Second Pair of Eyes: Evaluation of a Helmet-Integrated Multimodal HMI for Proactive Motorcycle Safety

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Abstract

Motorcyclists are highly vulnerable in complex traffic, where hazards are often detected too late for a timely response. We evaluated MOTEX, a helmet-integrated HMI that provides proactive directional cues through peripheral visual, auditory, and multimodal feedback. In a within-subject simulator study, 14 participants completed 16 scenarios based on common motorcycle crash typologies. The feedback mode did not significantly affect the reaction time or the minimum time-to-collision, although the visual and multimodal conditions showed numerically faster responses and greater safety margins than the audio and control conditions. Participants reported low cognitive workload, moderate trust, and generally positive evaluations of cue clarity. Perceived benefits of situation awareness were mixed, with most of participants reporting a neutral effect. These findings suggest that MOTEX may function less as a direct determinant of behavioural response and more as a supportive "second pair of eyes" for spatial confirmation.

CCS Concepts

• **Human-centered computing → Displays and imagers**; **Sound-based input / output**; **Laboratory experiments**.

Keywords

Motorcycle Safety, Proactive HMI, Situation Awareness, Multimodal Feedback, Riding Simulation

1 Introduction

Motorcyclists are among the most vulnerable road users. In the European Union, two-wheelers contribute a disproportionate share of road deaths, despite representing a small proportion of the total number of passenger kilometres travelled [5, 6]. Many urban motorcycle crashes involve perceptual failures, including "look-but-fail-to-see" situations in which another road user or the rider fails to register a visible conflict in time [8, 12]. This makes motorcycle safety not only a vehicle-control problem, but also an interaction-design problem: how can safety-critical information reach the rider early enough without increasing visual clutter, distraction, or dependency?

Work on helmet-mounted displays and automotive head-up displays suggests that feed-forward support is promising, but only when information is presented in a way that does not compete with roadway monitoring or narrow the effective visual field of the rider [9, 15]. Radar-based Advanced Rider Assistance Systems (ARAS) have been introduced in production motorcycles, primarily enabled by suppliers such as Bosch [2]. Bosch provides front- and rear-radar modules that support functions such as Adaptive Cruise Control, Blind Spot Detection, and Forward Collision Warning, which have been integrated into flagship models including the BMW R 1250 GS, Ducati Multistrada V4 and KTM Super Adventure. However, many commercial interfaces remain cockpit- or mirror-centred, requiring the rider to shift attention away from the forward scene at precisely the moment when attentional resources are constrained. Previous work on helmet-mounted displays, head-up displays, and multisensory driving warnings also shows that cue modality and redundancy matter to make warnings noticeable without adding visual demand [1, 7, 14]. This creates a design opportunity for peripheral, low-semantic, and directional cues that support scanning without prescribing manoeuvres.

We frame proactive rider assistance as a "second pair of eyes": an advisory layer that can confirm the direction of an emerging conflict before it reaches an emergency response window. The design is motivated by Situation Awareness theory, which distinguishes perception, comprehension, and projection of environmental elements [4]; by Distributed Situation Awareness, which treats awareness as distributed across people, artefacts, and representations [13]; and by Multiple Resource Theory, which suggests that cross-modal cueing can reduce interference when information is distributed across sensory channels [16]. On this basis, we designed MOTEX, a helmet-integrated interface that combines peripheral visual cues with spatial auditory feedback.

1.1 Aim of Study

The primary objective of this exploratory research is to evaluate the efficacy of a helmet-integrated proactive HMI to improve motorcyclist safety during critical urban interactions. To this end, we introduce MOTEX, a helmet-integrated multimodal HMI that uses a peripheral LED array and integrated helmet speakers. We evaluated the effectiveness of this decouple interface through a high-fidelity simulator study. Although traditional safety systems focus on reactive intervention, this study investigates whether feed-forward multimodal cues—specifically by systematically comparing baseline, visual, auditory, and multimodal feedback—can support a rider's SA without inducing cognitive overload or behavioural dependency [11]. We define the following research questions:

- **RQ1** (Behavioural): To what extent does the presence of proactive visual, auditory, or multimodal cues influence the physical response metrics of a motorcycle rider?
- **RQ2** (Perceptual): How do motorcycle riders perceive the utility and clarity of different feedback modalities, and which configuration is associated with the highest subjective gain in situational awareness?
- **RQ3** (Design rationale): To what extent does a decouple helmet interface influence a rider's internal confidence and hazard detection, independent of their response behaviour?

