Eine Frage der Zeit: Untersuchung des Warnzeitpunkts von Motorradfahrer-Assistenzsystemen

A matter of time: investigation of warning timing for motorcycle rider assistance systems

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Zusammenfassung

Die Forschung zur optimierten Gestaltung von Fahrerbenachrichtigungen für motorisierte Zweiräder ist von anhaltender Bedeutung, da immer mehr Fahrerassistenzsysteme, die auf Warnungen angewiesen sind, Verbreitung finden (z. B. Frontkollisionswarnung) oder kurz vor der Serienproduktion stehen.

Das Connected Motorcycle Consortium (CMC) setzte seine Forschungsaktivitäten zu diesem Thema mit einer Probandenstudie fort, welche Effekte unterschiedlicher Warnzeitpunkte untersuchte. $N = 30$ Fahrer absolvierten eine 35 km lange Testfahrt auf dem dynamischen DESMORI-Motorradfahrsimulator des WIVW. Das virtuelle Motorrad war mit einer C-ITS-Anwendung (Cooperative Intelligent Transport System) ausgestattet, welche die Fahrer vor lokalen Gefahren warnt. Dies können bspw. liegengebliebene Fahrzeuge auf der vorausliegenden Straße sein. Der Zeitpunkt der visuellen Warnung, die aus an den Spiegeln montierten LEDs bestand, wurde systematisch variiert. Als Auslösekriterium wurde die Zeit bis zur Kollision (sog. Time-to-Collision, TTC) zwischen 1,7 s und 3,2 s getestet. Die Effekte der unterschiedlichen Warnzeitpunkte wurden untereinander sowie in Bezug auf die Entwicklung der Situation in einem Szenario ohne Fahrerwarnung betrachtet.

Für das gegebene Szenario war die wahrgenommene Situationskritikalität bei jedem untersuchten Warnzeitpunkt (TTC = 1,7 s – 3,2 s) signifikant geringer als in der Vergleichsbedingung ohne Assistenzsystem. Eine Warnung im Bereich von TTC = 3,2 s verbesserte die Akzeptanz zusätzlich, da dieser Warnzeitpunkt im Mittel als perfekt angemessen wahrgenommen wurde. Die Ergebnisse zeigen zudem einen bedeutsamen Sicherheitsvorteil für die Warnauslösebedingungen von TTC = 2,2 s und früher. Die durchschnittlichen Reaktionszeiten lagen zwischen 700 ms und 1.100 ms. Eine Verzögerung in Form von Gas wegnehmen und Bremsen wurde eindeutig durch die Warnung selbst und unabhängig vom Zeitpunkt der Warnung ausgelöst. Diese neuen Erkenntnisse helfen bei der Aktualisierung von Modellen zum Motorradfahrverhalten, z. B. für Simulationszwecke. Darüber hinaus liefert die Studie den Herstellern empirische Belege für die angemessene, nutzerzentrierte und effiziente Warnkonzeptgestaltung. Dies wiederum sollte sich positiv auf die Verkehrssicherheit auswirken.

Abstract

Research into the optimized design of powered two-wheeler rider notifications is of continuing relevance as more advanced rider assistance systems relying on warnings are being introduced (e.g., Forward Collision Warning) or are on their way to series production.

The Connected Motorcycle Consortium (CMC) continued its research activities on this topic with a participant study investigating the temporal aspects of warnings. *N* = 30 riders completed a 35 km test ride on WIVW's dynamic DESMORI motorcycle riding simulator. The virtual motorcycle was equipped with a Cooperative Intelligent Transport System (C-ITS) application that alerts the riders of local hazards, such as a broken-down vehicle on the road ahead. The timing of the visual warning, which consisted of mirror-mounted LEDs, was systematically varied between a Time-to-Collision (TTC) based trigger of 1.7 s and 3.2 s. The different warning timings were set in relation to the evolution of the situation in a baseline scenario without any rider warning.

For the given scenario, significant safety benefits in terms of reduced situation criticality were measured for any warning timing (TTC = 1.7 s – 3.2 s). Providing a warning in the range of TTC = 3.2 s improves acceptance as it is perceived as perfectly timed, on average. The results show a significant safety benefit for the warning trigger conditions of TTC = 2.2 s and earlier. Average reaction times ranged from 700 ms to 1100 ms. Throttle off and braking were clearly triggered by the warning itself and independent of the warning timing. These new findings help to update rider behaviour models, e.g., for simulation purposes. Further, the outcome provides arguments and evidence for the implementation of appropriate warning timing, thereby supporting OEMs in designing their applications in a user-centred and efficient manner. This in turn should lead to improved road safety.

A matter of time: investigation of warning timing for motorcycle rider assistance systems

1. Background & Motivation

The CMC has conducted several scientific studies to better understand the appropriate design of rider warnings (e.g., Will, Hammer, Merkel, & Pleß, 2022). This study continues this series of experiments with a focus on the temporal characteristics of rider imminent crash warnings (ICW).

The potentially highest safety benefit of an advanced rider assistance system (ARAS) can be expected when the rider does not recognize the potential threat by himself/ herself. In this case, the warning needs to alert the rider, direct their attention and - for more imminent crash warnings – provoke an avoidance manoeuvre. For this purpose, the appropriate timing of the warning is very important. It is obvious that this involves technical discussions about at which point in time any sensor technology can detect and trigger a reliable warning. Yet, the focus in this study is on the human factors side: How is rider behaviour affected by different warning timings?

The *optimized warning* timing shall provoke a measurable safety benefit while being issued as late as possible. The later the warning is triggered, the more confident is the detection algorithm that a potentially dangerous situation is about to occur. It provides sufficient time for a rider reaction (time to perceive, recognize, process an information and initiate an action) and an avoidance manoeuvre (time to stop the vehicle / avoid the obstacle). *Too early* warnings may be perceived as unnecessary/ false positive warnings and decrease trust in the system. *Too late* warnings may result in too late responses, missings / false negatives or even crashes.

In order to understand this relation between warning timing and rider reactions a participant study was conducted. N = 30 riders completed a test course on rural roads on a motorcycle simulator. The virtual motorcycle was equipped with a C-ITS (Cooperative Intelligent Transport System) application able to detect local hazards such as a broken-down vehicle. The warning timing was varied in four levels based on the real-time-calculated TTC:

TTC = 1.7 s vs. TTC = 2.2 s vs. TTC = 2.7 s vs. TTC = 3.2 s

Apart from questionnaire data, rider reactions in terms of reaction times from warning onset to throttle off and brake onset were analysed. It is important to mention that this study provides new empirical evidence for point estimates and distributions of reaction times towards imminent crash warnings (ICW). It is also important to notice that the distribution of reaction times towards a 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 …). At this stage, 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 results of this study can be used to design trigger algorithms of ARAS effectively in order to increase its safety benefit while raising acceptance and trust among riders.

2. Methods

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 (dof) hydraulic Stewart platform. The mockup enables the rider to interact with fully realistic controls, such as a 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 at 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 floor projection and 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.

