Connected Motorcycle Consortium

Rider Reaction Time

Document Information

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1 Summary

This whitepaper describes a dynamic motorcycle riding simulator study, which investigated motorcycle riders' reaction times towards a warning on the dashboard. This warning was a generic visual warning which can act as a benchmark to improve upon in the future.
Reactions in an urban and a rural scenario were tested. These did not include imminent crash warnings, but advisory warnings with 3 seconds between warning onset and the potentially critical situation becoming visible.

This study is a first step towards empirical evidence in this domain; the following interesting outcomes could be observed:

- In 16.7% of cases, the purely visual warning was not recognized at all
- Among the other cases, the average time between onset of the notification and gaze towards the dashboard was about 1 second already.
- The average time between notification onset and 'throttle off' was about 2 seconds.
- The average time between notification onset and 'initiate braking' was about 2.5 seconds.
- The mentioned reaction times were shorter in the urban scenario compared to the rural one, where the situation was perceived as less critical.

Another interesting observation could be that, in the more time-critical urban scenario, all riders who had seen the warning, initiated braking before the obstacle became visible. In combination with the favourable evaluation of the test riders after the experiment, this shows a good potential for the safety benefit of C-ITS applications.

In comparison to driver reaction times in passenger car studies, more missed warnings were observed, reaction times seem longer and reaction time distributions seem wider; hence there is a clear need for PTW-specific reaction time studies.
Furthermore, new warning designs should ideally result in lower or at least equal rider reaction times and fewer missed warnings in comparison to the tested purely visual warning design. This study's results can contribute to rider safety e.g., by means of understanding user requirements for notification timing better or by delivering input to rider behaviour models in the context of simulation.

2 Background & Motivation

Technical systems, such as anti-lock braking (ABS) control units, can process data and operate within a few milliseconds. Yet, to stay with the ABS example, these very fast responses can only provide a benefit if the rider is actually braking. More precisely, if the rider is interpreting a situation or a warning correctly and reacts accordingly. So far, there is little knowledge about how long a rider reaction towards e.g., a warning takes. Additionally, the question arises whether reactions from the passenger car domain can be applied to PTW research and how a PTW rider behaviour model should be parameterized to represent realistic rider behaviour. This knowledge is missing for PTW riders. To shed more light on this topic, a user study was conducted on a dynamic motorcycle riding simulator in order to provide empirical data on PTW rider reaction times towards visual notifications. This study helps to understand whether and how well the investigated purely visual rider notification is suitable to reduce critical events. It provides information on the relation of PTW riders' reaction times to passenger car drivers' reaction times in a comparable simulated setup. Furthermore, it provides a reference reaction time for OEMs to achieve with their own HMI warning concepts. This knowledge bridges the gap between results from the accidentology side to the use case and test case specific strategies. The latter focus on the decision on how an application's display/ alert principle should be designed (e.g., advisory notification, crash warning, active intervention).

It is very important to mention that this participant study on a motorcycle simulator provides first empirical evidence for point estimates and spread of reaction times towards a visual C-ITS warning. It is also important to notice that the distribution of reaction times towards a visual warning on a real motorcycle in real traffic etc. might vary significantly as there is a huge number of additional factors influencing these reactions (e.g., type of motorcycle and its ergonomics, dashboard downward angle, type of warning addressing different sensory channels of the rider, rider skills and workload resulting from the scenario, behaviour of surrounding traffic …). As a first step, it is simply not feasible to vary all these potentially relevant influencing factors in a rather controlled way and in a naturalistic field test to get results on PTW rider reaction times.

The chosen study design follows a so-called conservative approach. This means that the rider notification, which is presumably one of the major impact factors on rider reaction times, is designed in a minimalistic and easy-to-be-implemented way. It consists of a generic warning icon without any attention capturing effects, such as flashing, and comes without any warning tone. This type of notification is assumed to be quite easily implemented on PTWs with state-of-the-art technology (i.e., TFT dashboard). Consequently, the study shall provide an estimate for the upper boundary of reaction times (i.e., long reactions), which must be assumed under non-ideal warning conditions (e.g., no additional tone etc.).

The results of this study can be used in the following ways:

1. Based on the temporal evolvement and Time-to-Collision of different accident scenarios, the results help to better estimate for which C-ITS applications running on a PTW, a purely visual warning could be appropriate, and for which ones not.
2. Any OEM's individual HMI solution, i.e., rider notification concept, should result in faster reaction times and less missed warnings in this test setup than the conservative rider notification assessed in this study.

3. The distribution of rider reaction times can clarify to which extent results from passenger car research are applicable to the PTW domain and serve as an input to parameterize rider behaviour models in traffic simulations necessary for the effectiveness estimation of (C-ITS) safety applications.

3 Methods

3.1 Motorcycle simulator description

The DESMORI dynamic motorcycle riding simulator has been used for the participant study (see Figure 1). It is equipped with a BMW F 800S as mockup, mounted on a six degrees of freedom hydraulic Stewart platform. The mockup enables the rider to interact with fully realistic controls, such as usual handlebar, brake lever / pedal, clutch, gear selector, etc. that he/ she is used to. The manual gear shift uses a sequential six-speed gearbox. An electrical actuator produces a steering torque at the handlebar up to 80 Nm. The rider steers the motorcycle through a combination of steering torque and induced roll torque by shifting his/ her weight. The cylindrical screen with a diameter of 4.5 m and 2.8 m of height enables 220° horizontal field of view. The two rear-mirrors are realized by 7-inch TFT-displays while the dashboard is displayed on a 10-inch TFT-touchscreen. Sound is provided via body shakers, which are attached to the riders' individual helmets. Moreover, a shaker that is installed below the seat delivers vibrations from the engine and high frequent road roughness. A rope-towing mechanism simulates longitudinal forces such as wind drag to the rider torso. A camera is mounted right above the dashboard pointing towards the rider's head, which is used for head tracking and gaze behaviour analyses.

Figure 1: DESMORI dynamic motorcycle riding simulator at WIVW.

3.2 Test course

The test course had a total length of approx. 37 km. It consisted of different modules on rural and urban roads. The order of modules was permuted in four versions to avoid sequence effects. As can be seen in Figure 2, there was one urban and one rural test scenario, which were experienced twice per participant (the geometry and resulting trajectories etc. were identical, while the virtual environment was different to avoid any kind of expectations). Both test scenarios had in common that the conflict partner was obscured by other objects and therefore could not be seen by the rider in the moment when the warning was emitted. Additionally, there was a rural and an urban baseline scenario without warning but elsewise comparable conditions. The urban test scenario was inspired by the FT Accidentology results. In this scenario, a so-called cross traffic scenario (accident type 302 in the GIDAS data base) was represented. The PTW was approaching a crossing and had the right of way. A passenger car that was obligated to wait came from the right-hand side. Still, the passenger car entered the crossing as the simulated driver did not see the PTW. The view was obstructed by buildings close to the road. The passenger car came to a stop covering approx. 1/3 of the PTW's lane. In the rural scenario, the obstacle was a construction site or a broken-down vehicle respectively. These obstacles could not be seen due to trees close to the road and a right-hand bend with a slight downhill section afterwards.

