idealized duration time and defines the lower limit of the time a lane change manoeuver may take. Although Fig. 12 shows all cases and is therefore a bit overloaded, one still can see that the lane change time does not vary much. In the next chapter we will investigate this in more details.

As previously stated, the duration of the manoeuver does not reflect whether a lane change was executed "slow/lazy" or "quick/ambitious". However, for the further analysis and for developing driver models, a parameter is needed that describes this human factor. One may speculate that the steering torque applied to the handlebar by the rider might be the best mechanical parameter to quantify this factor, but unfortunately in our case there is no sensor installed to measure the steering torque. Therefore, the parameter needs to be derived from other quantities.

As already announced in Chapter 4 a new parameter termed "Intensity (of the lane change manoeuver)" is introduced. The definition is based on a pure heuristic approach. Since a highly "intense" manoeuver will lead to high maximum values of the roll angle and the roll rate, it was obvious to base the definition on these measured parameters. After trying out several approaches, a simple definition was found to be useful for the parameter "Intensity":

$$Intensity = 5\frac{\sqrt{RA}}{\sqrt{13}}$$

RA stands for the roll angle (deg). The intensity level is defined for roll angles on the interval [0° : 52°] and the dimensionless output on this interval is [0 : 10]. The formula gives for the average value of the measured maximum roll angle RA=13° an intensity value of 5. We will see later that in the test rides the roll angle mostly was in the range from 5° to 26,5°. The according intensity level varies between 3.1 to 7.1. The degressively increasing function seems to be an adequate representation of riders attitude in performing such a lane change manoeuver. In addition, the scale ranging from 0 to 10 is quite handy. Of course, one can try to find another formulae, that e.g. makes use also of the roll rate.

6. RESULTS AND DISCUSSION

As mentioned in Section 4, this study is based on measurements of only two riders, who are of significantly different age and motorcycle riding background. Therefore, it might be of interest, how different these two riders did behave in the tests. Fig. 14 shows a histogram of the maximum roll angle frequency measured at low speed tests at 50km/h (31 mph). A two-peak distribution is obtained, with prominent peaks at 10-12 deg and at 18-20 deg. Coloring the histogram reveals that the

peak at lower angles is associated with rider HE and the other with rider SL. Indeed, rider SL was "over-motivated" in these tests, and his performance demonstrates the upper end of the range, while rider HE tried to behave like an every-day rider. Since these tests were made at low speeds, it may give a good idea of the maximum lean angle to be expected when riding in an urban environment.

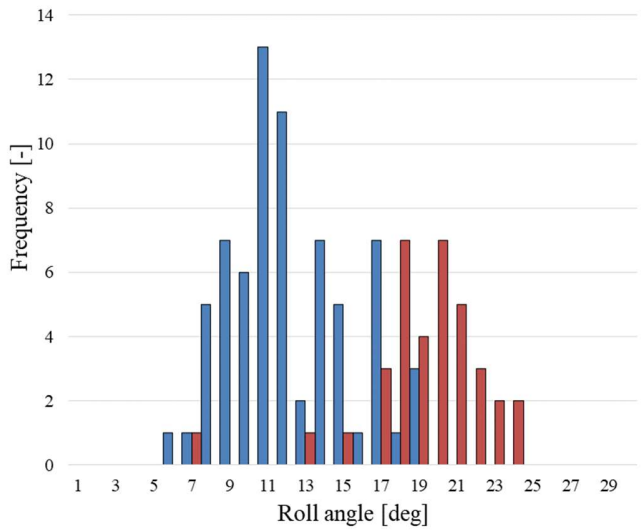

Figure 14: Histogram of maximum roll angle at low speeds of both riders; blue (HE) red (SL)

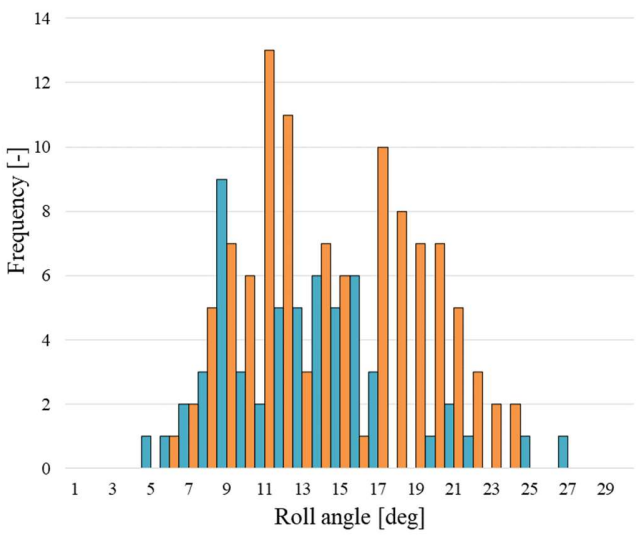

Figure 15: Histogram of roll angle at all speeds of both riders; orange (HE+SL @ low speed), blue (high speed)