Figure 1: DESMORI dynamic motorcycle riding simulator at WIVW.

Test course

The test course had a total length of 35 km, which took approx. 30 - 35 minutes to complete the course. It consisted of different modules on rural roads. As can be seen in Figure 2, there were two rural test scenarios, which each were experienced four times per participant (the geometry and resulting trajectories etc. were identical, while the virtual environment was changing to avoid any kind of expectations). In the first scenario, the obstacle was a broken-down passenger car blocking the right half of the PTW's lane. In the second scenario, the obstacle was a recently broken-down motorbike still blocking the left half of the PTW's lane. This design was chosen to motivate any kind of deceleration as response to the warning, which still did not require coming to standstill. Swerving as alternative avoidance manoeuvre would need a situation-specific assessment of the available direction. This takes some time and time in turn increases the chance of deceleration as initial response. From an ethical point of view, the test scenarios were scripted to leave enough space on the PTW's lane to avoid the obstacle without entering the opposing lane or leaving the road.

The order of the scenarios was randomly selected. Both test scenarios had in common that the conflict partner was obscured by a field of ground fog and therefore could not be seen by the rider in the moment when the warning was emitted. To make the appearance of the ground fog more realistic the overall weather conditions were set to a cloudy scenario with a shortened visual range. Additionally, there was a rural baseline scenario without warning, but otherwise comparable conditions. During the test course, there were about twice as much dummy scenarios as test scenarios. These dummy scenarios were characterized by identical geometry, ground fog appearance etc., while no critical event happened. The aim of these scenarios was to avoid that the ground fog becomes a trigger for critical events by itself.

Figure 2: Local Hazard Warnings: PTW (left) and passenger car (right) test scenario with obscured obstacles due to ground fog (upper row) and recognizable obstacles when approaching the test scenarios (lower row).

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. It was followed by a 15-minutes ride in a rural environment to familiarize with the virtual vehicle control again. At the end of this ride the participants experienced the test scenario for the first time without a warning for baseline measurements. Following the successful completion of this ride, 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. The communicated purpose of the study was to receive riders' feedback on this new type of safety application. The riders were not informed about the focus of the study lying on effects of different levels of warning timing. However, all participants were aware that variations in reception due to peripheral buildings, weather conditions, etc. could affect the warning timing. In order to ensure trust in the application, which increases the likelihood of a reaction towards the warning, there were only true positives in the test ride. After each test scenario, the riders answered three questions while riding. At the end of the appointment, a final inquiry was conducted and riders received an expense allowance.

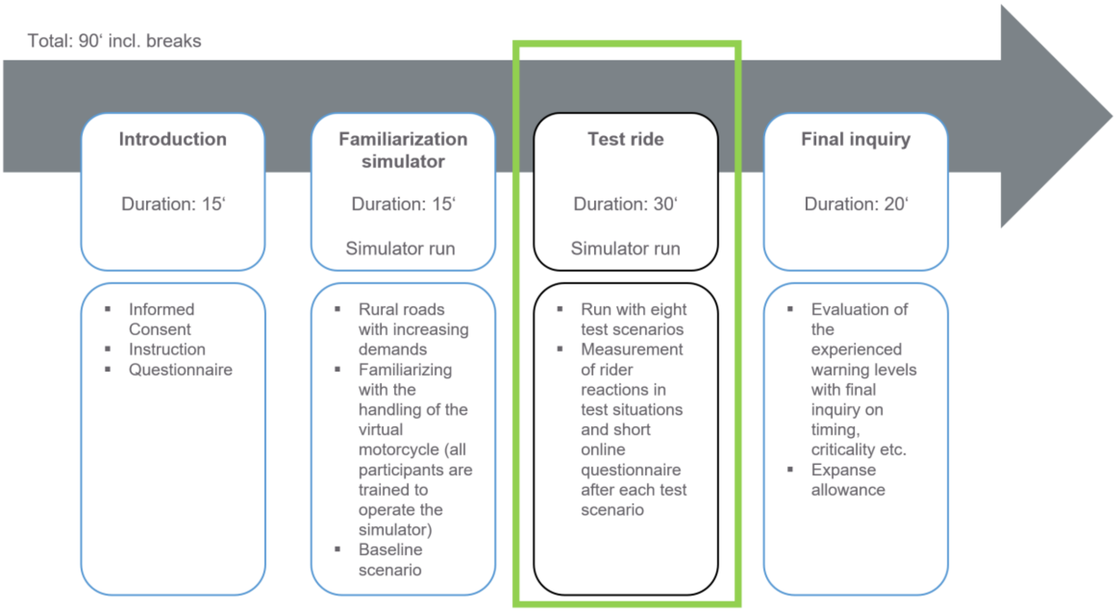

Figure 3: Schematic of the study procedure

Rider notification

The riders were notified by a visual warning with mirror-mounted LEDs. This type of warning represents a PTW-fixed visual solution. Eight Arduino-controlled LEDs with approximately 1000 mcd luminous intensity per LED were fixed on top of each mirror (see Figure 4). The LEDs provide a visual warning to the rider by flashing for 3 s with a constant frequency of 2 Hz in the colour red. The warning was designed in accordance with CMC’s Basic Specification on HMIs referring to ISO2575: Road vehicles — Symbols for controls, indicators and tell-tales (ISO, 2021a) and ISO6727: Road vehicles — Motorcycles — Symbols for controls, indicators and tell-tales (ISO, 2021b). There were four different warning timings to be compared: Time-to-collision (TTC) = 1,7 s vs. 2,2 s vs. 2,7 s vs. 3,2 s, which were experienced twice per participant. The order of the warning timings was permuted in eight versions to avoid sequence effects.

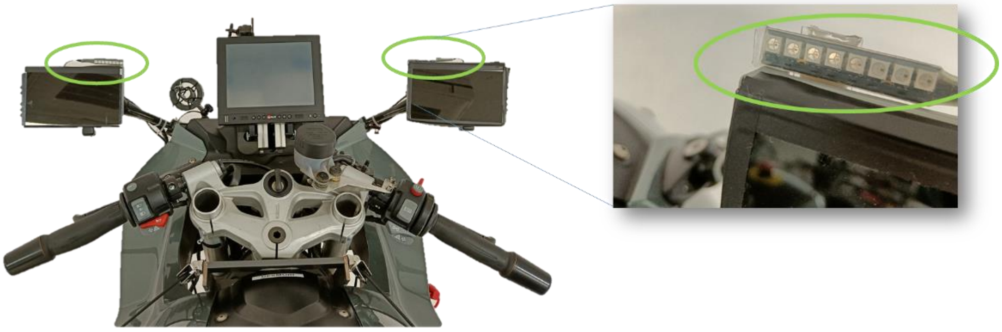

Figure 4: Simulator mockup with warning LEDs mounted on top of the mirrors.

Measures and statistical analysis

In addition to the questionnaire data, two different types of reactions were analysed. Schematic representations of these measures can be found in Figure 5.