Figure 2: Urban (left) and rural (right) test scenario.

3.3 Study procedure

Figure 3 illustrates the study procedure. All participants were welcomed and received an informed consent document providing all necessary information related to the study. Following the study instruction, a rating on the general attitude towards C-ITS applications on PTWs was collected. Two short rides in a rural and an urban environment on the simulator followed with the main aim of familiarizing with the virtual vehicle control again. Following the successful completion of these rides, the participants received specific instructions for the test ride. Besides trip length, traffic regulations etc., it contained information on the C-ITS application. The working principle of Vehicle-to-X (V2X) communication was explained as well as the type of rider notification. A broken-down vehicle warning as well as a green light optimised speed advisory (GLOSA) as comfort function were named as exemplary use cases. A rider notification for GLOSA was shown on the info sheet in order to divert attention away from potentially upcoming critical situations.

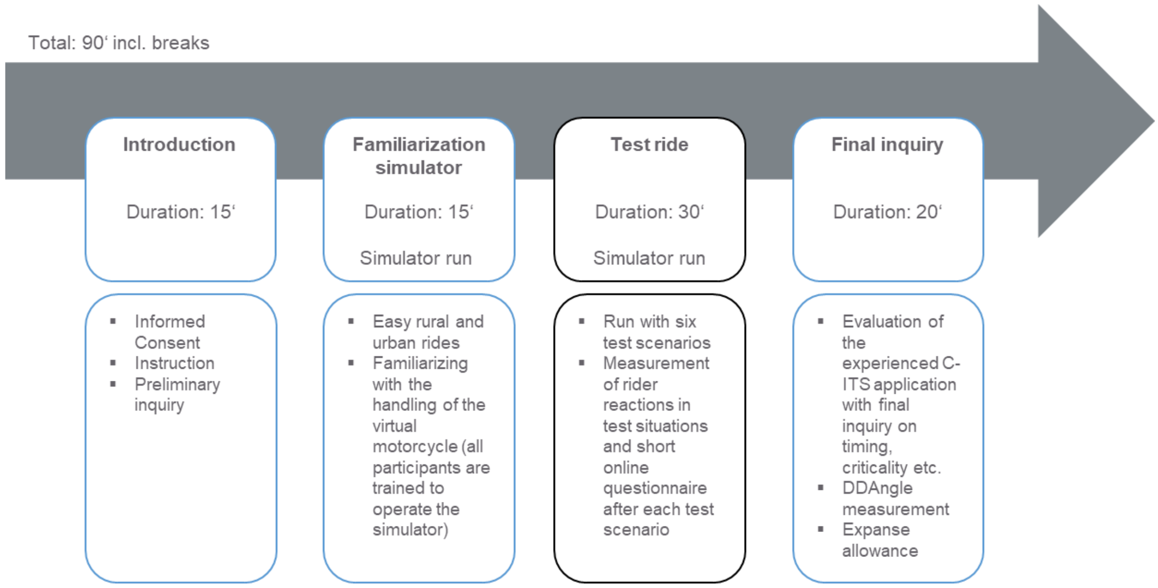

Figure 3: Schematic of the study procedure.

After each test scenario the riders answered two questions while riding. At the end of the appointment, a final inquiry was conducted and riders received an expense allowance. In order to facilitate the interpretation of the data, every participant mounted the mockup again and assessed whether he/ she could recognize the dashboard in the peripheral field of view. Additionally, the dashboard downward angle (DDAngle) was measured as illustrated in Figure 4.

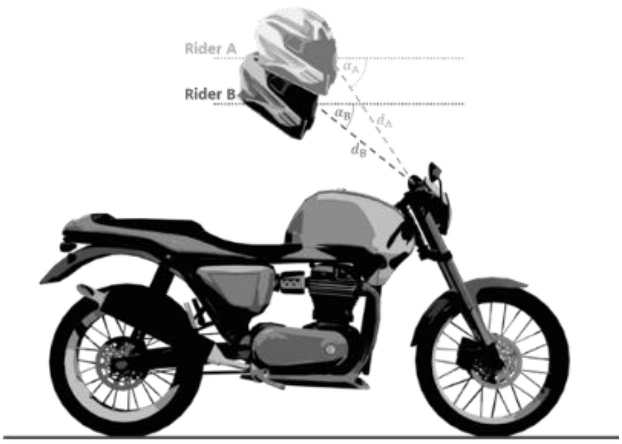

Figure 4: Schematic representation of different dashboard downward angles as a function of different rider heights.

3.4 Rider notification

The rider notification provides a purely visual warning to the rider, which is shown on the upper edge of the dashboard (see Figure 5). The dashboard has a size of 7-inch with a resolution of 1920 x 1080 and it is mounted at an average dashboard downward angle of approx. 33°.
The warning was designed as a non-specific warning with a red rectangle at a size of 16 mm x 27 mm. This decision was taken to investigate an OEM-independent generic warning.

Figure 5: Rider notification (red rectangle) in the dashboard.

Furthermore, it is a result of the conservative approach, which means that a minimum notification would be investigated. The notification was triggered with a time-to-arrival (TTA) = 3 s prior to when the potential threat became visible. The warning was then displayed for three seconds and disappeared automatically.

3.5 Measures and statistical analysis

Three different types of reactions were analysed (Figure 6).

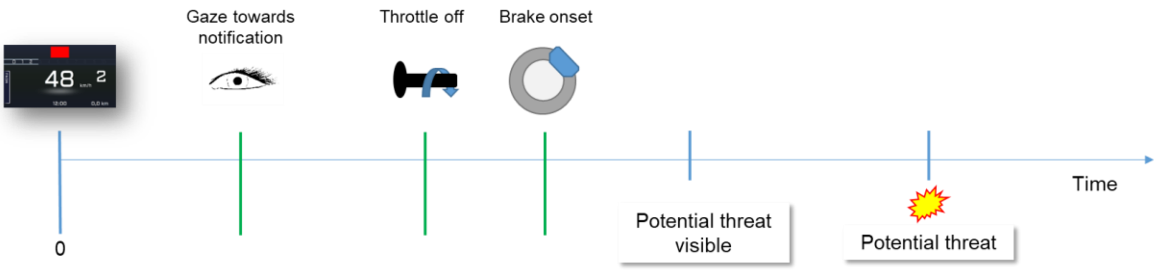

Figure 6: Schematic representation of different possibilities to calculate reaction times.