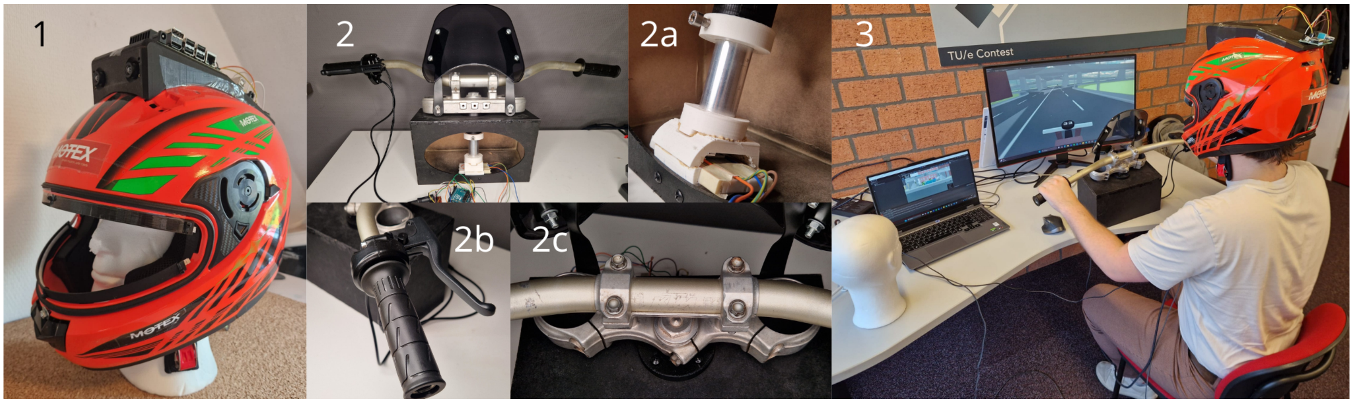

Figure 1: Image 1: MOTEX prototype. Image 2: stationary motorcycle handlebar assembly, including steering sensor integration (2a), throttle and brake lever (2b), and steering mount (2c). Image 3: laboratory setup showing the simulator, control interface, display, and MOTEX helmet worn by a participant.

2 Method

Fourteen licenced motorcycle riders participated in the exploratory study (M = 32.9, SD = 11.2). Data were available for 13 participants (9 male, 4 female). Within the sample, four participants reported regular riding experience (daily or weekly), while the remaining participants reported occasional riding. The study was approved by the Ethics Review Board of Eindhoven University of Technology, and all participants gave their informed consent.

2.1 Apparatus and Virtual Environment

The experimental setup consisted of a stationary motorcycle simulator combined with a helmet-integrated feedback prototype (MOTEX), as shown in Figure 1. The MOTEX helmet setup is based on the Nolan N60-6 Sport Hotfoot. The physical interface consisted of a static motorcycle handlebar assembly equipped with a 12-bit magnetic encoder (AS5600) for steering input, a Sur-Ron electric throttle and an electronic brake lever, both based on potentiometer sensing. These components were selected to provide realistic tactile interaction through familiar control inputs. Sensor data were processed via an Arduino Uno R3 microcontroller at a sampling rate of 50 Hz, enabling accurate capture of steering, throttle, and braking behaviour (see supplementary material in Appendix A).

The virtual environment was developed in Unity 2022.3.51f1 and presented from a first-person rider perspective, with the camera rigidly coupled to the motorcycle and a horizontal field of view of 70° (see supplementary material). The participants viewed a simplified motorcycle interface that included handlebars, a rotating front wheel, and a speedometer that displays the velocity in km/h. Steering inputs were visually reflected in handlebar and wheel orientation, providing a direct correspondence between physical input and on-screen motion. The environment consisted of a low-poly urban setting with multiple intersections. The scene included buildings of varying size and colour, roadside elements such as trees and benches, and pedestrian pathways (without animated pedestrians). Visual occlusions were deliberately introduced through the environmental layout and placement of objects to partially obstruct approaching traffic.

Figure 2: First-person rider perspective within the simulator. Multimodal feedback cues (peripheral visual illumination and spatial audio indicator) are overlaid to illustrate how a hazard event is presented to the participant. The number 51 is the current velocity (km/h).