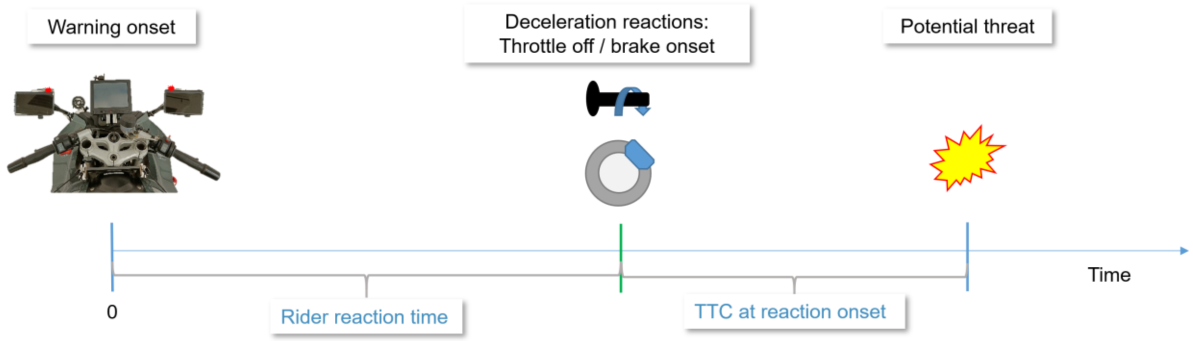

Figure 5: Schematic representation of different possibilities to calculate reaction times.

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

1. *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.
2. *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. Any rider response later than 300 ms after warning onset was regarded as response to the warning. Further, some riders start braking with the front brake without a full release of the throttle.

In addition to the vehicle dynamics data, subjective measures were gathered. After every test situation the riders were asked whether the C-ITS application emitted a warning. If the answer was positive, the riders were asked how they did react. This information helps to interpret the riding data.

way too early			too early			perfect	too late			way too late		
-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6

Figure 6: 13-point verbal categorisation scale.

For instance, a rider may reply that he / she recognised the warning, but decided not to brake, as there was enough space on his / her lane to pass the potential conflict situation. The second question targeted the perceived warning timing. The answers were given on a 13-point categorisation scale as shown in Figure 6. The third question targeted the perceived criticality of the experienced situation. The answers were given on the situation criticality scale as displayed in Figure 7. All three questions were answered while riding.

Figure 7: Situation criticality scale. English version translated from Neukum, Lübbeke, Krüger, Mayser, and Steinle (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 categorisation scale ranging from ‘0 impossible’ to ’15 very good’. Furthermore, they were asked how likely they would want such kind of warning also on a 16-point categorisation scale ranging from ‘0 not at all’ to ’15 very likely’.

As the perception of time may vary based on the experienced situation or the point in time when the warning was actually recognized, the riders should estimate the time they had left between the warning onset and the potential thread. They were asked whether they prefer an early warning even if they cannot relate it immediately to a potential thread or if they prefer a late warning even if they might have already seen the potential thread and reacted to it. Both questions were answered on a seven-point scale from ‘-3 strongly disagree’ to ‘+3 strongly agree’.

Different types of graphs are used to display the distribution of data. Scatterplots show the raw data. Boxplots display the central 50 % of data within the box. The central line is the median value. Whiskers show 1.5-times the inter-quartile range (IQR i.e., height of the box) as a measure of variance in the data set. Alternatively, the whisker length is limited to the observed minimum or maximum if those lie below 1.5-times IQR. If those lie outside 1.5-times IQR the values are marked as circles or stars (outside 3-times IQR) indicating outliers and extreme values.

Panel description

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.

A total of *N* = 30 riders participated in the study, while *n* = 4 were female. The panel covers a wide spread of different age groups and levels of riding experience as can be seen in Table 1. 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: Participant panel description (N = 30 with n = 4 female).

	Mean	***Standard deviation***	***Minimum***	***Maximum***
Age in years	36	12	19	69
Motorcycle mileage covered during the last 12 months in km	3 926	2 748	0	11 000
Motorcycle mileage during lifetime in km	65 103	73 379	2 000	300 000

3. Results

The analysed segments start with the warning onset and stop when the rider has passed the potentially critical situation. For the analysis in chapter 0 the rider response marks t_0. In total, there were N = 234 test scenarios recorded (20 riders x 8 test scenarios with 6 scenarios missing).

Table 2: Data set description.

Braking when arriving at the ground fog section (test scenario)	No braking 194 (82.9 %)	Braking 40 (17.1 %)
Throttle open when arriving at the ground fog section (test scenario)	Throttle open 156 (66.7 %)	Throttle off 78 (33.3 %)
Reactions earlier than 300 ms after warning onset	Brake onset 10	Throttle off 2

Out of these, a subset is used for the calculations (Table 2), which is always mentioned in the respective tables. The reduction occurs, when people were already decelerating before the warning was issued or within 300 ms after warning onset. These deceleration reactions would not be interpreted as response to the warning.

Throttle off

On average, the observed throttle off response is not significantly varying between warning timings (Figure 8). Reaction time median values lie between 667 ms and 750 ms and mean values lie between 697 ms and 1,019 ms.

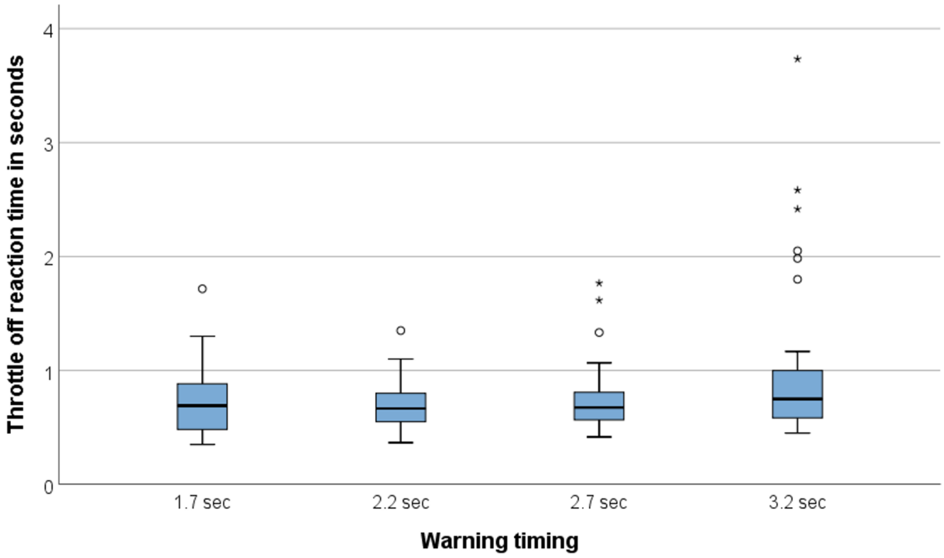

Figure 8: Boxplot of riders' throttle off rection times after warning onset as a function of warning timing.

Detailed descriptive statistics can be found in Table 3. There is an observable variation within all levels of warning timing (Figure 9). Tendentially, the maximal values increase with increasing warning time.