The starting time t_0 for any calculation is always the issuing of the visual warning in the dashboard (warning onset). The following three types of reactions are analysed:

1. *Warning onset until gaze towards notification.* The gaze behaviour, which distinguishes between 'gaze towards dashboard' and 'gaze not towards dashboard' is retrieved from the video data via manual video annotation. It is assumed that a gaze towards the dashboard while the warning is displayed goes along with the recognition of the warning, which is one of the major variables of interest.
2. *Warning onset until throttle off.* This parameter measures the time between warning onset and the release of the throttle twist grip as the potentially first and intuitive reaction to reduce the speed. A throttle twist grip release is defined as complete release to the neutral throttle position.
3. *Warning onset until brake onset.* This parameter measures the time between warning onset and the start of mechanical braking (either front or rear brake or both) as a rider reaction for significant speed reduction. Brake onset is defined as an operation of any brake lever.

Depending on the evolution of each specific test scenario, throttle off and brake onset must not necessarily occur, if a rider judges the situation as sufficiently controllable and safe. If there is no gaze towards the dashboard, the situation is counted as a missed warning. Consequently, no type of reaction towards a warning can be calculated in this case. Any rider response later than 300 ms after warning onset was regarded as response to the warning instead of a regular control gaze towards the dashboard.

In addition to the vehicle dynamics data, subjective measures were gathered. After every test situation (baseline as well as warning situations) the riders were asked whether the C-ITS application emitted a warning. If the answer was positive, the riders were asked what their reaction was. This information helps to interpret the riding data. For instance, a rider may reply that he recognised the warning but decided not to brake, because there was enough space on his lane to pass the potential conflict situation. The second question targeted the perceived criticality of the experienced situation. The answers were given on the situation criticality scale as displayed in Figure 7. Both questions were answered while riding.

Figure 7: Situation criticality scale (English version translated from Neukum et al., 2008).

A final inquiry completed the appointment. The riders were asked to rate the recognizability of the rider notification that they were shown on a 16-point verbal categorisation scale ranging from ‘0 impossible’ to ’15 very good’. Furthermore, the riders were asked about the perceived warning timing and their general attitude towards C-ITS based assistance systems on motorcycles. The latter question has also been asked in the very beginning before riders experienced the C-ITS application in the simulation. The answers were given on a 13-point verbal categorisation scale as shown in Figure 8. For acceptance ratings below ‘0’, participants were asked for the underlying reasons.

Way too early/ Strongly disagree			Too early/ Disagree			Neither nor/ Neither nor	Too late/ Agree			Way too late/ Strongly agree		
-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6

Figure 8: 13-point verbal categorisation scale.

The dashboard downward angle was measured in degrees by the experimenter with a goniometer, while the participant was sitting on the motorcycle simulator wearing his/ her full-face helmet. Figure 9 shows an average dashboard downward angle towards the dashboard of 33° with a considerable spread between participants depending on rider height respectively torso length etc. The interquartile range covers 5.3° from 30.9° to 36.2°.

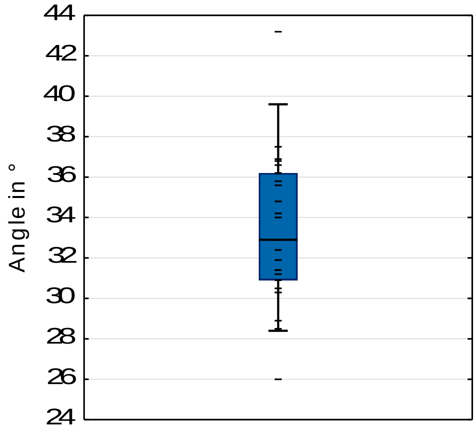

Figure 9: Measured dashboard downward angles towards the dashboard.

The data analysis is based on different subgroups in the data set:

1. Complete data set for the estimation of the warning's effect in comparison to the baseline
2. Comparison of urban and rural test scenarios for the estimation of the riding environment's effect on riders' behaviour
3. Analysis of the trials for which the riders stated to have seen the warning in order to analyse rider reactions that can be attributed as a reaction to the warning

Video annotation was done with *SILAB VideoAnalysis*®. Data has been pre-processed with *MatLab*® and further analysed using *Statistica*® *and SPSS*®. Descriptive data, such as means, distributions etc. show raw data if not elsewise stated. A base 10-logarithm was calculated for inferential statistics of the reaction times to account for skewness and non-normal distribution of the raw data.

3.6 Participants panel

A total of *N* = 24 riders participated in the study, while *n* = 3 were female. The panel covers a wide spread of different ages and levels of riding experience as can be seen in Table 1. The study has been approved by WIVW's group in charge for ethical assessment. The strict ethical guideline as defined in the standard operating procedures based on the Guidelines for Safeguarding Good Research Practice of the German Research Foundation (DFG) as well as the Code of Professional Ethics of the German Association of Psychologists (bdp) and the German Psychological Society (DGPs) has been followed. All participants were recruited from the WIVW motorcycle rider panel, which consists of non-professional riders that had previously been trained to ride the simulator safely.

Table 1: Panel description (N = 24 with n = 3 female riders).

	Mean	***Standard deviation***	***Minimum***	***Maximum***
Age in years	36	12	20	60
Motorcycle mileage covered during the last 12 months in km	3 854	3 232	500	12,000
Motorcycle mileage during lifetime in km	78,500	79,900	2 000	300,000

4 Results

The analysed segments start with the warning onset and stop when the rider has passed the potentially critical situation. The presentation of the results follows the defined rider reaction variables ‘gaze behaviour’, ‘throttle off’, ‘brake onset’, and ‘subjective measures’ (chapter 3.5). Detailed descriptive statistics can be found in chapter 7 Appendix.

4.1 Gaze behaviour

In both warning and baseline scenarios, riders show (control) gazes towards the dashboard. On average, one gaze towards the dashboard takes approx. 400 ms. In the baseline condition, more regular control gazes towards the dashboard can be observed in the urban area as compared to the rural setting. The number of riders with at least one gaze towards the dashboard increases with a warning being presented, as can be seen from Figure 10 left (Rural: with a warning 56% (27/ 48) instead of 9% (2/ 22) without warning; Urban: with a warning 94% (45/ 48) instead of 63% (15/ 24) without warning). In total, in 16 out of 96 trials including a warning no gaze towards the dashboard was observed within the 3 sec warning period.

