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Warning design for motorcycle safety enhancement in sight obstruction scenarios based on cooperative intelligent transport systems

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Abstract

Motorcycles are often at more risk of being involved in crashes, particularly in the presence of line-of-sight obstructions. Cooperative Intelligent Transport System (C-ITS) technologies enable road behaviour alerts through wireless communication, promoting safer actions However, little emphasis has been conducted to explore how C-ITS-based motorcycle warning systems optimally provide crash alerts to maximise the rider's incident avoidance response. This study aims to enhance motorcycle rider safety by connecting riders with infrastructure, cloud, and vehicle data, providing warnings related to safety issues. Collaborating with over 30 riders, we developed cautionary and imminent warnings for various Human-Machine Interfaces (HMIs). We deployed the warning system in a motorcycle simulator and conducted trials with 25 riders to investigate the relationship between road warnings, timing, and rider reaction. The results indicated that delivering cautionary warnings at 7 seconds before the potential hazards represent the optimal configuration for this warning system.

1 Introduction

Motorcyclists are among the most vulnerable road users. Although motorcycle crashes occur as often as other types of accidents (Al-Bayati, Shakoree, & Ramadan, 2021), riders face a much higher risk of injury or death. The likelihood of being killed on the road is between twenty and thirty-two times greater for motorcyclists than for car occupants (Lisboa et al., 2024).

Several factors contribute to this heightened risk for motorcyclists and other powered two-wheeler users. Unlike car drivers, motorcycle riders experience faster movements, ride lighter vehicles, and are more vulnerable due to a lack of common safety features such as seatbelt or airbags, all of which limit their ability to react to sudden changes in visibility (Yousif et al., 2020). Motorcycles can be harder for other road users to see, increasing the chance they will be missed. This makes it essential for riders to stay highly alert to their surroundings (Vlahogianni, Yannis, & Golias, 2012), especially in sight obstruction scenarios.

C-ITS enables the reliable exchange of standardised messages between vehicles and infrastructure. This improves situational awareness and supports better decisions making on the road (Javed & Hamida, 2016). C-ITS can assist riders by issuing warnings before situations become critical, giving them more time to respond. The potential of C-ITS for motorcycles is clear, as they are an integral part of the transport ecosystem (Santa et al., 2016). Studies show that early warnings for motorcyclists reduce the risk of crashes (Phan et al., 2010).

For C-ITS warnings to be accepted, they must integrate naturally within the riding experience. Riders should be able to keep their attention on the road. If alerts are not well designed, delivered too late or too early, go unnoticed or distract, riders will either not benefit, or they will reject the system.

Taking this into account, we designed and evaluated auditory, haptic, and visual warnings across seven Human Machine Interface (HMI) devices utilising a user-centered approach.

This involved a pre-design market scan, and a co-design session with 32 riders to refine the warnings. We then tested a simulator prototype with 25 riders to assess three different warning timings across two scenarios, identifying optimal timing for rider response.

This research makes the following key contributions:

The main innovation of this work is its user-centered design approach. To the best of our knowledge, this study is the first to investigate the most effective way to communicate warnings to motorcyclists using seven different HMI devices that deliver various types of warnings, including auditory, tactile, and visual signals. We incorporated riders' feedback to design warnings that they are most likely to perceive effectively. We believe this approach can significantly improve how riders interact with HMI devices, enhance their road awareness, and improve rider safety.

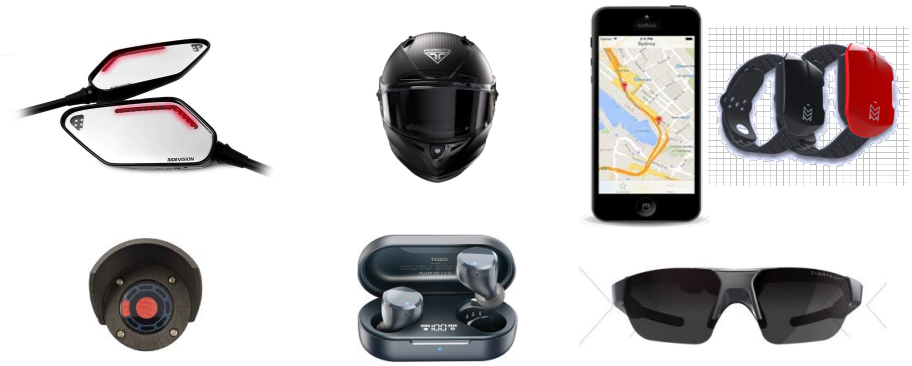
This study provides the first empirical evidence on how different warning timings affect motorcyclists' reaction to crash warnings. By systematically varying the timing of C-ITS alerts across three levels of warning timing, we identified an optimal window that balances early detection with timely rider response. This optimised timing improves the likelihood that riders have sufficient time to perceive, process, and act on warnings, while avoiding the drawbacks of alerts that are either too early or too late. These findings establish a critical foundation for designing C-ITS warnings tailored to motorcyclists' unique needs and response behaviours.

2 Preliminary design and development of motorcycle warnings

2.1 Exploring warning delivery options

Given the need to seamlessly integrate warnings into the riding experience, we conducted targeted market research and industry engagement to identify feasible HMI solutions for motorcyclists. Warning modalities were categorised into three primary types: auditory, visual, and haptic. We contacted over 20 global and Australian vendors of potential HMI technologies and established collaborations with six, to adapt their devices for C-ITS warning delivery. This process resulted in the prototyping of seven HMI devices, including smart helmets, smartphone-based applications, LED-integrated mirrors, dashboard alerts, audio-based systems, and haptic wristbands (Figure 1).

Figure 1: Prototyped HMI devices.