Table 3: Descriptive statistics on throttle off responses in ms.

Condition	Timing	*N*	*Mean*	*Median*	*Min*	*Max*	*SD*	*5th %ile*	*25th %ile*	*75th %ile*	*95th %ile*
Baseline	-										
Warning	1.7 s	26	744	692	350	1,717	324	362	479	883	1,571
	2.2 s	30	697	667	367	1,350	214	403	546	817	1,213
	2.7 s	36	747	675	417	1,767	300	431	567	813	1,639
	3.2 s	33	1,019	750	450	3,733	748	462	575	1,017	2,928

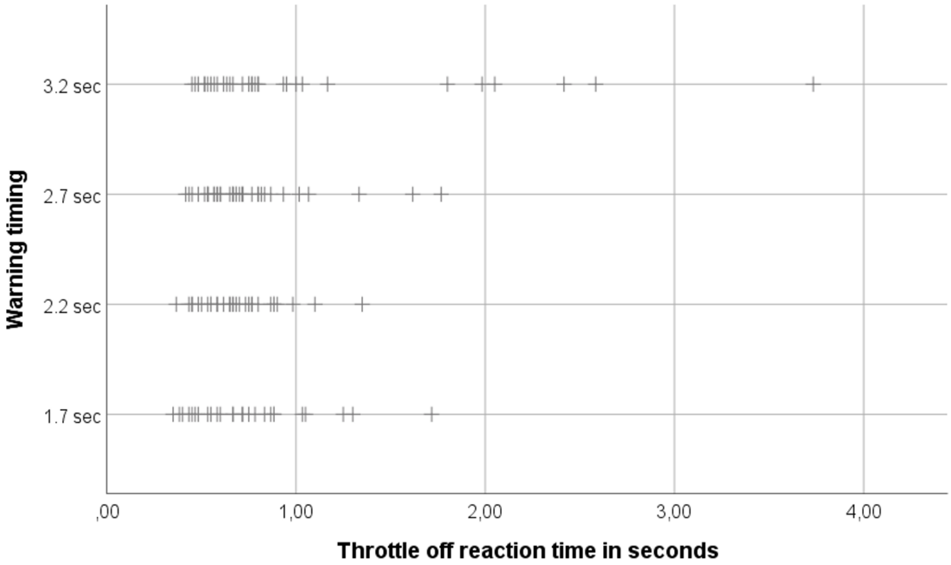

Figure 9: Riders' throttle off reaction times after warning onset as a function of warning timing.

Brake reaction

As for the throttle off responses, the observed brake onset is not significantly varying between warning timings (Figure 10). The reaction time means lie between 809 ms and 1,141 ms. The median values fall within the range of 792 ms to 858 ms. Detailed statistics can be found in Table 4.

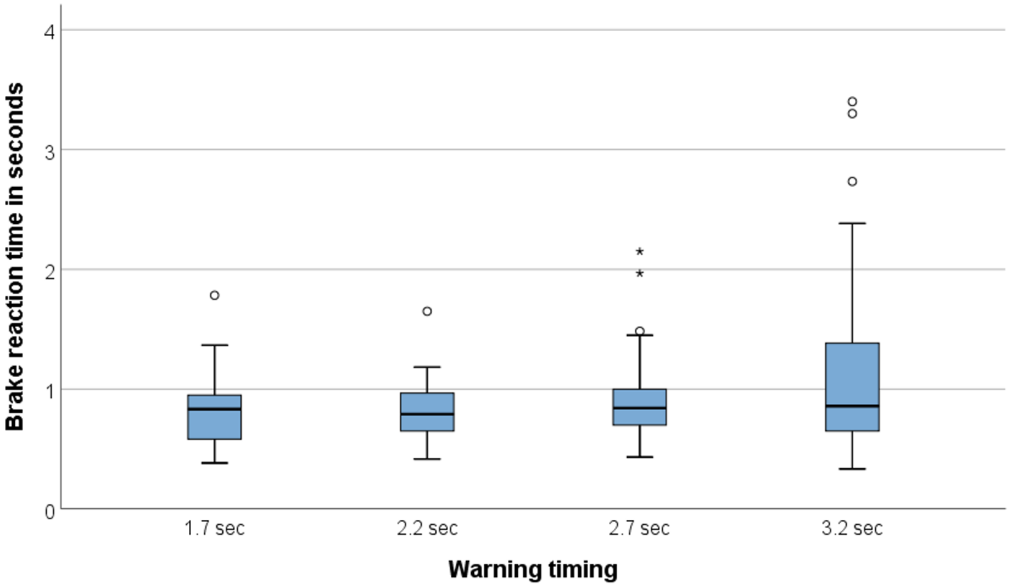

Figure 10: Boxplot of riders' brake reaction times after warning onset as a function of warning timing.

There is an observable variation within all levels of warning timing, again with tendentially increasing maximal values with increasing warning time (Figure 11).

Table 4: Descriptive statistics on brake responses in ms.

Condition	Timing	*N*	*Mean*	*Median*	*Min*	*Max*	*SD*	*5th %ile*	*25th %ile*	*75th %ile*	*95th %ile*
Baseline	-										
Warning	1.7 s	27	809	833	383	1,783	305	417	583	967	1,617
	2.2 s	34	824	792	417	1,650	258	417	642	979	1,300
	2.7 s	38	920	842	433	2,150	374	449	696	1,033	1,979
	3.2 s	44	1,141	858	333	3,400	725	371	633	1,417	3,158

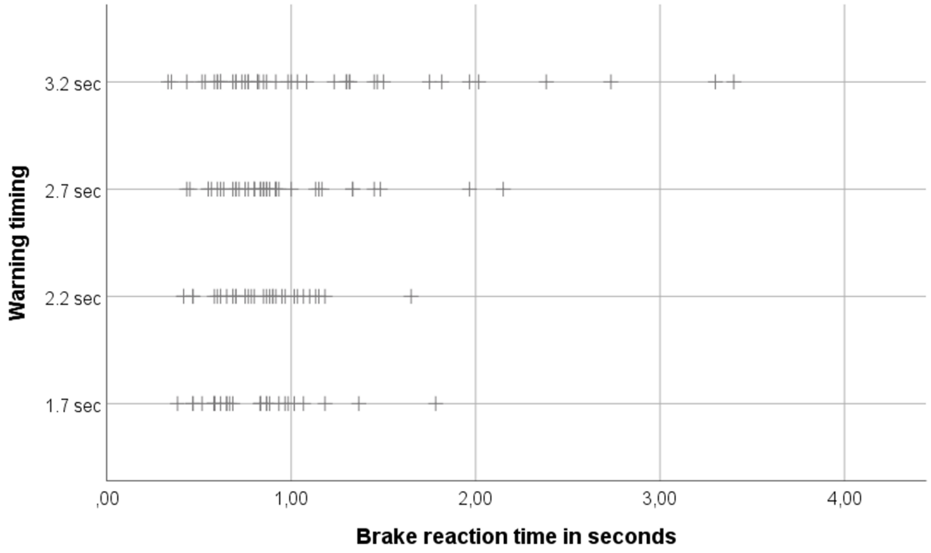

Figure 11: Riders' brake reaction times after warning onset as a function of warning timing.