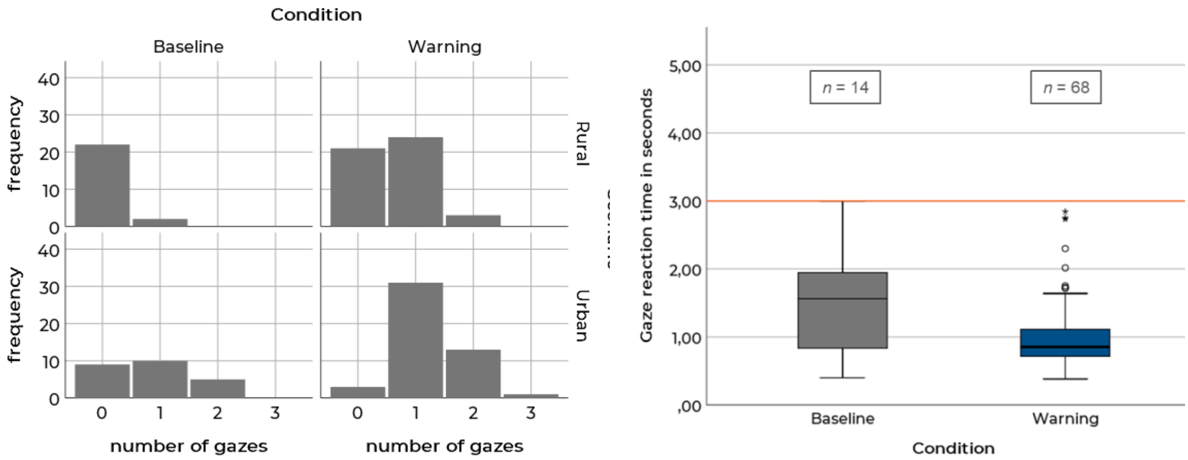

Figure 10: Distribution of gaze frequency towards the dashboard in the warning period (left; hypothetical warning period for baseline). Boxplot for riders’ gaze reaction times after the (hypothetical) emission of a warning towards the dashboard (right). The orange horizontal line indicates the point in time when the obstacle becomes visible and the warning disappears.

Regarding gaze reaction time (Figure 10 right), within the warning condition most riders react on a rather homogeneous level. While 50% of the participants look at the warning within 0.85 sec or less (median value), 25% need more than 1.12 sec (75th percentile). In comparison to the baseline condition, the riders show earlier gazes towards the dashboard in the warning condition (F(1,11) = 6.89, p = .024, η^2_{part} = .385).

Figure 11 shows a more detailed analysis of the participants’ gaze reaction times, taking into account the differences between the investigated rural and urban scenarios. Within the warning scenarios a difference regarding the frequency of gaze reactions towards the warning can be observed (42/ 48 reactions within the urban scenarios vs. 26/ 48 within the rural scenarios). Besides the higher number of participants who directed their gaze towards the dashboard after the warning got visible within the urban scenarios, faster reaction times can be observed on average (m_{Rural} = 1.22 sec; m_{Urban} = 0.91 sec).

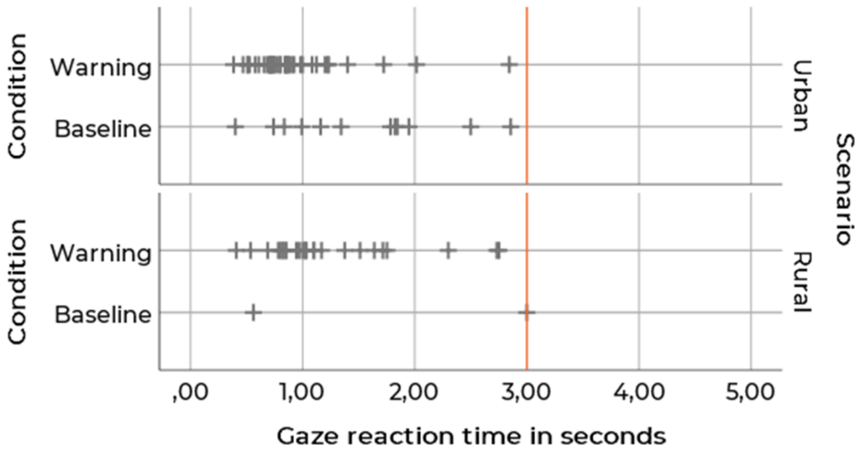

Figure 11: Riders' gaze reaction time after the warning has been emitted for rural and urban scenarios in warning and baseline condition. + indicates a single measurement, the orange vertical line indicates the point in time when the obstacle becomes visible and the warning disappears.

4.2 Throttle off

Regarding the throttle off reaction a comparable ratio of rider reactions between the baseline and the warning condition can be observed compared to riders' gaze reactions. Again, more riders react within the warning condition ($n_{Warning}$ = 55/ 96; $n_{Baseline}$ = 10/ 48).

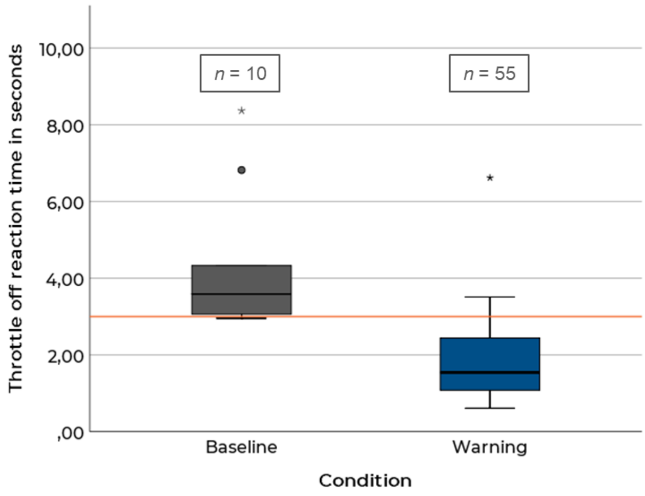

Figure 12: Boxplot for riders' throttle reaction time after the emission of a warning (hypothetical warning period for baseline). The orange horizontal line indicates the point in time when the obstacle becomes visible and the warning disappears.

In the warning condition a median value of *Mdn* = 1.51 sec for the throttle reaction time can be observed. Taking into account the difference between rural and the urban scenario, a higher number of reactions can be observed in the urban scenarios (n_{Urban} = 34/ 48; n_{Rural} = 21/ 48). Additionally, riders react earlier in the urban scenarios compared to the rural scenarios within the warning condition (Mdn_{Urban} = 1.27 sec; Mdn_{Rural} = 2.13 sec). The baseline throttle response is shown in Figure 13, as a comparison, to see that the warning must have been the reason to release the throttle and not the scenario itself.