2.2 Design considerations for effective motorcycle warning communication

The development of warning systems for motorcycles has gained increasing attention in recent years, with several industry and academic initiatives exploring ways to deliver timely, effective alerts to riders. Studies consistently show that motorcycles' unique dynamics and exposure require dedicated HMI solutions that differ from systems designed for passenger cars. Each of sensory channels for communicating warnings visual, auditory, and haptic cues have advantages and limitations:

Auditory warnings, which can be delivered through helmet speakers or Bluetooth headsets, are valued for enabling riders to keep their eyes on the road. It has been evaluated by several studies (Di Stasi et al., 2010; Pieve et al., 2009; Song et al., 2017; Touliou et al., 2012). However, studies show their effectiveness can be compromised by engine and wind noise, especially at higher speeds (Haasper & Vallese, 2009). For example, Savino et al. (2020) reviewed active safety systems for motorcycles and highlighted limitations of purely auditory warnings in real-world conditions. Another major limitation of audible interfaces lies in how to deliver directional information based on simple tones. Using simple speech such as ‘‘left,” ‘‘front,” and ‘‘intersection” or combining other sensory channels such as visual or haptic could address these limitations.

Haptic interfaces are also an important way to provide warning information to motorcyclists. Haptic interfaces can be presented in different device forms, including haptic handles, haptic gloves (Biral et al., 2010; Huth et al., 2012), wristbands (Song et al., 2017) and helmets (Touliou et al., 2012). Haptic alerts are increasingly recommended due to their ability to immediately capture rider attention without requiring visual diversion. Pieve et al. (2009) demonstrated that vibration-based warnings could significantly reduce riders' response times in emergency scenarios. Further, Will and Pleß (2023) provided empirical evidence that haptic warnings can prompt quicker throttle-off and brake reactions than auditory or visual cues alone. Vibration patterns need further investigation regarding recognisability and acceptability in a real riding setting when there are more disturbances from engine vibration or wind pressure (Diederichs et al., 2010).

Visual signals, such as dashboard indicators, helmet head-up displays, or LED mirror lights, are widely used in motorcycle crash warning systems (Motorrad, 2023; Touliou et al., 2012). Studies have found that generally, riders prefer warning information to be presented with icons or short words with head-up displays (Ito et al., 2018; Jenkins & Young, 2016). The application of visual interfaces to hazard warning has been investigated in existing studies with the helmet and mirror in three representative hazardous situations (i.e., intersection, overtaking, braking) (Song et al., 2017). However, they carry risks of distraction if poorly placed or overly complex. Schwarz and Fastenmeier (2018) showed that spatial referencing in visual warnings can reduce unnecessary driver responses but also cautioned that excessive or poorly timed visual warnings may undermine trust in the system.

The combination of the three sensory channels has been shown to outperform a single sensory channel in warning delivery. For example, audible & visual warnings have higher detection rates and result in a better understanding of the warning content (urgency and direction of threat) than audible warnings alone in hazardous situations (Pieve et al., 2009). Generally, multi-sensory warnings have the highest acceptance and objectively better rider behaviour in terms of reaction time (Valtolina et al., 2011).

International standards such as ISO15008, ISO2575, and ISO6727 define design requirements for visual displays and symbols, underscoring the need for legibility and minimal distraction. The Connected Motorcycle Consortium (CMC, 2020) provides additional guidelines on multi-modal warning systems, recommending the integration of tactile, auditory, and visual channels for motorcycles.

Research supports the use of two-stage warnings to communicate hazard urgency: Cautionary Warnings (CW) and Imminent Warnings (IW). For instance, Will et al. (2023) examined how different warning timings affect rider response, finding that optimal timing can significantly improve reaction times while avoiding false positives that diminish trust. Naujoks et al. (2015) found advisory warnings about hidden hazards to be effective, particularly when warnings were delivered before the situation became critical.

2.3 Initial warnings design

Based on the above findings, our initial design phase systematically assessed auditory, tactile, and visual warnings across seven HMI devices split between on-bike solutions (e.g., dashboard, LEDs mounted on mirrors) and mobile solutions (e.g., helmet, wristband, smart

glasses, and map-based phone app). This approach guided the development of preliminary cautionary and imminent warnings which were later refined through the co-design phase with riders to ensure the system aligned with the unique needs of powered two-wheeler users. Table 1 show the initial warning designs for each HMI device. The road situations addressed by these warnings include curve, rear-end, and intersection use cases.

Table 1: Overview of on-bike and mobile HMIs warning design.

HMI	Initial warning design
LED mirrors	All scenarios received the same patterns without directional information. CW: Walking Yellow LED IW: Flashing Red
Dashboard	Each scenario received its own set of icons showing the risk. CW IW
	Each scenario showed its own indication from 4 directions. Some showed multiple directions at the same time. CW IW
Helmet visual	All scenarios received the same lighting pattern across all LED lights. CW: Flickering Yellow IW: Flashing Red
Smartphone Display	Each scenario received its own set of icons showing the risk. Method 1: In map placement, Method 2: Full screen pop-up CW IW
Smart glasses	Each scenario received its own set of icons showing the risk. CW IW
Helmet audio	Simple: Beeping pattern CW: Lower volume IW: Higher volume + pitch change Rich: Spoken word
Wristband	All scenarios received the same pattern. CW: Low intensity buzz IW: High intensity buzz

2.4 Warning timing for motorcyclists

The timing of C-ITS warnings is critical for preventing motorcycle crashes, especially in sight-obstructed situations. Optimised timing ensures that riders have enough time to perceive, process, and respond to warnings. Alerts that are too early can reduce trust and cause unnecessary distraction.

CMC (2025) investigated how different warning timings affect rider responses. Their findings show that earlier warnings generally give riders more time to react and increase safety margins. Riders preferred warnings issued around 3.2 seconds before a potential collision, as

these provided a good balance between timely alerts and avoiding unnecessary early warnings.