Remaining time after reaction

The first reaction to occur (throttle off or brake onset) is used for the calculations. As the reaction times across warning levels were comparable, the remaining time to collision after the reaction varies significantly (Figure 12). The according descriptive statistics can be found in Table 5.

Table 5: Descriptive statistics on remaining TTC after rider reaction in ms.

Condition	**Timing**	***N***	***Mean***	***Median***	***Min***	***Max***	***SD***	***5th %ile***	***25th %ile***	***75th %ile***	***95th %ile***
Baseline	-	24	1,040	875	333	3,133	583	350	733	1,213	2,863
Warning	1.7 s	31	860	866	97	1,310	313	99	694	1,125	1,275
	2.2 s	38	1,405	1,421	646	1,835	245	913	1,260	1,563	1,824
	2.7 s	44	1,833	1,933	509	2,334	361	1,013	1,757	2,050	2,306
	3.2 s	48	2,084	2,348	358	2,907	693	465	1,859	2,574	2,828

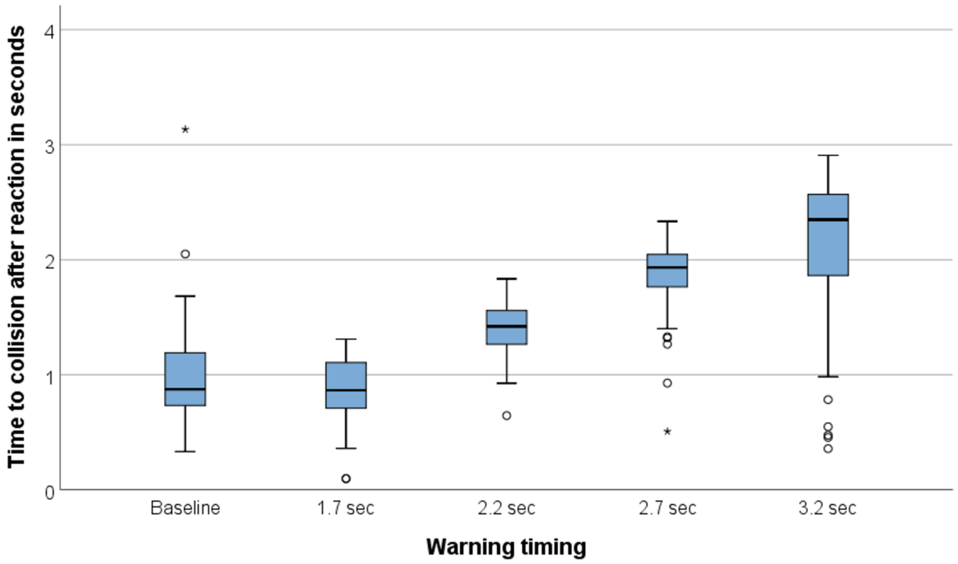

Figure 12: Boxplot of the remaining time to collision after the riders' first means of deceleration as a function of warning timing.

The earlier the warning, the more time available after the reaction has occurred.

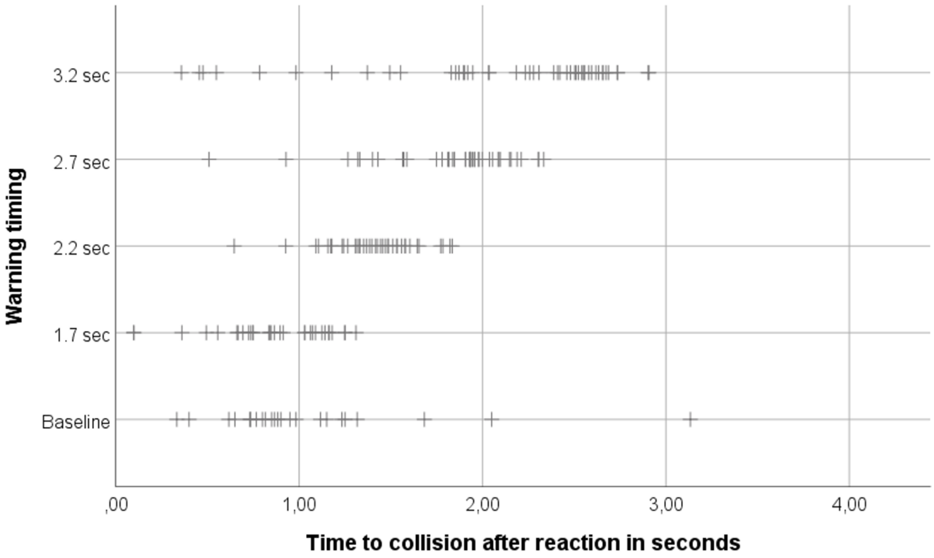

Figure 13: Remaining time to collision after the riders' first means of deceleration as a function of warning timing.

Baseline reactions are statistically comparable to reactions in the 1.7 s warning condition.

Subjective measures

All riders stated to have recognized the warning once it was issued (no missings). This is an important precondition to be met before interpreting other results as response to the warnings. As indicated in the final interview, on average, the participants rate the perceptibility of the red LED warning as good to very good. The clear majority of riders describe the warning concept as desirable to very desirable.

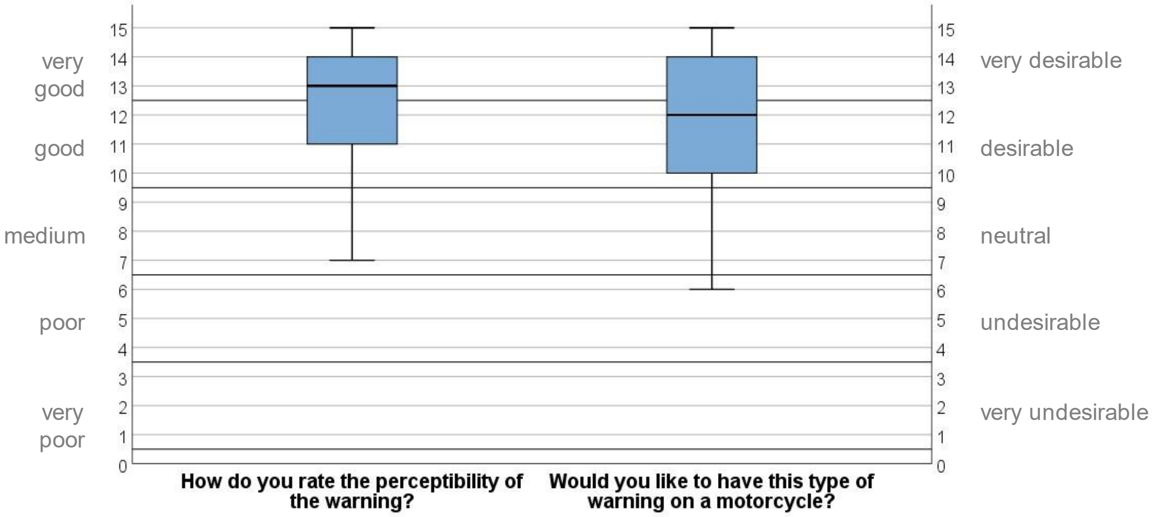

Figure 14: Rating of warning's perceptibility (left) and warning concept acceptance (right).