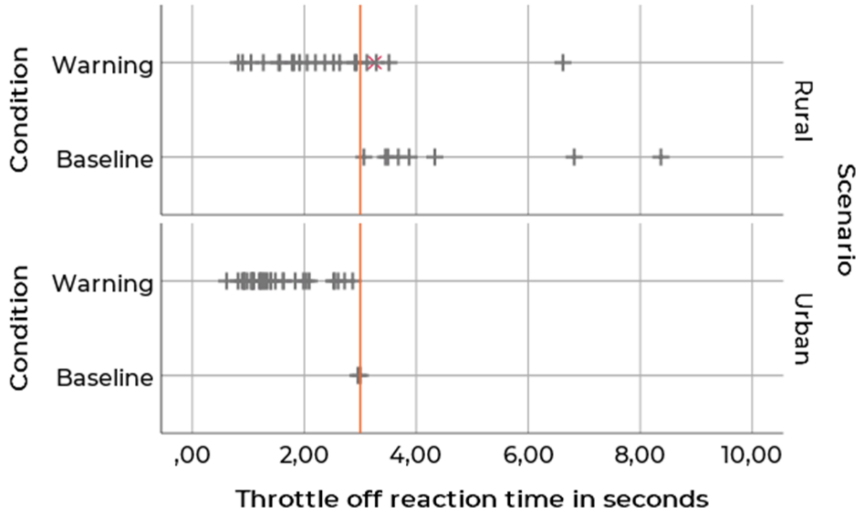

Figure 13: Riders' throttle off reaction times after the warning has been emitted for rural and urban scenarios in warning and baseline (hypothetical warning period for baseline) condition. + indicates a single measurement, x indicates a reaction, where the rider stated to not have seen a warning, the orange vertical line indicates the point in time when the obstacle becomes visible and the warning disappears.

4.3 Brake reaction

The measured brake reaction times are well in line with the gaze and throttle off reaction times. Figure 14 summarizes the brake reaction times. Once again, the baseline values are given as a comparison to estimate the effect of the warning instead of the scenario itself.

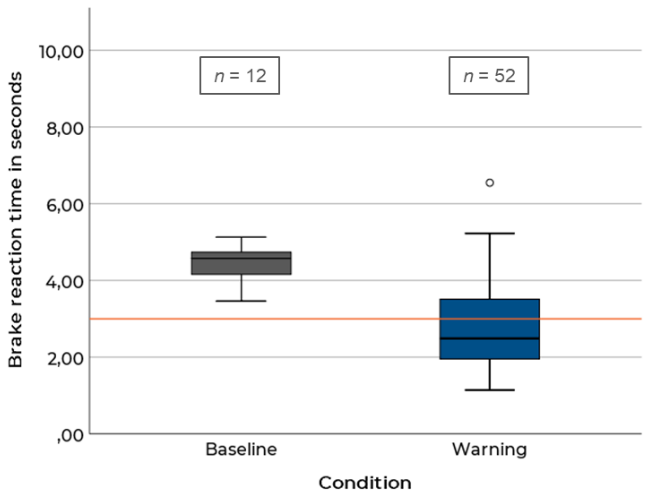

Figure 14: Boxplot for riders' brake reaction times after the emission of a warning (hypothetical warning period for baseline). The orange horizontal line indicates the point in time when the obstacle becomes visible and the warning disappears.

While all riders in the baseline condition react after the point in time at which the obstacle becomes visible, more than 50% of the riders in the warning condition show a brake reaction initiation before the obstacle becomes visible (*Mdn* = 2.49 sec). Figure 15 shows a more detailed analysis of riders' brake reaction times.

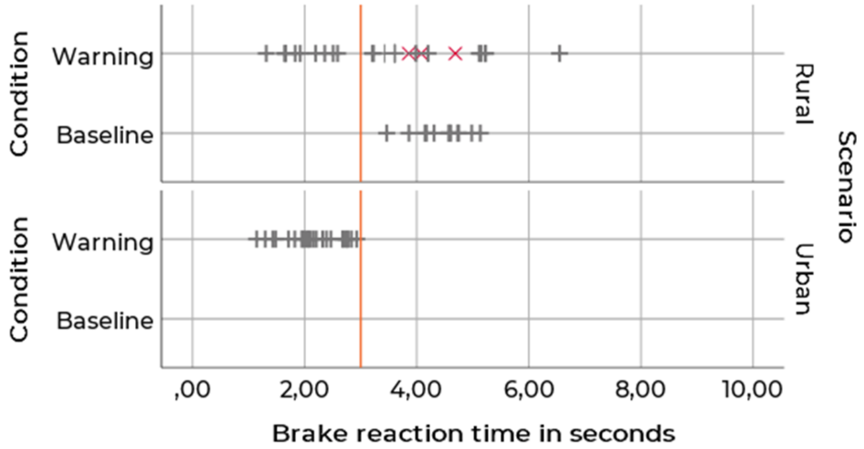

Figure 15: Riders' brake reaction time after the warning has been emitted for rural and urban scenarios in warning and baseline (hypothetical warning period for baseline) condition. + indicates a single measurement, x indicates a reaction, where the rider stated to not have seen a warning, the orange vertical line indicates the point in time when the obstacle becomes visible and the warning disappears.

All brake reactions in the urban warning condition are observed before the obstacle becomes visible (*Max* = 2.93 sec; obstacle becoming visible at 3 sec). In contrast, less than 50% of the participants show a brake reaction before the obstacle becomes visible in the rural scenario (*Mdn* = 3.51 sec; obstacle becomes visible at 3 sec). In the baseline conditions no brake reactions can be observed in the urban scenarios while there are *n* = 12 participants who react in the rural scenario between *Min* = 3.46 sec and *Max* = 5.13 sec as response to the potential obstacle (after the point in time at which the warning would have been emitted).

Figure 16 shows a summarizing rider reaction time plot which displays data from riders who have seen the warning so that throttle off and brake onset can be interpreted as reaction to the warning. This is especially true for reactions within the warning period of three seconds (left to the orange vertical line) as the potentially critical situation only became visible afterwards. As can be seen from the plot, rider reactions for gaze, throttle and brake start earlier in the urban scenario compared to the rural scenario (Figure 16, median values represented by the vertical black lines within the blue boxes displaying the interquartile range). Within the urban and rural scenarios, a shift of the reaction times can be observed with gaze reaction times occurring first, followed by throttle off reactions and brake reactions occurring last. Within the urban scenario all participants react within the warning period or, in other words, before the obstacle becomes visible. In the rural scenario especially brake reactions which start after the warning period can be observed in more than 50% of the investigated cases.

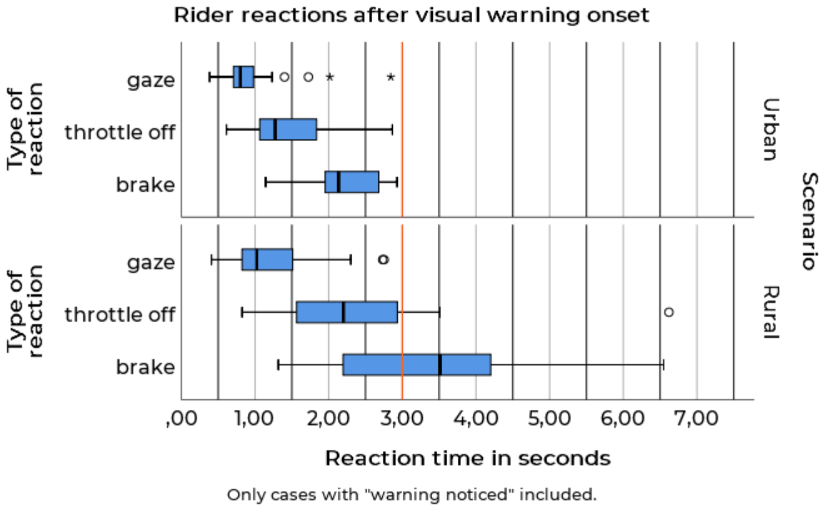

Figure 16: Summarizing rider reaction time boxplot containing data from participants who reported to have seen the warning. The plot shows rider reaction times for gaze, throttle and brake reactions separately for urban and rural scenarios. The orange vertical line indicates the point in time when the obstacle becomes visible and the warning disappears.