These findings align with previous research showing that early warnings improve rider confidence and reduce the perceived criticality of situations (Will & Pleß, 2023; Naujoks et al., 2015). However, if warnings are triggered too late, riders may not have enough time to avoid hazards, increasing the risk of crashes. Conversely, warnings that come too early can feel irrelevant and lead to riders ignoring future alerts.

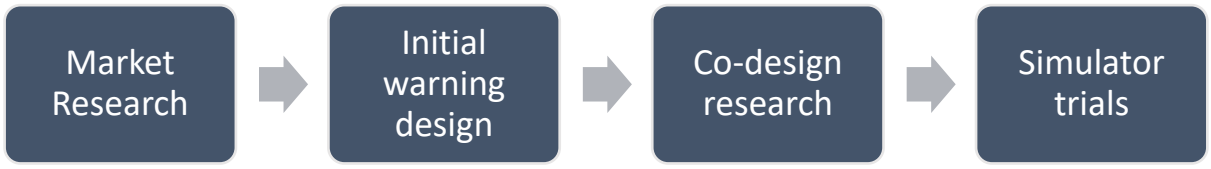
International standards like ISO 15623:2013 set performance requirements for Forward Collision Warning (FCW) systems but are largely focused on cars. Research suggests that motorcyclists' reaction times are broadly similar to car drivers, but motorcycles require earlier warnings due to their greater instability and exposure (Winkler et al., 2015).

Together, these studies show that carefully selecting warning timing is essential for effective motorcycle crash warning systems, but further research is needed to tailor timing guidelines to the unique dynamics of motorcycles and rider workloads.

3 Methodology

This study employed a user-centred design approach to develop and evaluate a connected motorcycle warning system using C-ITS. The research process included four main phases (see Figure 2): market research, followed by an initial design stage, a co-design session with riders to refine the warning concepts, and simulator trials to identify the optimal timing for delivering the warnings.

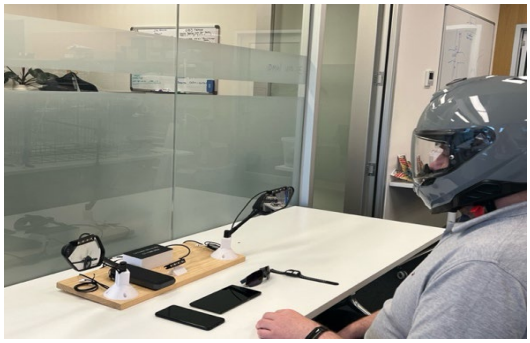
Figure 2: Method phases



3.1 Co-design research

We conducted in-depth co-design workshops with 32 motorcycle riders at La Trobe University to gather qualitative feedback on the initial warning designs (refer to section 2.1). Participants represented a diverse range of riding experience levels, ages, and motorcycle types. Before the workshops, 32 riders completed a short survey to collect demographic information, motorcycle usage patterns, bike types, and self-assessed riding style, rated from low risk to high risk. The HMI evaluation was conducted in a controlled indoor setting with riders seated at a desk (Figure 3). Each rider was assigned three HMI devices for testing and wore the relevant equipment where applicable, such as a helmet, wristband, or smart glasses. Warnings were manually triggered by a researcher using a custom Android application that sent Bluetooth signals to the devices. Structured interviews were conducted using three simulated C-ITS use cases: curve warning, FCW, and Intersection Warning Scenario (IWS), to explore riders' typical riding styles, initial responses to HMI warnings, and perceptions of each device. Riders provided feedback on the clarity, perceived urgency, distraction potential, and overall usefulness of each warning modality. Insights from this phase were analysed thematically and used to refine warning intensity, duration, and delivery methods, ensuring the system aligned with the unique needs of powered two-wheeler riders.

Figure 3: Co-design study setup (captured by La Trobe staff).



3.2 Simulator trials

Following the co-design phase, the optimised warning strategies were integrated into a dynamic motorcycle simulator to evaluate the optimal timing for delivering warnings. The simulator recreated complex urban environments featuring sight obstructions, with key scenarios focused on IWS and FCW. To simplify the study design, a single HMI device was used to deliver the warnings via LED lights mounted on the motorcycle simulator's mirrors, representing the final on-bike configuration selected during the design phase.

A total of 25 riders participated in simulator trials, each exposed to three distinct warning timings delivered at 4, 7, and 8 seconds before a potential hazard, based on predefined time-to-collision (TTC) thresholds.

$$TTC = 4\,\mathrm{sec}\,vs.TTC = 7\,\mathrm{sec}\,vs.TTC = 8\,sec$$

The 4-second timing was chosen as the minimum required for a safe response, considering riders typically need 1.7 to 2 seconds to process a warning and about 2 seconds to stop when travelling at 50 km/h (CMC, 2025). The 7- and 8-second timings were added as safety buffers, providing an extra 3 to 4 seconds to evaluate whether earlier warnings improve reaction and decision-making.

The trials were conducted under two warning conditions: IWS and FCW to evaluate the impact of different warning timings on rider alertness and response. To maintain consistency, the simulated riding speed was set at 50 km/h, a speed considered critical for motorcycle safety. Each rider experienced all three warning timings in both IWS and FCW scenarios. These conditions were designed to examine how variations in TTC thresholds influence rider reaction and the perceived usefulness of warnings. Riders were instructed to respond contextually to each warning by slowing down, changing lanes, or stopping, depending on the hazard presented.

Multiple vehicle telemetry data was collected every 100 milliseconds, which included speed, throttle percentage, brake activation, steering angle, gear position, lane ID, and indicator status. Simultaneously, hazard-related data—such as distance and position of the hazard or use case, timestamp and the rider's current location—was also logged at the same frequency. To account for real-time timeseries event detection, the moment a warning was issued via the HMI, a dedicated timestamp was recorded. This event-based marker briefly interrupted the standard 100-millisecond logging cycle to capture the exact warning onset. All data was stored in a MongoDB database hosted on DigitalOcean.