The histogram in Fig.15 combines maximum roll angles for low speeds (< 60 km/h) and high speeds (> 70 km/h) for both riders. The low speed distribution (orange) combines the results of Fig. 14 with the double-peak caused by the two different riders. The high speed distribution was gathered only by rider HE and has a wide distribution between 12-17 deg, and a small peak near 9 deg. Thorough data analysis revealed that this peak is primarily caused by half lane changes. It is quite reasonable that for a half lane change the roll to one side must be stopped earlier than for the full lane change. Consequently, a fully completed large roll angle may not be reached in time and roll motion may be stopped prematurely.

Another important dynamic parameter to describe a lane change maneuver is the maximum roll rate. It can be expected, that this parameter also gives insight into the riding behavior. In Fig. 16 a histogram of the frequency of the maximum roll rate is shown. The orange bars of the chart represent the frequency for low speed tests for both riders. The distribution has an outstanding peak at 30 deg/s, but covers a range from 15 to 60 deg/s. A declining trend is visible from 30 up to 70 deg/s. Rates between 15 and 30 deg/s are almost on the same level. The blue bars in Fig.16 hold for high speeds and show a similar distribution, with a maximum peak again at 30 deg/s.

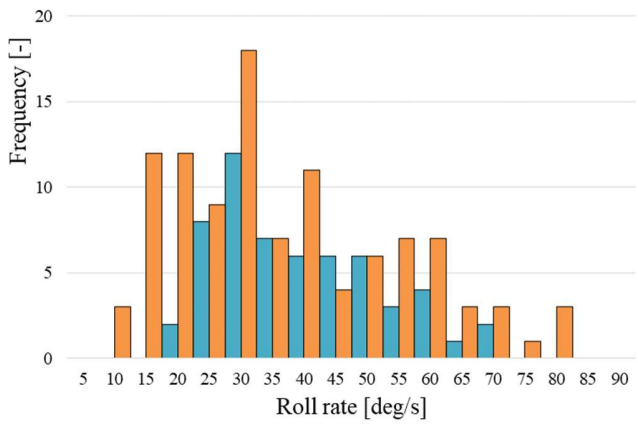

Figure 16: Histogram of the roll rate at all speeds of both riders; orange (HE+SL @ low speed), blue (high speed)

To point out once more the difference in riding behavior, the low speed maximum roll rates are separated for the two riders used in this study. Figure 17 shows the results for rider HE (blue bars) and rider SL (red bars). It is not surprising that the same rider that had high scores at the maximum roll angles is also the one with high roll rates. A more general conclusion is that the roll rate is an even better characteristic parameter to distinguish a riding style. Maximum roll rates between 10 and 40 deg/s can be associated with easy/moderate to normal riding. The range of normal to ambitious/speedy riding leads to maximum roll rates between 40 to 80 deg/s.

Next, the dependency of the dynamic roll parameters on the cruising speed is studied. Figure 18 is a scatter plot showing marks for each evaluable test. The majority of high quality tests were performed at 50-60km/h. There are many more high speed lane change maneuvers, but a quite large number have been only half lane changes. These were excluded to not mix them up with

the full lane change tests. Also only excellent tests have been included, to avoid "data noise" from less good results. In the future, an alternative method for data evaluation will be used to take advantage of these fuzzy measurements.

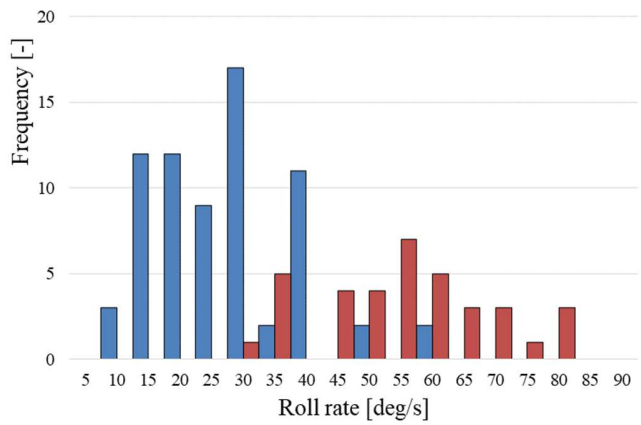

Figure 17: Histogram of roll rates at low speed of both riders; blue (HE) red (SL)