2.2 Scenarios and Cues

Sixteen hazard scenarios were implemented based on four common urban motorcycle crash typologies derived from the SaferWheels framework [10]: cross-traffic from the right (C1), cross-traffic from the left (C2), lateral conflicts through lane intrusion (L2), and opposing vehicles turning across the path of the rider (T7). Each typology was implemented at four distinct locations within the virtual environment, introducing variation in approach direction, road geometry, and relative positioning. For each trial, a hazard vehicle was triggered when the participant crossed an invisible activation point. The trajectory and speed of the hazard vehicle were scripted such that, at the instructed riding speed of 50 km/h, a collision would occur near the centre of the driver's lane if no evasive action was taken. Hazard vehicles emerged from partially occluded positions and became visible approximately 3–4 s prior to the predicted collision. No other traffic was present.

Three types of cues were given. Visual cues were displayed using two WS2812B LED strips integrated in the upper and lower visor of the helmet, located just inside peripheral vision. When activated, a high-intensity red (R:255, G:0, B:0) warning was activated, consisting of five adjacent LEDs. The position of this block was dynamically updated based on the relative angle between the forward vector of the rider and the predicted collision point in the Unity environment, providing a clear spatial orientation. Auditory feedback was delivered as a series of spatialised, procedurally generated sine-wave tones. Using a dedicated audio synthesis script, an 800 Hz signal was generated with a duration of 250 ms per pulse. These signals were mapped to the helmet's 8Ω 1W speakers using a linear roll-off spatial blend ($1.0f$) to ensure that the sound appeared to originate from the direction of the specific hazard. To ensure high saliency and prevent perceptual adaptation, visual and auditory cues were delivered in a pulsing duty cycle of 300 ms (3.33 Hz) for as long as the hazard remained within the critical TTC threshold. In the multimodal condition, the LED pulses and auditory tones were synchronised to provide a unified cross-modal warning.

2.3 Procedure

Each experimental session took about an hour and consisted of four phases: an intake questionnaire, an acclimatisation phase, simulator trials, and a post-test questionnaire.

Intake questionnaire. At the beginning of the session, participants completed a digital intake questionnaire capturing demographic data (age, gender) and riding profile (annual mileage and frequency) (approximately 3–5 minutes). The questionnaire also established a baseline for technological readiness by measuring general trust in automation, preferences for warning modalities and prior experiences with near-miss traffic conflicts. Participants rated their initial expectations regarding the credibility of a helmet-integrated predictive system on a 5-point Likert scale.

Acclimatisation phase. Participants performed a 5-minute acclimatisation drive to familiarise themselves with the simulator controls and the different feedback modalities. This phase ensured that participants reached a steady-state comfort level with the interaction dynamics prior to data collection.

Simulator trials. The main experiment followed a within-subject design. Each participant completed 16 randomised trials as described in subsection 2.2 above.

Post-test questionnaire. After the trials, the participants completed a post-test questionnaire (approximately 5–10 minutes). The questionnaire evaluated the MOTEX interface across four dimensions: (a) *Perceptual quality*: clarity of cues, realism of the simulation, and perceived timing (earliness) of alerts; (b) *Psychological impact*: situation awareness, cognitive workload, and trust in the accuracy of the system, measured using 5-point Likert scales; (c) *Behavioural change*: open-ended questions on how cues influenced response behaviour compared to unassisted riding; (d) *Feasibility and future adoption*: preferences for hardware integration (modular vs. built-in), expected price points, and perceived barriers to adoption. Open-ended responses were collected as part of the post-test questionnaire, allowing participants to elaborate on their experiences with the system in their own words. These responses focused on perceived usefulness, clarity, timing of feedback, and any experienced distraction or cognitive load. The questionnaire was completed immediately after the trials to capture fresh impressions. All responses were recorded digitally and included in anonymised form in the supplementary material.

2.4 Data Analysis

Reaction time (RT) and minimum time-to-collision (TTC) were calculated relative to the onset of the hazard warning, defined at a TTC threshold of ≤ 2.0 s. Reaction time was operationalised as the earliest meaningful rider response following cue onset ($RT_{primary}$), defined as braking input or sustained steering action. Throttle-only responses were excluded because they did not constitute concrete evasive behaviour, as participants often switched between acceleration and engine braking within the simulator. Behavioural data were analysed using repeated-measures analyses of variance (RM-ANOVA) with feedback modality (Control, Visual, Audio, Multimodal) as a within-subject factor. For each participant, reaction time and minimum TTC values were aggregated within each modality prior to analysis. Participants with valid observations in all four conditions were retained in the final analyses. The C1C and all L2 variant scenario variants were excluded from the TTC-based analyses because their kinematic structure produced invalid TTC behaviour. In these scenarios, near-zero closing velocities resulted in non-monotonic or frozen TTC values, preventing meaningful interpretation of safety margins. These exclusions were applied uniformly before the analysis and did not affect the reaction-time or reaction-strategy analyses. The quantitative data were analysed using a Friedman test with Bonferroni-corrected Wilcoxon post-hoc comparisons.