Rider behaviour in response to these warnings was analysed using a decision-based MATLAB algorithm designed to detect the rider's initial reaction as a post-trial analysis. The reaction timestamp was estimated as the first measurable deviation in rider behaviour in terms of deceleration, throttle release, or braking following a warning. Also, a specific lane-change detection module was integrated to improve identification of manoeuvres/lateral movements (e.g., lane changes or swerving) typically associated with hazard avoidance.

Importantly, the algorithm did not attempt to directly compare absolute reaction times across participants, as individual hazard visibility could not be consistently determined. Instead, the focus was on identifying the earliest reliable behavioural marker—such as throttle release, braking, or lane deviation—following the issuance of a warning. This marker, defined as the reaction timestamp, served as a consistent reference point for quantifying rider response and calculating reaction distance.

Reaction distance was defined as the linear distance, derived from GPS coordinates, between the rider's position at the moment of first reaction initiation and the location of the concealed hazard (if the hazard is stationary) or collision point (if the hazard is moving). Vincenty's formula was used to compute this distance, as it calculates geodesic distances on an ellipsoidal model of the Earth, offering higher accuracy than simpler models.

Finally, each rider completed a post-trial questionnaire to provide subjective feedback on the timing appropriateness and perceived helpfulness of the warnings, supporting the evaluation of user acceptability.

3.3 Ethics and Participant Recruitment

Ethical approval for this study was obtained from the La Trobe University Human Ethics Committee, ensuring that all procedures complied with relevant ethical guidelines for human research. Participants were informed about the purpose of the study, the experimental procedures, and any potential risks. A written informed consent was obtained from all participants prior to their involvement.

Motorcycle riders were recruited through local motorcycle clubs, social media, and university mailing lists. Eligibility criteria included holding a valid motorcycle license and having at least one year of riding experience. Efforts were made to ensure diversity in rider age, gender, and riding style (commuter, sport, touring) to cover the national motorcycle rider profile of Australia. Riders were compensated for their time with a small gift voucher.

4 Results and discussion

4.1 Final HMI designs

The co-design workshop engaged 32 motorcycle riders with diverse backgrounds, ensuring the findings reflect a broad cross-section of the motorcycling community. Participants ranged in age from 21 to 68 years old. The majority of riders were highly experienced, with around 66.7% having more than 15 years of riding experience. The sample included both daily commuters and recreational riders, covering a mix of bike types such as sport bikes, cruisers, adventure bikes, and scooters. Around 66.7% of the riders identified themselves as low to medium-risk riders, with the remainder assessing themselves as high-risk riders. This demographic diversity contributed to the robustness of the insights gathered.

The results from the interviews show that most riders are alert on their bikes, actively scanning for dangers, safe spots, and anticipating road conditions. Most welcomed risk warnings to complement their own awareness, provided the warnings clearly identified the nature and location of the danger, were easy to notice, required little interpretation, and could be customised to their preferences and riding context. Table 2 summarises riders' evaluation of how different warning options performed for each HMI device.

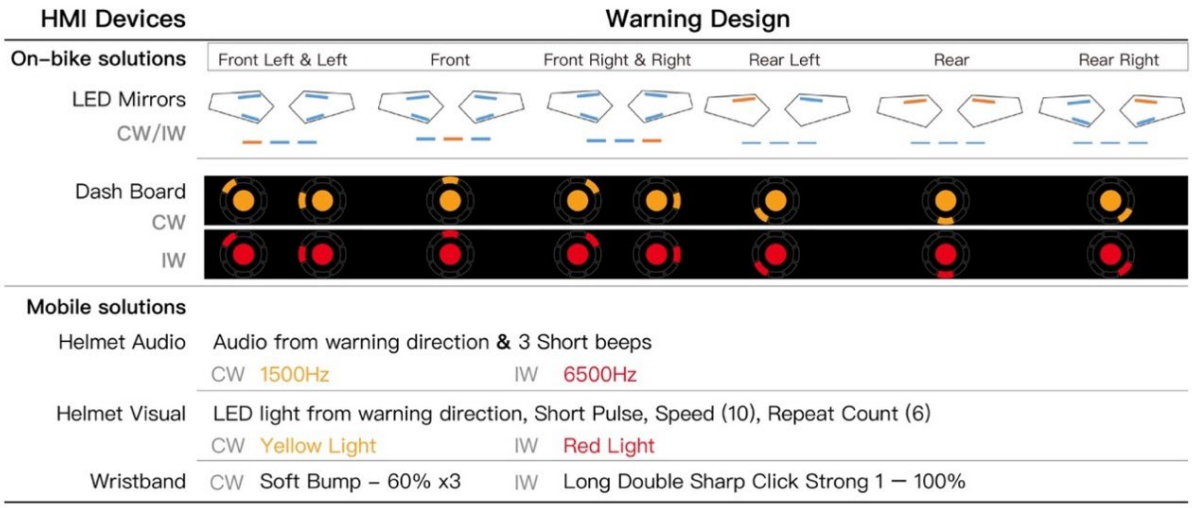
Table 2: Summary of rider's evaluation of HMI suitability based on rider feedback.

Modality	Integration	Salience	Distraction	Appeal
LED Mirrors	Most riders	High	Minimal	Broad
Helmet Visuals	Most riders	High	Minimal	Broad

Modality	Integration	Salience	Distraction	Appeal
Dashboard	Some riders	Medium	Medium	Medium
Smartphone	Some riders	Medium	Medium	Medium
Audio Voice	Some riders	Low	Polarising	Medium
Audio Beeps	Some riders	High	Polarising	Niche
Smart glasses	A few riders	High	High	Niche
Haptic	New concept	Medium	Polarising	Niche

Based on rider feedback, the final warning signals were developed across two categories of HMIs: on-bike solutions and mobile solutions, as shown in Figure 4. The main changes in design were altering the dashboard and changing how the LED mirrors worked. The signal types were designed in two levels: Cautionary Warning (CW), which serves as an early alert to inform riders of a potential risk ahead, and Imminent Warning (IW), triggered when a rider has not responded adequately to the cautionary warning and is at immediate risk of encountering a hazard.