4.4 Reaction times following the gaze reaction

In the following section, rider reaction times between the gaze reaction time and the throttle off reaction and respectively the gaze reaction time and the brake onset reaction time will be reported (Figure 17). Once again, the focus is on events where the riders stated to have seen the warning.

The majority of riders shows a throttle off response within approx. one second after the gaze has been directed towards the warning.

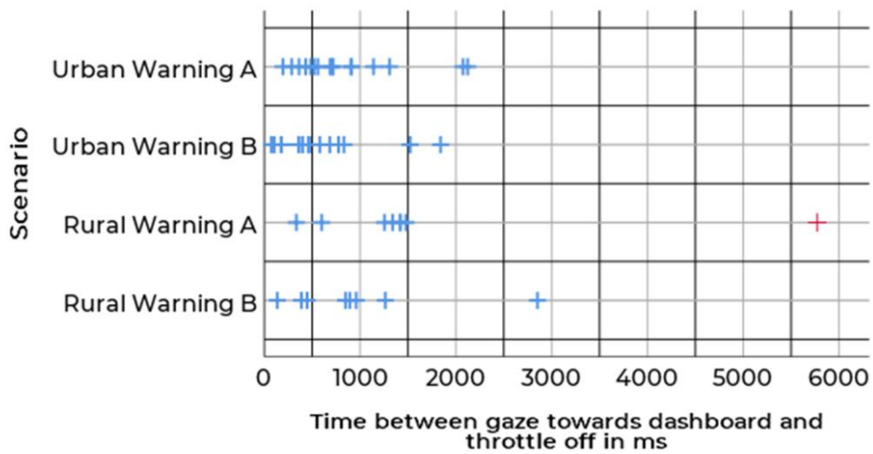

Figure 17: Rider reaction times between gaze reaction and throttle off for the individual warning scenarios.

In the majority of observations, the riders react within approx. 1.5 seconds with a brake onset after directing the gaze towards the dashboard (Figure 18).

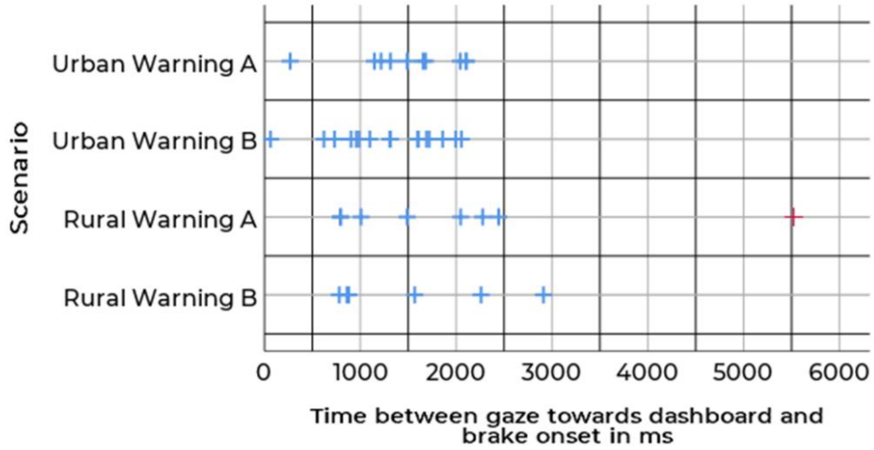

Figure 18: Rider reaction times between gaze reaction and brake onset for the individual warning scenarios.

4.5 Subjective measures

The participants were asked to rate the perceived situation criticality after each scenario. On average, the scenarios created unpleasant to dangerous situations as intended (Figure 19). Obviously, the situation itself was not subject to investigation, but it serves as a plausible reason for the riders to receive a notification. As can be seen from Figure 19, the warning decreases the perceived criticality in the urban scenario, which is more time-critical. It does not change the rating in the rural scenario (interaction effect: $F(1,23) = 45.60$, $p < .001$, $\eta^2_{part} = .66$).

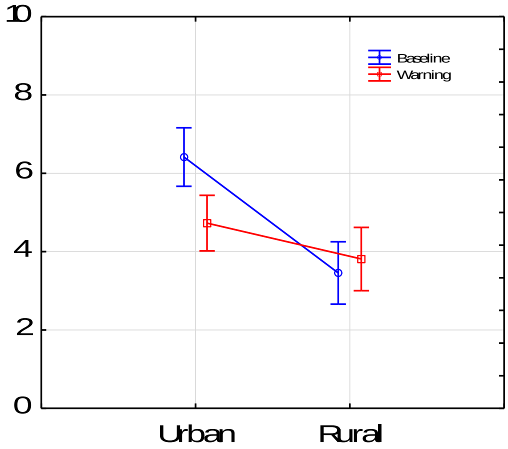

Figure 19: Situation criticality rating for baseline and warning condition for rural and urban scenarios.

At the end of the study, the participants were asked to rate the perceptibility of the warning (Figure 20 left). On average, the riders rate the perceptibility of the warning as ‘medium’ (*Mdn* = 8), with a majority of the participants rating the warning in a range from ‘medium’ to ‘good’. The participants gave feedback regarding potential for improvement (Table 2), which include feedback regarding the visual representation of the warning (e.g., a flashing warning icon), the warning position (e.g., a higher position of the warning), warning size, and the inclusion of other modalities, especially the inclusion of an acoustic warning.