A least-square trend line was computed for the scattered data and plotted. As one may expect, for lower speeds the two test riders did use higher maximum roll angles. However, this trend is not that prominent. Only the few excellent measurements near 100 km/h showed a lower maximum value of approx. 17 deg compared to that for lower speeds. Of course, one must take into account that these results were gathered in regular traffic and not on a test track. Safety issues were even more important than anything else and made the testing difficult.

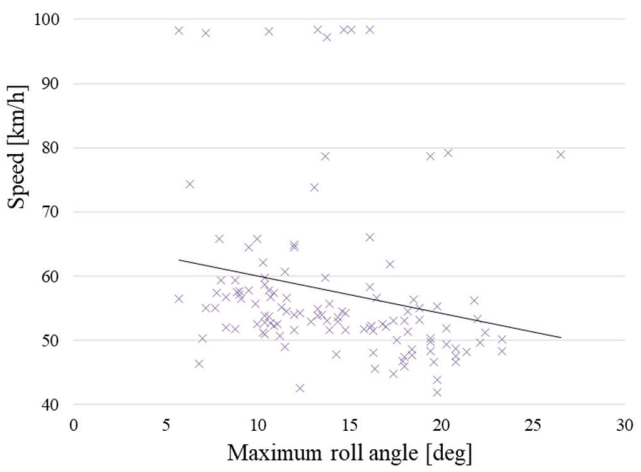

Figure 18: Speed vs. maximum roll angle for full lane changes

Probably the most interesting result was obtained for the correlation between the duration of a lane change and the maximum roll angle. This result is plotted in Figs. 19 and 20. Figure 19 only contains full lane changes, whereas in Fig. 20 also half lane changes have been included. A trend is visible, that confirms a rather weak decrease of the duration of a lane change with increasing roll angle. It is plausible that a more aggressive lane change will be executed in a shorter period of time. However, this gain in duration is smaller than one might think. Almost all full lane changes have been completed within 2-4 seconds, no matter of the riding speed. The high speed results of Fig. 16 have been marked with red squares in Figs. 19 and 20 to make them visible. As one can see, they are well distributed in the cloud of measurement points.

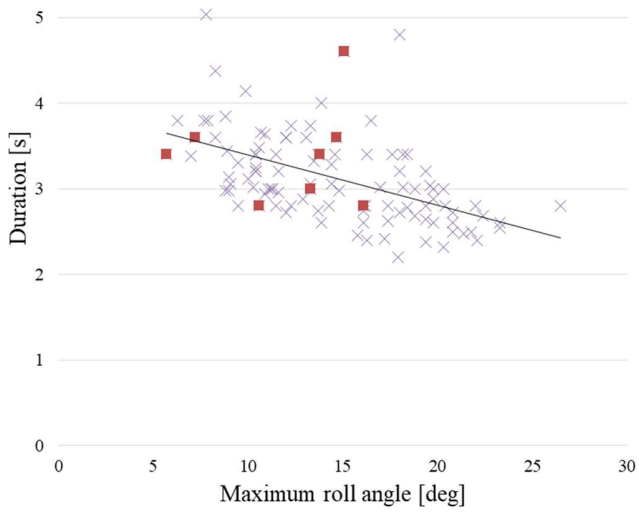

Figure 19: Dependency of the lane change duration on the maximum roll angle for full lane changes.

In Fig. 20 the half lane changes are also shown by blue diamonds. Those results form a local group that is situated predominantly between 2 and 3 seconds, indicating that the lane change offset has, as expected, an influence on that result.