Figure 4: HMIs in motorcycle CWS design



4.2 Simulator trials results

A total of 25 riders provided their feedback on the timing and delivery of crash warnings. Participants were diverse in terms of age, riding experience, and risk tolerance. Table 3 provides a summary of participant demographics.

Table 3: Rider Demographics (N = 25).

Characteristic	Categories	% Percentage
Gender	Male	76
	Female	20
	others	4

Characteristic	Categories	% Percentage
Age	18-25	8
	26-35	21
	36-45	17
	46-55	17
	56-65	25
	66-75	13
Riding Experience	0-5 years	28
	6-10 years	8
	16-20 years	20
	more than 20 years	44
Type of motorcycle they ride	Adventure	27
	Cruiser	14
	Naked/Sport	50
	Touring/Riser	9
Type of riders	Adventure rider	16
	Commuter rider	24
	Me-time rider	16
	Enthusiast rider	12
	Social rider	28
	Thrill seeker rider	4
Self-assessed Risk Type	Low risk	58
	High risk	42

4.2.1 Subjective results

All riders stated that they could see the warnings delivered through LED lights mounted on the mirror and the dashboard of the motorcycle simulator from their peripheral vision. They were able to interpret directional information quickly while maintaining visual focus on the road. This is a necessary precondition for evaluating the effectiveness of the warnings.

Riders consistently reported that the warnings supported earlier hazard recognition and response. As illustrated in Figure 5, the average rating for how much the cautionary warnings improved their reaction time was 7.2 out of 10. The standard deviation was 1.77, with ratings ranging from 3 to 10, indicating a generally positive but varied perception across participants.

Figure 5: Subjective reaction improvement.

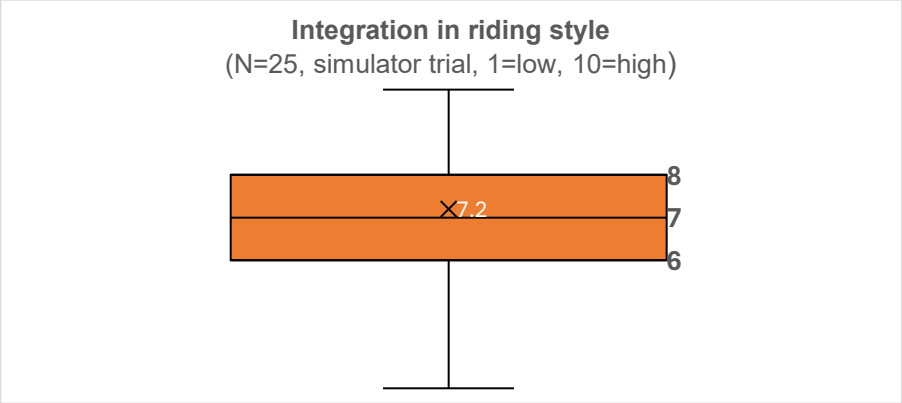
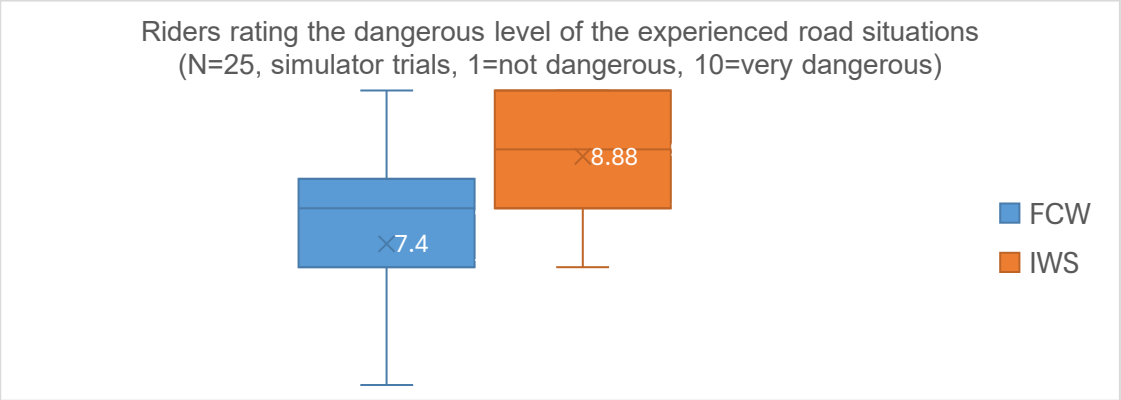


Figure 6 presents rider perceptions of the criticality of the two simulated scenarios. As expected, both test scenarios were recognised as safety-critical, though riders judged the IWS scenario as more dangerous than the FCW scenario. This outcome was anticipated, as IWS events, especially those occurring around blind corners, are less predictable and harder for riders to anticipate or control.