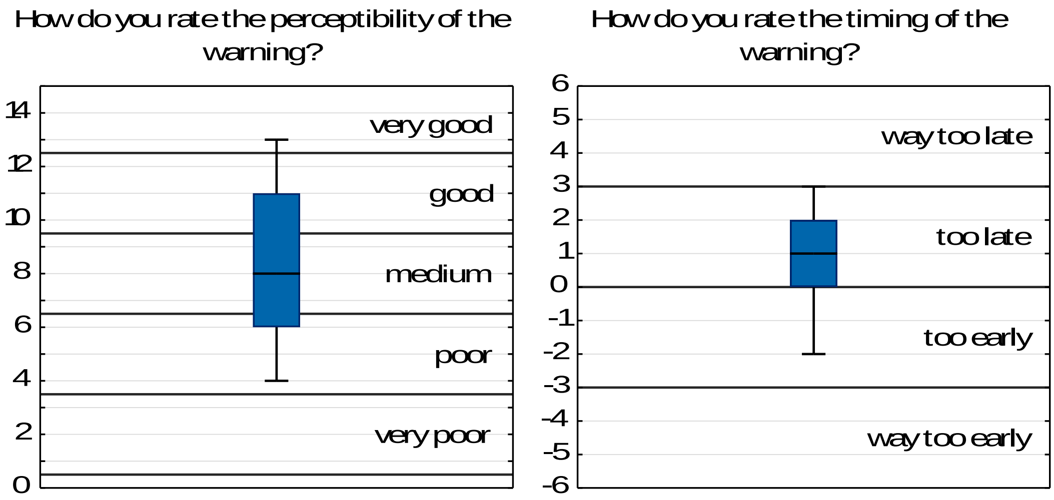

Figure 20: Rating of warning's perceptibility (left) and rating of the warning's timing (right).

The majority of participants rate the warning timing somewhere between from 'appropriate' to 'too late' (Figure 20 right). Only few participants rate the warning as being too early.

Table 2: Feedback and proposed improvements for the warning concept from the participants' perspective. Numbers in parentheses indicate frequency of mention.

visual representation	warning position	warning size	other modalities
Flashing icon (5)	higher warning position (5) or even head-mounted presentation of visual warnings (4)	red rectangle should be increased in size e.g., with the whole display flashing periodically (3)	Inclusion of acoustic warning (7)
Better visual perceptibility needed especially for hazardous situations (3)			Innovative solutions such as a vibrating handle bar
Warning should be specific (regarding situation criticality; red rectangle is associated with extreme criticality)			

The participants were asked before and after the ride to rate their attitude towards C-ITS applications on PTWs. Both, before and after the ride the majority of participants stated to have a 'favourable' to 'strongly favourable' opinion towards C-ITS with only few individuals who state to have a 'negative' opinion (Figure 21 left). Figure 21 right depicts participants' individual change in attitude before and after the experiment.

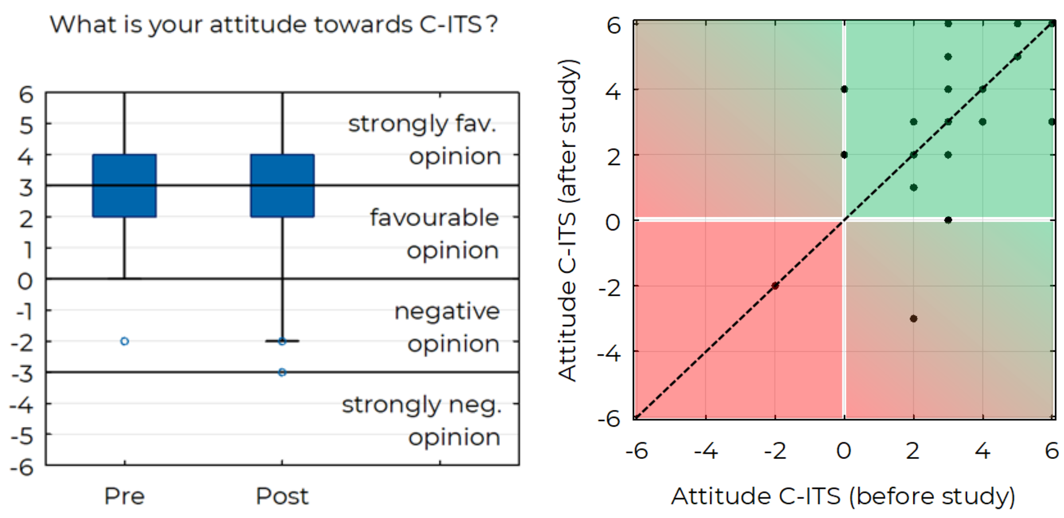

Figure 21: Attitude towards C-ITS applications on PTWs before and after the study (left) and change in attitude towards before and after the study per participant (right).

Data points in the upper right area represent participants who rated the system before and after the study positively, which covers the majority of values. Data points along the angle bisector (dashed line) represent participants that did not change their attitude. Values below the angle bisector indicate changes towards more negative and above the angle bisector towards more positive evaluations after the study. The values seem evenly spread so that experiencing the system in the study did not significantly change the attitude.

5 Discussion

The present deliverable described a dynamic motorcycle simulator study, which investigated motorcycle riders' reaction times towards visual warnings. A 'conservative' rider notification in terms of a red rectangle in the dashboard without any auditory sound has been subject to investigation. Two scenario types were included: a cross traffic scenario in an urban environment and a broken-down vehicle/ road works scenario on a rural road. Both scenario types were experienced twice with a warning and once without a warning by every participant. To prevent expectancy effects, dummy scenarios were included that resembled the test scenarios in terms of road geometry, view obstruction etc., but did not include any potentially critical situation. This scenario design worked well as the participants could not identify the scripted critical scenarios while approaching them. This means that no expectancy effects occurred, such as unnaturally cautious behaviour while approaching the test scenarios.

Gaze reactions

The first rider reaction time of interest, was the time between warning onset and gaze directed towards the dashboard. Even in the baseline condition, riders have shown control gazes towards the dashboard during the hypothetical warning period. This occurred more often in the urban environment, which has a high face validity as riders seem to control their speed more often in the city as compared to the approach phase of a rural curve. Yet, in the warning condition the number of gazes towards the dashboard was clearly increased. Additionally, the riders directed their gaze earlier towards the dashboard, which indicates that the warning was salient enough to catch the riders' attention. Yet, 16 out of 96 warnings were missed, which primarily occurred in the rural scenarios. This might be a result of different gaze behaviour for rural and urban scenarios. The latter providing a more vivid environment and potentially a higher perceived need to control the velocity on a more regular basis. In summary, the purely visual warning could be notified by a majority of riders, given an average dashboard downward angle of 33°. Yet, an improved rider notification design (e.g., warning tone, visual signals closer to the natural line of sight etc.) was requested by the riders, which could increase the acceptance of an application and should have the potential to create fewer missed warnings and potentially shorten reaction times further. The investigated scenarios did not include imminent crash warnings, but advisory warnings with 3 sec between warning onset and a potentially critical situation becoming visible. Given the gaze reaction times, 3 sec are still regarded as slightly too late on average based on the riders' interview data. With an average gaze reaction time of approx. 1 sec, one could interpret that 2 sec between recognizing a warning and a potential threat becoming visible is experienced as slightly too late on average.