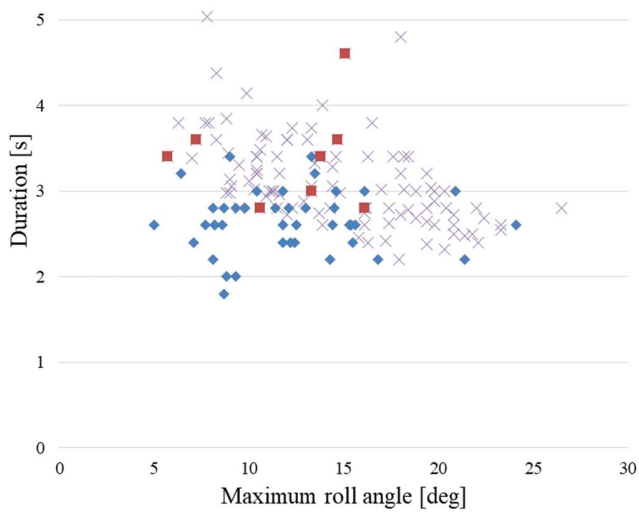

Figure 20: Dependency of the lane change duration on the maximum roll angle - half and full lane change

One of the goals of this study was to derive mathematical functions to describe characteristic parameters of a lane change manoeuver. In [8] regression models were employed to find analytical expressions for the lane change duration, the maximum roll rate, and finally the time functions of roll angle and roll rate.

Various Ansatz-functions were tried and the parameters of these functions were found by linear and non-linear regression analysis executed on the data set, as presented here. For this numerical approach the data analysis functions and toolboxes included in the software package Matlab © were used. The full derivation of the sought for functions is explained in details in [8]. Here we only show the most interesting functions obtained.

The duration of a lane change manoeuver can be calculated by the following expression:

$$d = -0.2346\, I + 0.3379\, w + 3.1715$$

where d is the duration [sec], I is the intensity [-] and w denotes the width [m] of the lane change.

The maximum amplitude of the roll rate can be obtained from

$$r_{max} = 11.5724\, I - 10.5877\, d + 13.4428$$

where r_{max} is the max. amplitude [deg/s], I and d are known from above. Finally the time function of the roll rate is given by

$$r(t) = r_{max}\, e^{\frac{-3.14t^2}{d^2}} \cos\left(\frac{3\pi}{d}|t|^{1.21}\right)$$

and the roll angle can be obtained by integration of the roll rate function.

The presented functions allow to generate synthetic time histories of the essential parameters of a lane change manoeuver. Therefore, the ultimate test for the quality of these analytical expressions is a comparison with actually measured data. Such a comparison is shown in the diagrams of Figs. 21-24. These are essentially the diagrams of Figs. 8-11, but now the synthetic functions are added and can be compared with the measured signals.

As one can see, measured and synthetic functions match very well. Of course, the synthetic functions are smoother, since measurement noise is absent and driver's control actions are not present in the synthetic solution. Occasionally the second peak of the roll angle is overestimated. This problem arises especially if the original data are less smooth and the fit for the roll rate is not perfect already.

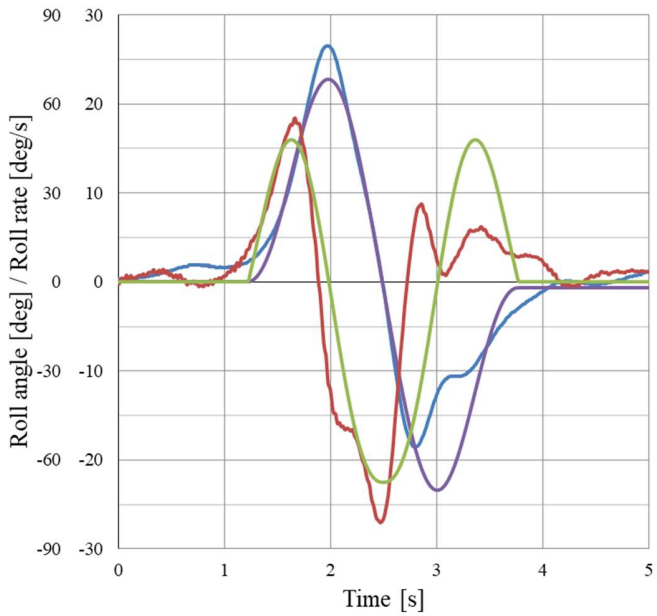

Figure 21: Same time series as in Fig.8 but now the synthetic function for roll angle (purple) and the roll rate (green) were added.