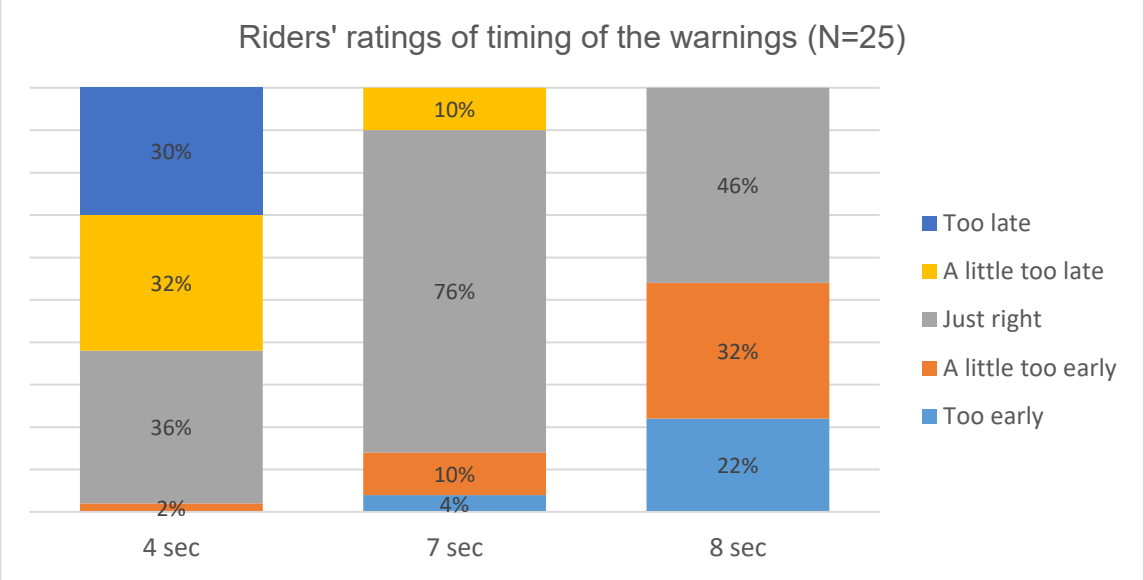
Figure 6: Rider's perceptions of the dangerous level of the road situations.



Once a warning was recognised, braking and hazard avoidance were the dominant response strategies. For both FCW and IWS situations, warnings delivered at a 4-second interval prompted immediate braking, often resulting in a complete stop. Riders described these warnings as "imminent", noting there was little time to prepare or adjust their riding behaviour. In contrast, when warnings were delivered at 7 or 8 seconds, riders adopted more anticipatory behaviours such as backing off the throttle, downshifting, and preparing to brake or change lanes.

The subjective results indicated a clear preference for the 7-second warning across both FCW and IWS. As illustrated in Figure 7, the majority of participants (76%) rated the 7-second timing as “just right”, suggesting it aligned well with their situational awareness and response capability. In contrast, the 4-second warning was frequently rated as “too late” (30%) or “a little too late” (32%), reflecting limited opportunity for anticipatory action. The 8-second warning received a more mixed response; while 46% still found it appropriately timed, 32% considered it “a little too early” and 22% “too early”, indicating that earlier warnings may sometimes precede hazard perception, diminishing their impact.

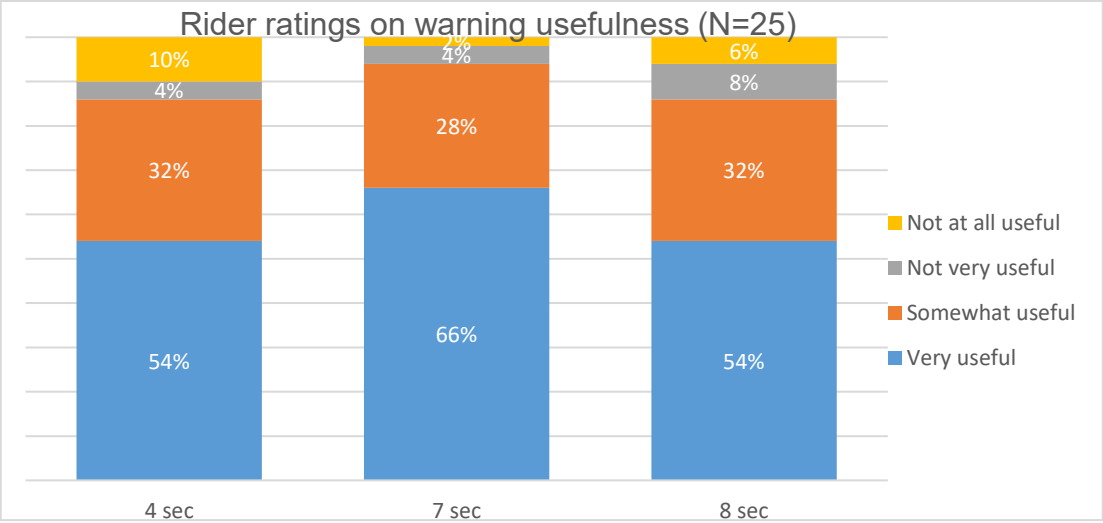
Figure 7: Rider perceptions of three warning timings.



These results are supported by riders’ qualitative feedback. For example, several participants described the 7-second warning as timely and actionable without prompting premature or unnecessary scanning for threats: *“They were early enough that they were relevant to the hazard, but not so early that I had to look for the hazard.”* and *“It gave me enough time to set my controls up to respond, but not so early that I would ignore it.”*

Ratings of warning usefulness also followed this trend (Figure 8). The 7-second warnings were rated as “very useful” by 66% of participants, the highest among all tested timings, suggesting that this timing provided an optimal window for processing and response. Although both 4- and 8-second warnings received similar proportions of “very useful” ratings (54%), they also exhibited greater variability, with more riders rating them as only “somewhat useful” or “not useful”.

Figure 8: Rider perceptions of warning usefulness based on three different timings.



Overall, these findings suggest that warnings delivered at a 7-second time-to-collision threshold are perceived as more effective, timely, and actionable than both earlier (8s) and later (4s) alternatives. This supports prior research advocating for intermediate warning periods that provide sufficient time for hazard identification and action, while avoiding the drawbacks associated with either late or excessively early warnings.

4.2.2 Objective *results*

The objective results include only data from 14 out of 25 riders who participated in the simulator trials. We have excluded those who encountered technical issues during the trial.