Once the warning was recognized, braking and avoiding the potential threat as response to the warning are the clearly dominating strategies (Figure 15). Some people state to first direct their attention voluntarily to the forward roadway, while others claim to let go off the throttle. Only rarely, people state to not react at all even if the warning was recognized. There is no changing pattern in the type of reaction over time.

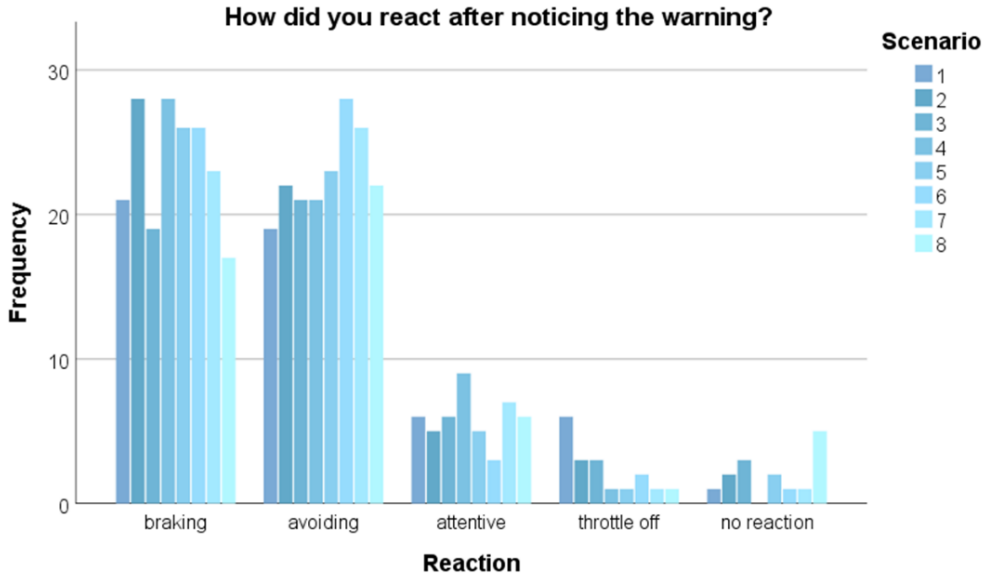

Figure 15: Claimed reactions as response to the warning for different scenarios.

Figure 16 shows the perceived situation criticality for the different test scenarios. As intended, all test scenarios created safety critical situations ranging from uncomfortable to dangerous. Any warning timing decreased the perceived criticality compared to the baseline without warning (*F*(1,25) = 38.27, *p* < .001, η_{partial} = .605). Moreover, any timing earlier than 1.7 s tendentially decreases the experienced situation criticality even further.

Figure 16: Situation criticality rating for baseline and different warning timings.

A repeated presentation of one specific warning timing leads to a less critically perceived situation (first contact vs. second contact: *F*(1,25) = 66.29, *p* < .001, η_{partial} = .726). This pattern for first contact (1) and second contact (2) can be seen in Figure 17.

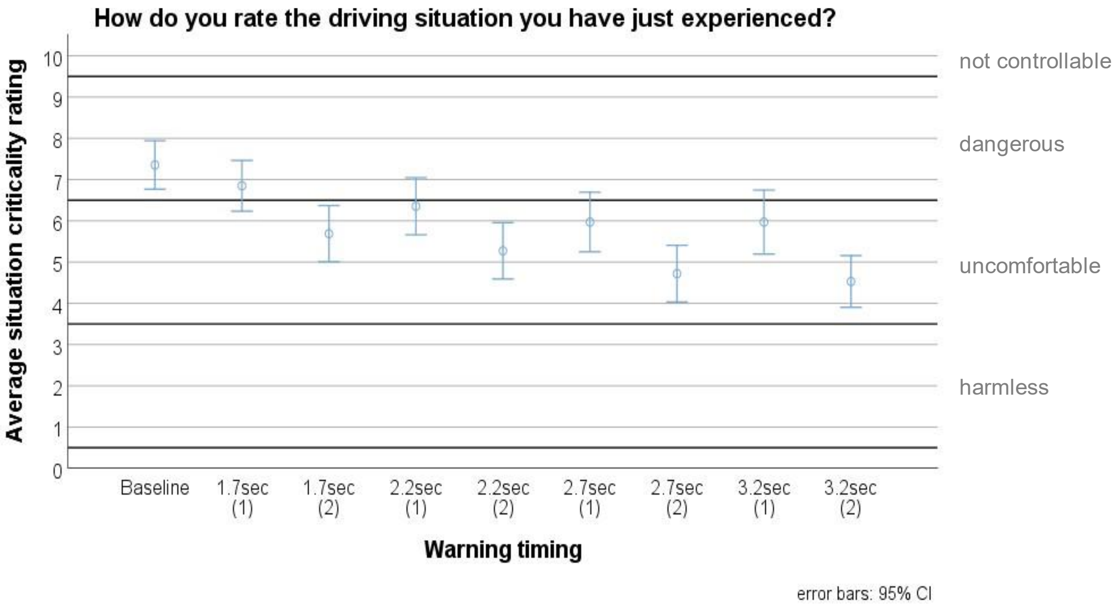

Figure 17: Situation criticality rating for baseline and all warning scenarios.

On average, triggering a warning in the given scenario at TTC = 1.7 s results in people rating this warning as coming too late (Figure 18). Even 2.2 s and 2.7 s are on average perceived as slightly too late and only 3.2 s receives a perfect rating. Yet, any warning timing earlier than 1.7 s improves the rating significantly. Yet, one must recognize that there is a certain spread. Once again, the second contact scenarios with the identical warning timing are perceived as being more appropriate (Figure 19).