Deceleration reactions

In the baseline condition no throttle off or brake reactions were observed in the hypothetical warning period. This means that the throttle off and brake reactions observed in the warning condition were really a response to the warning and not the scenario itself. It is important to mention that the participants did not stay passive in potentially critical situations. When the obstacle became visible the majority showed an avoidance manoeuvre in terms of swerving as – especially in the urban scenario – braking did not seem to be a promising avoidance manoeuvre anymore. Yet, these reactions occurred when the potential threat became visible and were therefore not subject to investigation in this study. The difference between the rural and urban scenarios which was already found for riders' gaze reaction times was also found for throttle off and brake reactions. Thus, the road type seems clearly to make a difference. The underlying reason for the different reaction times might be the scenario itself (e.g., the urban crossing scenario requires a faster reaction than the rural broken-down vehicle warning from the point in time when the critical situation becomes visible) or psychological effects such as imposed rider workload (e.g., higher level of awareness in the urban setting with more action in the periphery) as a result of the scenario.

Comparison with passenger car driver reactions

The collected data set seems to show differences to data sets on driver reaction times in the passenger car domain. For instance, guidelines such as the ISO 15623 2013 (E) suggest minimal driver reaction times of 0.4 sec and maximal reaction times of 1.5 sec or SAE J2400 names 1.18 sec before starting a response to a Forward Collision Warning. Passenger car simulator study results, for instance, Winkler et al., 2015 measured 0.86 sec on average as brake reaction time with a purely visual generic warning in a HUD in a time-critical crossing scenario with a pedestrian. Bella and Silvestri, 2017 investigated a cross traffic scenario in a driving simulator with a purely visual warning in the dashboard triggered approx. with a TTC = 4 sec. Their average reaction, defined as time between warning onset and the moment when the driver starts to decrease the speed (throttle off), is 0.94 sec. For the crossing scenario in this study as fairest comparison (this was the more urgent-danger scenario as compared to the rural scenario), the mean throttle response was 1.47 sec and 2.18 sec for braking. Completely missed warnings were not really an issue in the cited passenger car research as opposed to this study.

Limitations and advantages of the chosen approach

Obviously, simulator studies go along with certain limitations. For instance, there are some missing environmental factors (e.g., sun glare) or the focus on relative or scenario-dependent validity. This should avoid the expectancy of a one-to-one match to results gained in a field study. At the same time, the chosen simulator study is considered an appropriate and efficient set-up to investigate rider reaction times. First of all, there is almost no information on PTW rider reaction times available and this study should be a first step towards empirical evidence in this domain. The advantages such as a fully controlled environment in terms of behaviour of other traffic participants, repeatable critical scenarios or convenient and precise measurement of all necessary data etc., dominate. Furthermore, there are ethical and safety constraints in investigating rider reaction times in potentially critical scenarios in a field test and the results would not have been generalisable either. This is because, one specific PTW with its given ergonomics, dashboard downward angle etc. would have been investigated and the results gained with another PTW (e.g., touring vs. chopper) could have been completely different.

6 Conclusion

The results of the presented user-centred simulator study successfully provide a first estimation of motorcycle rider reaction times in response to a generic purely visual warning. These reaction times can be seen as a benchmark for future visual warning designs. Thus, they provide an opportunity for OEMs or TIER1-suppliers to compare the reactions triggered by their rider notification solutions in a comparable setup to the generic visual warning design in order to assess their efficacy. New warning designs should ideally result in lower or at least equal rider reaction times and fewer missed warnings as compared to the given generic rider notification. Besides the already acceptable salience of the investigated warning, potentials for improvement were identified, which should be taken into account for further developments.

Another conclusion to draw is that the available data suggests a need for PTW-specific reaction time studies as more missed warnings were observed and reaction time distributions differ compared to passenger car literature. This seems to hold true even if it is rather impossible to identify absolutely comparable studies from the passenger car domain.

Finally, the distributions of rider reaction times can serve as important input to the tuning of rider behaviour models. These models are central components of simulated environments, which are e.g., required to create effectiveness estimations for (C-ITS) safety applications by means of traffic simulation.

7 Appendix

The following subchapters summarize descriptive statistics regarding the different types of reaction times. The number of observations is always given in column ‘*N*’. This is important to notice as not every type of reaction was observed in every test trial.

7.1 Descriptive statistics: Gaze reaction times

Condition	Scenario	*N*	*Mean*	*Median*	*Minimum*	*Maximum*	*Standard deviation*	*5th percentile*	*25th percentile*	*75th percentile*	*95th percentile*
Baseline	Urban	12	1.52	1.56	0.40	2.86	0.74	-	0.88	1.92	-
	Rural	2	1.78	1.78	0.56	3.00	1.73	-	-	-	-
Warning	Urban	42	0.91	0.80	0.38	2.84	0.44	0.47	0.71	0.99	1.97
	Rural	26	1.22	1.02	0.41	2.75	0.61	0.45	0.82	1.54	2.75

7.2 Descriptive statistics: Throttle off reaction times

Condition	Scenario	*N*	*Mean*	*Median*	*Minimum*	*Maximum*	*Standard deviation*	*5th percentile*	*25th percentile*	*75th percentile*	*95th percentile*
Baseline	Urban	2	2.98	2.98	2.96	3.00	0.03	-	-	-	-
	Rural	8	4.64	3.78	3.06	8.,37	1.91	-	3.47	5.58	-
Warning	Urban	34	1.47	1.27	0.61	2.86	0.61	0.82	1.06	1.84	2.72
	Rural	21	2.34	2.13	0.82	6.62	1.28	0.86	1.55	2.92	5.07

7.3 Descriptive statistics: Brake reaction times

Condition	Scenario	*N*	*Mean*	*Median*	*Minimum*	*Maximum*	*Standard deviation*	*5th percentile*	*25th percentile*	*75th percentile*	*95th percentile*
Baseline	Urban	0									
	Rural	12	4.44	4.58	3.46	5.13	0.47	-	4.15	4.74	-
Warning	Urban	26	2.18	2.13	1.14	2.93	0.51	1.20	1.92	2.69	2.90
	Rural	26	3.40	3.51	1.32	6.55	1.39	1.43	1.65	4.32	6.09

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Abbreviations

C2C-CC	CAR 2 CAR Communication Consortium
CMC	Connected Motorcycle Consortium
C-ITS	Cooperative Intelligent Transport Systems
DDA	Dashboard Downward Angle
FT	Feature Team
GIDAS	German In-Depth Accident Study
GLOSA	Green Light Optimised Speed Advisory
HMI	Human-Machine Interface
ITS	Intelligent Transport Systems
Mdn	Median
OEM	Original Equipment Manufacturer
PTW	Powered Two-Wheeler
TFT	Thin-film transistor (display)
TTA	Time-to-arrival
TTC	Time-to-collision
V2X	Vehicle-to-X
WIVW	Würzburger Institut für Verkehrswissenschaften (Wuerzburg Institute for Traffic Sciences)