Figure 9 illustrates the distance between the vehicle’s position at the rider's first reaction and the collision’s position under the FCW condition at approximately 50 km/h, under three warning timings: 4, 7, and 8 seconds. In the 4-second warnings, riders were significantly closer to the hazard at the time of warning (mean = 25.86 m), leaving limited time to perceive and respond. The boxplot shows a narrow range, indicating constrained reaction opportunities. In contrast, the 8-second warning condition yielded the greatest reaction distances (mean = 56.45 m), with warnings triggered when the hazard was still distant. Although this provided ample time to respond, the lack of perceived urgency may have led to delayed reactions. The 7-second warning timing represented a balance between immediacy and preparedness (mean = 44.19 m), offering riders sufficient time to process the warning and react effectively, without perceiving the threat as either too close or too remote. This suggests that the 7-second warning timing offers a more optimal warning timing configuration for FCW scenarios.

Figure 9: Mean distance to the hazard from the starting timestamp of the reaction to a FCW at 50 km/h.

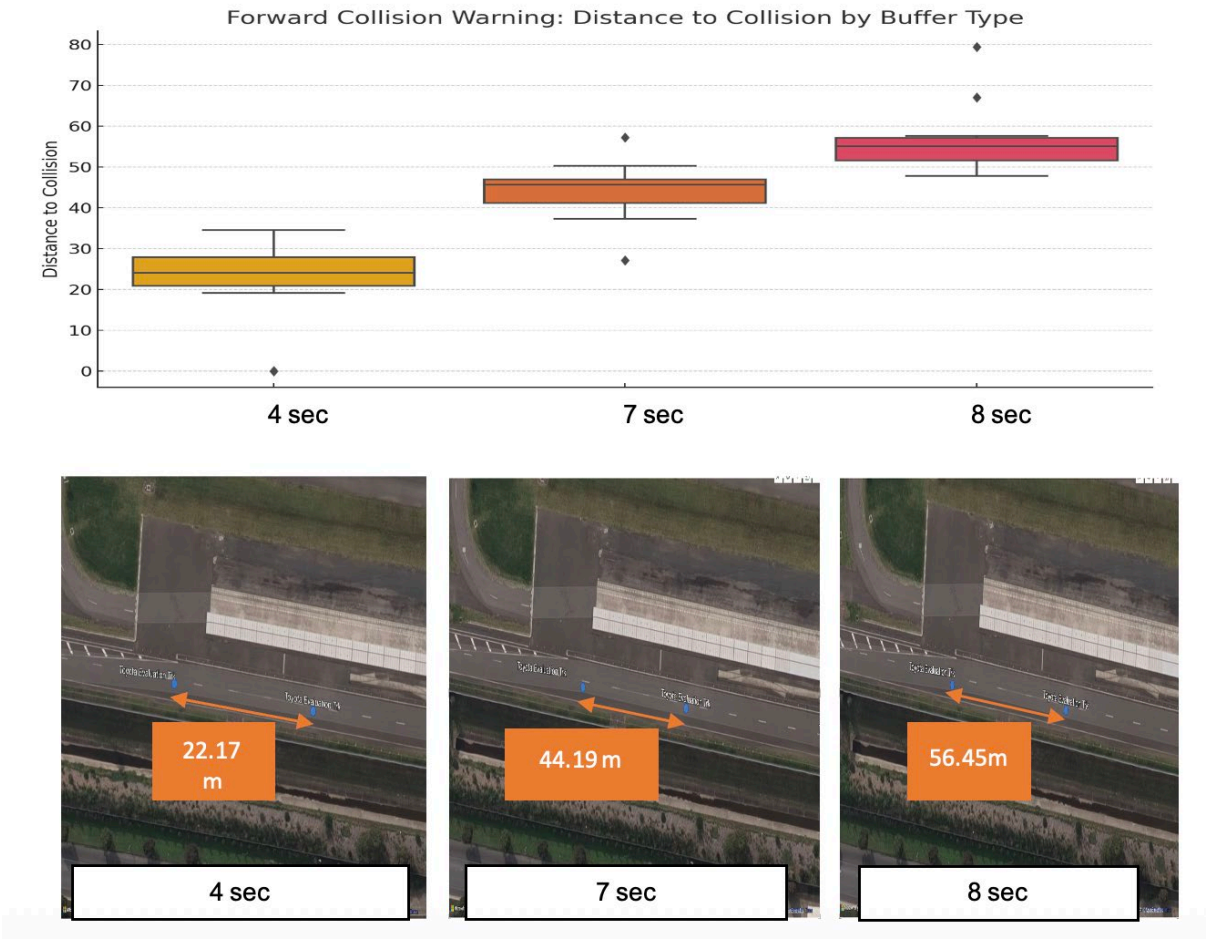
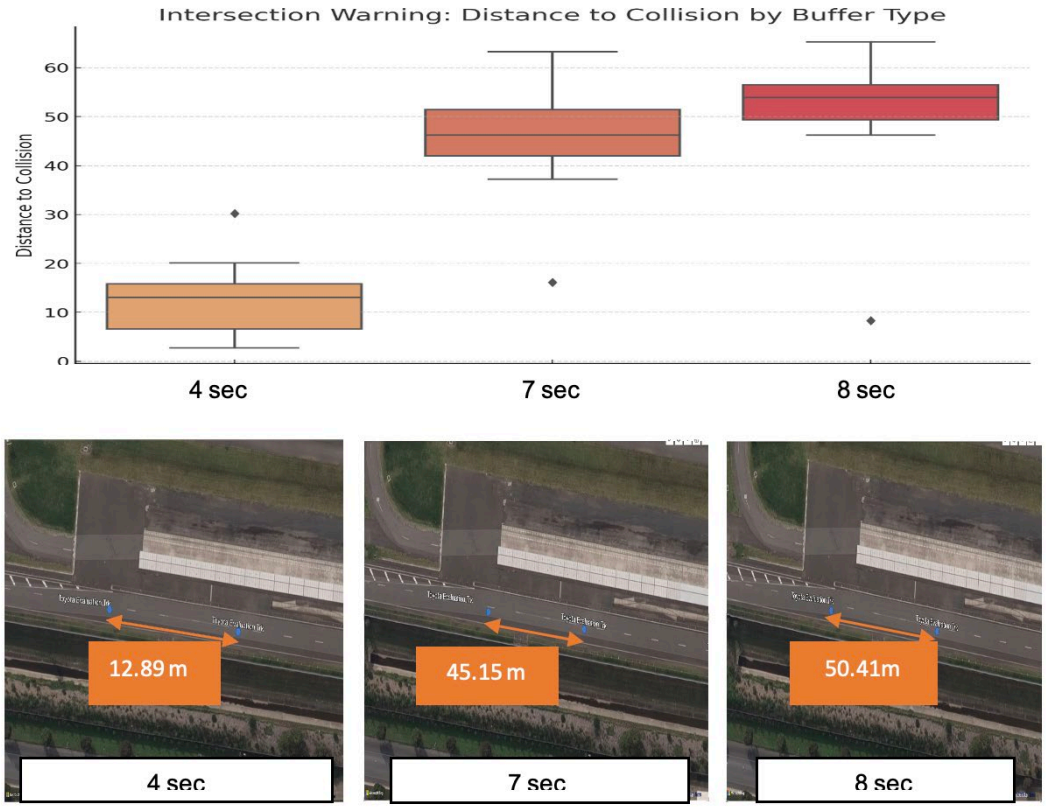