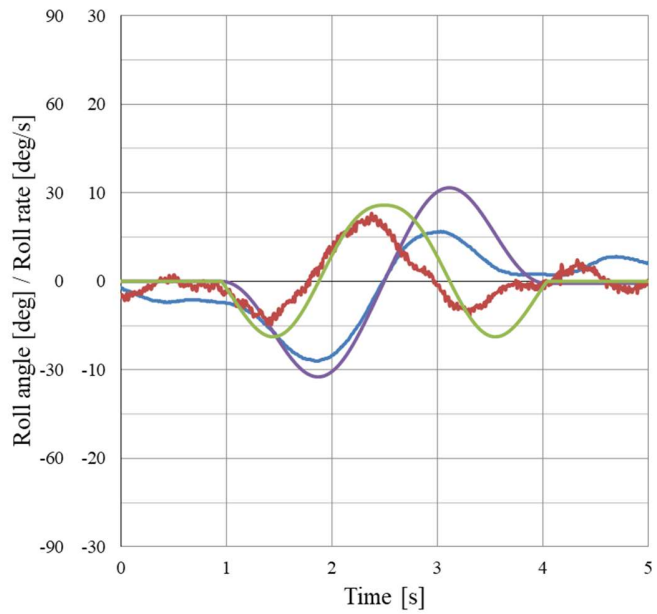

Figure 22: Same time series as in Fig.9 but now the synthetic function for roll angle (purple) and the roll rate (green) were added.

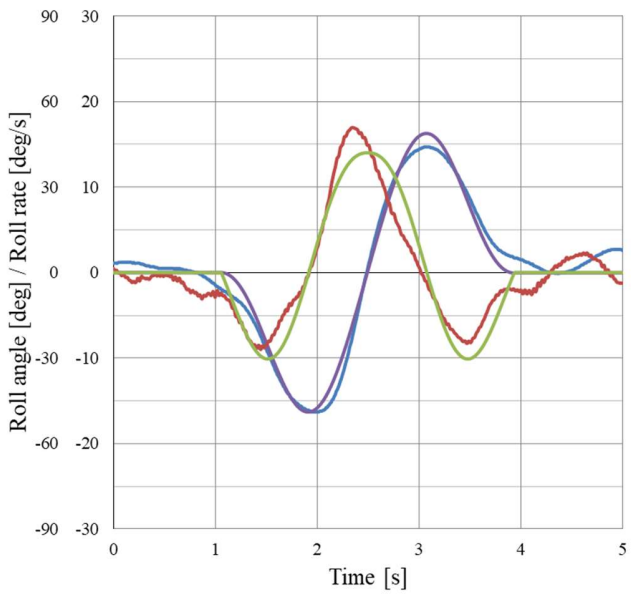

Figure 23: Same time series as in Fig.10 but now the synthetic function for roll angle (purpure) and the roll rate (green) were added.

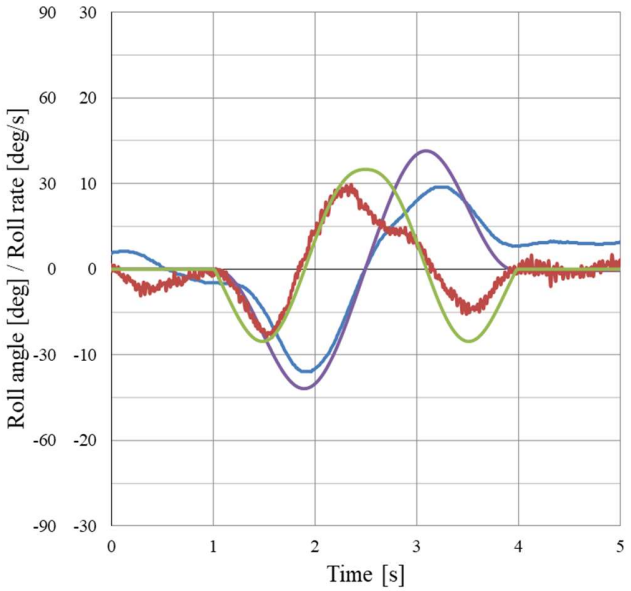

Figure 24: Same time series as in Fig.11 but now the synthetic function for roll angle (purpure) and the roll rate (green) were added.

7. CONCLUSION

Numerous lane change maneuvers have been carried out with an instrumented motorcycle and various vehicle dynamic parameters have been measured and recorded. These data show significant correlations, especially between vehicle speed, maximum roll angle and roll rate, rider behavior, lane change offset and time needed for a maneuver. A new parameter, the manoeuver *intensity*, was introduced and defined to describe the rider behavior when executing such a lane change. As a first result of the analysis of this large database, an analytical formulation for the duration of a lane change manoeuver could be derived. Based on this result and including the human parameter *manoeuver intensity*, the maximum roll rate can be estimated and finally analytic functions e.g. for the roll rate over time can be calculated. This outcome of the study is a first step to describe the kinematics of such maneuvers and also to generate and improve control models of motorcycle riders.

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