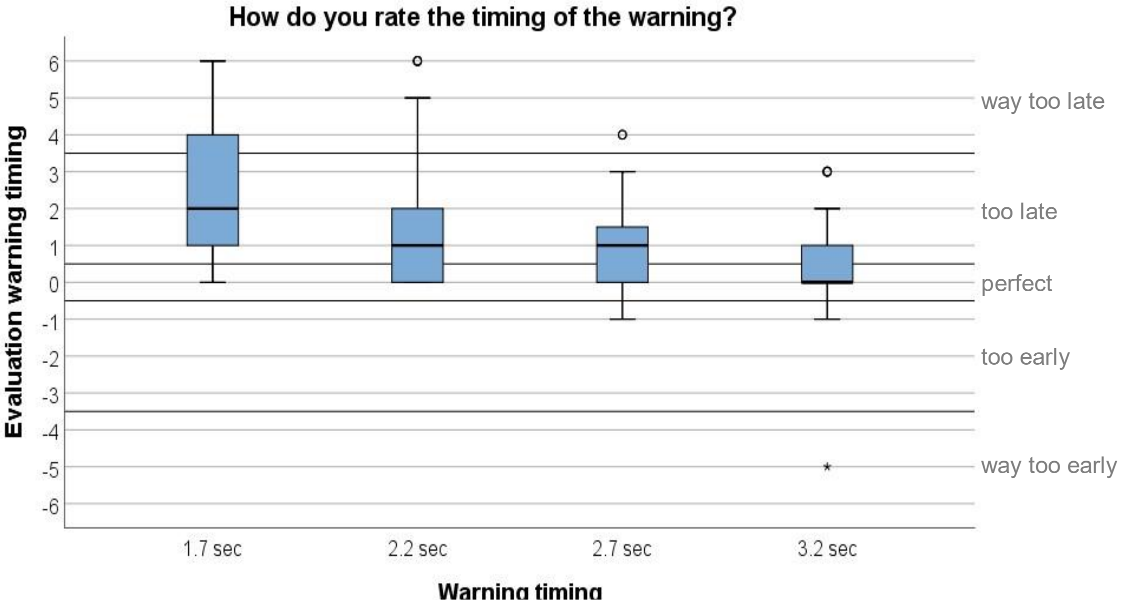

Figure 18: Rating of the different warning timings.

Additionally, no participant perceives any of the warnings as coming too early.

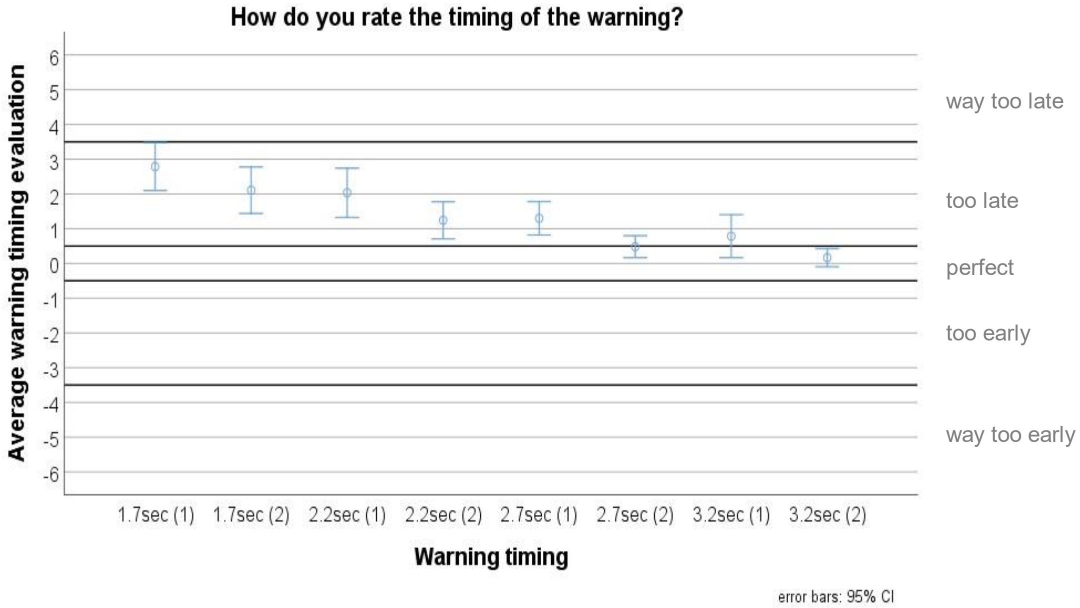

Figure 19: Rating of the different warning timings for all warning scenarios.

At the end of the study, the participants were asked if they would prefer an earlier or a later warning and what range of warning timings, they think that they have experienced in the study. On average, riders tend to underestimate the remaining time from warning onset to arrival at the hazardous situation (Figure 20). Yet, the distribution for minimum times is right-skewed indicating an underestimation by the majority of riders. The maximum times distribution is left-skewed showing that the majority of people estimate to have even more time than they actually had.

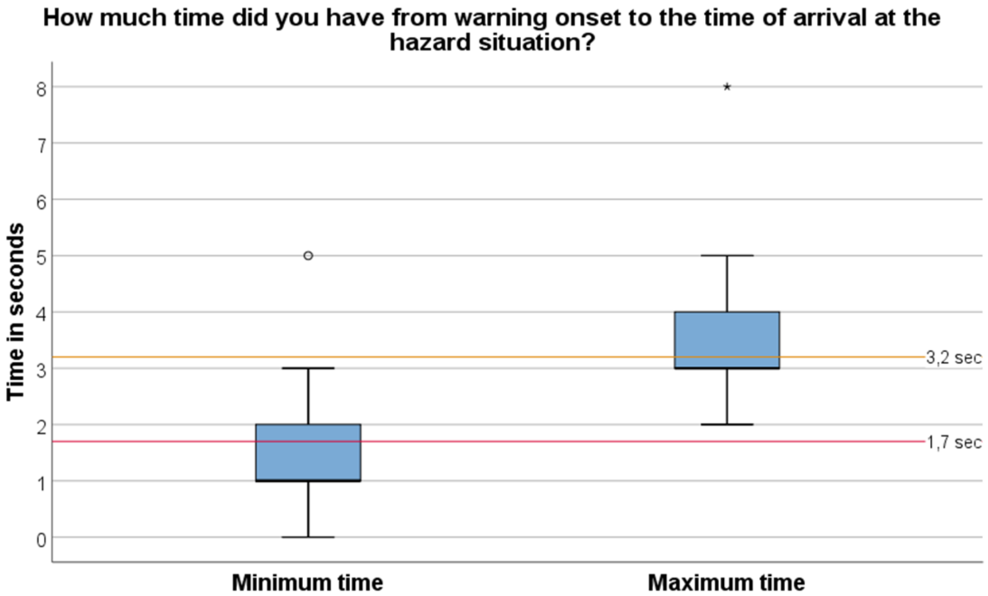

Figure 20: Estimated range of the experienced warning timings (an outlier value of 20 s for maximum time is not displayed).

In terms of personal preference, participants were fairly consistent in their preference for early warnings (Figure 21). They accept the fact that a warning is not immediately associated with a recognizable threat.