Figure 10 presents the distance to the hazard at the initiation of rider reaction in the IWS while approaching intersections at approximately 50 km/h. The comparison across 4-, 7-, and 8-second warning timings reveals distinct behavioural patterns in response timing and distance.

In the 4-second timing, warnings were delivered when riders were already in close proximity to the hazard (mean = 12.89 m), offering minimal time to react. The constrained range in the boxplot reflects limited variability in response distance. The tight reaction window left riders with little opportunity to manoeuvre safely. In contrast, the 8-second warning timing showed the greatest reaction distances (mean = 50.41 m), with warnings triggered early. While this provided ample time, many riders delayed their response until the hazard became visually identifiable. This pattern was more pronounced in the intersection scenario than in the forward collision case, likely due to the dynamic and often occluded nature of cross-traffic hazards. The perception that the warning was premature often led to delayed or absent reactions. The 7-second warning timing offered a balanced warning distance (mean = 45.15 m), where riders received the alert early enough to plan and execute an effective response, but not so early that urgency was diminished. The boxplot reflects this intermediate zone, suggesting that the 7-second warning timing may offer a more context-appropriate trade-off between reaction time and situational awareness, particularly in visually complex intersection environments.

Figure 10: Mean distance to the hazard from the starting timestamp of the reaction to an IWS at 50 km/h.



The simulator trial results across both FCW and IWS indicate that the 7-second timing provides the most effective timing for delivering hazard alerts. With similar mean reaction distances in both use cases (44.19 m and 45.15 m, respectively), this setting offers a balanced window, neither too early to reduce urgency, nor too late to limit response time.

Together with subjective results discussed in Section 4.2.1, the objective data and rider perceptions suggest that the 7-second warning timing helps strike an optimal balance, providing sufficient distance for hazard recognition and appropriate response. This enhances the overall effectiveness of the warning system, making it a preferred option for improving rider safety and hazard awareness.

While previous research presented by CMC (2025) has proposed shorter lead times such as 3.2 seconds for urgent braking scenarios, our findings highlight that longer warning durations may be more suitable in complex road environments, such as intersections or scenarios involving limited visibility. In these contexts, shorter timings may not allow riders adequate time to prepare, while excessively early alerts risk being disregarded as false alarms. Thus, the optimal timing appears to depend on the use case, and in this study, 7 seconds emerged as the most effective setting across both scenarios.

In summary, the 7-second warning timing emerges as the optimal configuration from this trial, offering a practical compromise between timely reactions and perceived urgency. It presents a valuable design choice for warning systems aimed at improving rider response in complex and visually obstructed environments.

5 Conclusion and future work

This study addressed a critical gap in motorcycle safety research by examining how C-ITS warnings can be effectively designed and delivered to motorcyclists through different HMI

devices and timing strategies. Through a two-phase user-centred approach, we first refined the warning modalities and delivery methods using feedback from a diverse group of riders. This phase confirmed that riders strongly prefer warning systems that clearly identified the nature and location of the danger, were easy to notice, and required little interpretation, with visual, audible and haptic modalities proving particularly promising when integrated into peripheral locations such as mirrors and dashboards.

Building on these findings, we implemented optimised warnings in a dynamic motorcycle simulator to investigate the impact of timing on rider perception and behaviour. The results revealed a clear preference for warnings delivered 7-second before potential collision events in both FCW and IWS. Warnings at this timing were rated as more useful, better aligned with the natural reactions of the riders, and more likely to prompt anticipatory responses. In contrast, warnings delivered at 4-second were often perceived as too late, while those at 8-second occasionally arrived before the hazard was recognisable, risking being ignored.

Future work will involve controlled test track trials and simulator trials to validate warning feasibility, effectiveness and desirability across a wider range of real-world conditions. These trials will cover additional use cases and test the impact of using various HMI devices on improving rider reaction to hazardous situations. These findings will be published separately and are expected to inform practical HMI configurations that support timely and intuitive rider responses.

A key challenge moving forward lies with system manufacturers. There is a growing need to integrate warning functions into the overall riding experience by leveraging emerging technologies such as directional sound engineering, augmented reality displays, and advanced haptic feedback. These developments offer the potential to create seamless, context-sensitive warning systems that enhance safety without overwhelming the rider or distracting from the primary task of riding.

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