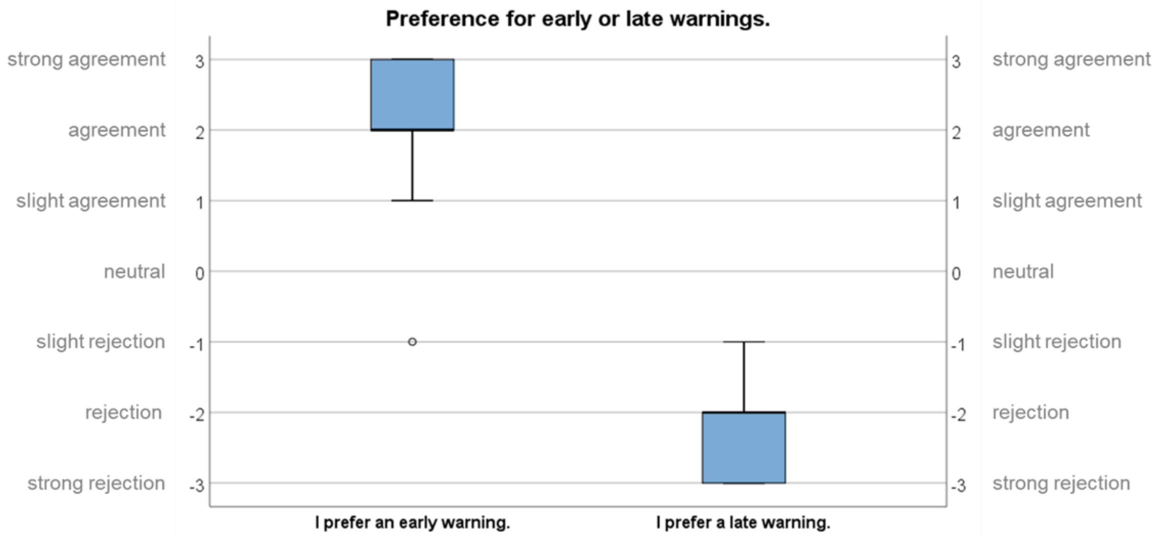

Figure 21: Preference for an early warning (left) or a late warning (right).

4. Discussion

This study investigated the effects of different levels of warning timing on rider reactions and the subjectively experienced safety benefit.

Questionnaire data

- **Riders prefer to have earlier warnings** for the given imminent crash warning scenario. They state to accept that it might not be possible to reliably attribute the warning to an already recognizable threat.
- For the given scenario, significant safety benefits in terms of **decreased situation criticality** were measured for any warning timing between TTC = 1.7 s and TTC = 3.2 s.
- Yet, providing a warning in with a **TTC = 3.2 s improves the acceptance even further** as it is perceived as being perfectly timed (not too early and not too late), on average.
- **Habituation** effect: once a level of warning timing has been experienced, the following scenarios with identical warning timing are perceived as less critical.
- The **effects of timing are exaggerated**. For late warnings, riders perceive to have even less time. For early warnings people think that they have had even more time than they actually had.

Deceleration reactions

- On average, throttle off responses were observed **700 ms – 1,000 ms** after warning onset, braking responses after **800 ms – 1,100 ms**.
- Across levels of warning timing the **reaction times were comparable**.
- As a result, the **time** remaining between deceleration and potential hazard **increased with earlier warnings**.
- Observed variations in reaction times and increasing maximum reaction times with increasing warning time may indicate some **delay between warning onset and warning recognition**, and a **voluntary delay**. The latter may indicate that riders are alert to the potential hazard, but wait to slow down until they recognise the need to do so.

Comparison with passenger car driver reactions

The previous CMC studies were interested in how similar the reactions of PTW riders are to those of car drivers. For a given simulator setup and for imminent crash warnings, the reactions seem to be closer than for advisory notifications. For example, guidelines such as the ISO 15623:2013 (ISO, 2013) assume minimum driver reaction times of 0.4 s and maximum reaction times of 1.5 s before initiating a response to a Forward Collision Warning. The SAE J2400 allows a maximum time of 1.18 s between the onset of the warning and the start of the driver response (SAE, 2003). Other study results from passenger car simulators, such as Winkler, Kazazi, and Vollrath (2015) measured 0.86 s on average as brake reaction time with a purely visual generic warning in a HUD in a time-critical crossing scenario with a pedestrian. These values are in a comparable range to the observations in the present study.

Limitations and advantages of the chosen approach

The study setup worked well. It was expected that a certain proportion of riders would slow down in the fog due to limited visibility. Yet, there were enough reactions as response to the warning to base statistical analysis on. In reality, a major contributing factor to crashes is human error. The truly critical situations arise when riders are either visually or cognitively distracted and therefore fail to recognize a potentially critical situation in time. This is where assistance systems can show their biggest benefit. The study design aimed to simulate this visual distraction by obscuring the potential threat with a field of ground fog. Elsewise, one would measure reactions as response to the threat instead of the warning. Even if dummy scenarios were included and the whole test ride was completed under adverse weather conditions, some participants may already have been more attentive or riding more slowly when approaching a field of ground fog. This might lead to an overestimation of reaction times (people react faster, because they are prepared). Given the research question at hand, the interest lies in the comparison between warning timings. A potential bias would occur across all conditions so that the relative measures can still be interpreted.

5. Conclusion

In general, the study setup worked well as the riders experienced critical situations, as they recognized all warnings and as they chose appropriate action.

An important finding is that the type of warning has a significant impact on the rider's response in the specific scenario. Red flashing LEDs clearly indicate an imminent threat and contribute to the observed stable reaction times across warning timing levels. Coding the warning criticality with the appropriate warning design (advisory vs. imminent crash, etc.) therefore becomes very important. This design choice shapes the rider's response and is related to the acceptance of the system. For example, the same LED warning concept, but with a slightly slower flash rate of 1.5 Hz, an earlier warning time of 3s before the threat becomes visible and an amber colour, was used in a previous CMC study (RRT II). This conveyed a warning with an advisory notification character. It elicited mean deceleration responses of 1,470 ms (urban scenario) and 2,340 ms (rural scenario) instead of mean responses between 700 ms and 1,000 ms in this study. However, in the different studies, riders perceived a match between the visual warning character and their required response and rated the different warnings as appropriate/ desirable for the situation experienced.

Another important aspect was that the riders' reactions in the 1.7 s warning condition and the baseline condition without warning were comparable. The warning was given at about the same time as the potential hazard was perceived. Consequently, the 1.7 s warning did not provide any safety benefit in terms of reaction time, as the riders' focus was on the road ahead anyway. Of course, even this late warning would still be beneficial if the riders were distracted and did not recognise the potential threat. Regardless of this lack of reaction time benefit, the 1.7 s warning increased perceived safety and acceptance. Riders who trusted the warning were shown to actually slowdown in response to the warning. They did not just shift their attention, they actively decelerated. This gave them more time to reach the potential hazard in the warning conditions between 2.2 s and 3.2 s. However, even a late warning (in this scenario TTC = 1.7 s), given simultaneously with the visibility of the potential hazard, can be recommended because the riders felt safer, even though there was no benefit in terms of reaction times.

Interesting topics that still remain a blind spot in the scientific literature related to PTW safety are the right way to deal with false positive warnings (system confidence, changing reactions, etc.) and rider reaction times measured in a real riding setup (relative and absolute validity). The knowledge gained from this study will help to understand riders' reactions to differently timed warnings and will allow for beneficial assistance system design and more appropriate rider behaviour modelling in simulation.

6. Acknowledgements

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