Qualitative data collected through open-ended questionnaire responses were analysed using a thematic analysis approach. The initial codes were derived inductively from the data, focusing on recurring themes related to perceived usefulness, timing of feedback, clarity, and cognitive load. The responses were then grouped into higher-level themes to support the interpretation of the quantitative findings.

3 Results

3.1 Behavioural Patterns

Among 13 participants, mean primary reaction times were 732 ± 363 ms in the visual condition, 887 ± 577 ms in the audio condition, 711 ± 454 ms in the multimodal condition, and 722 ± 439 ms in the control condition. As shown in Figure 3, visual and multimodal cues were numerically faster than audio, but the distributions overlap strongly. RM-ANOVA did not show a statistically significant main effect of the modality on reaction time ($F(3, 36) = 2.43$, $p = .081$). The scenario-level reaction-time plots in Appendix Figure 7 show the same cautionary pattern: modality differences are visible in some scenarios, but scenario and participant variability are substantial.

The minimum TTC showed a similar descriptive pattern. The mean minimum TTC values were 0.97 ± 0.45 s for visual, 0.90 ± 0.38 s for audio, 1.01 ± 0.52 s for multimodal, and 0.89 ± 0.41 s for control. Figure 4 shows slightly larger safety margins for visual and multimodal feedback, but RM-ANOVA did not show a significant

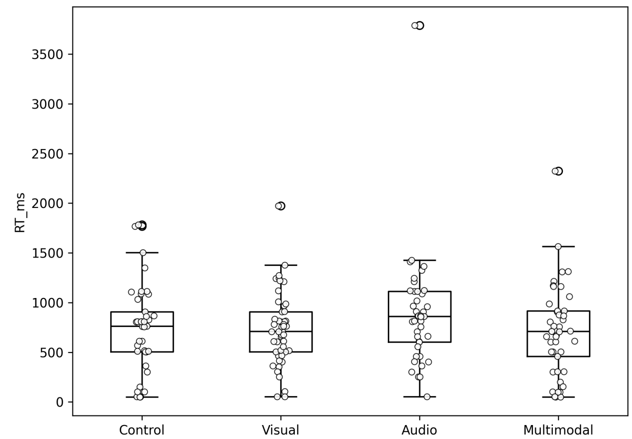

Figure 3: Primary reaction-time distributions by modality. Visual and multimodal cues showed numerically faster responses, but the exploratory test did not reach statistical significance.

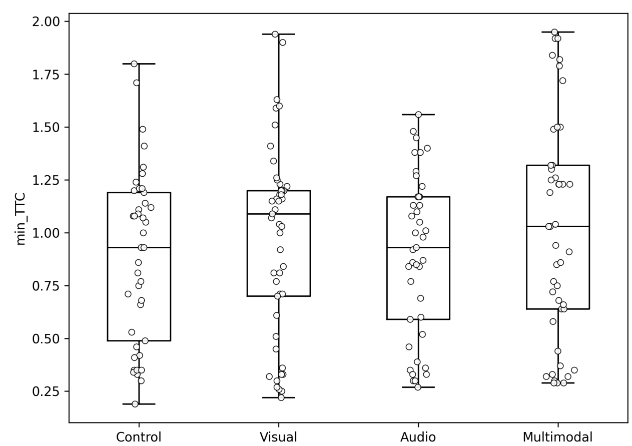

Figure 4: Minimum time-to-collision distributions by modality. Visual and multimodal cues showed slightly larger descriptive safety margins, but the pilot does not support a causal modality-effect claim.

modality effect on minimum TTC ($F(2, 24) = 0.90$, $p = .42$). Appendix Figure 8 illustrates that safety margins varied substantially across scenario variants, and some TTC values were not meaningful for all scenario geometries.

The reaction strategy also remained stable under the cue conditions. Braking dominated the responses, accounting for 95.2% of the responses in the multimodal condition, 91.3% in the visual condition and 89.5% in the audio condition; steering was rare. The feedback mode was not associated with the reaction strategy ($\chi^2(2) = 0.96$, $p = .62$), and 80% of the respondents indicated that the alerts did not change how they reacted. Reaction-time consistency showed the same limited effect of modality: within-participant RT variability was highest for audio ($M_{SD} = 415.16$ ms), followed by multimodal ($M_{SD} = 338.88$ ms) and visual ($M_{SD} = 264.52$ ms), but a median-centred Levene test was not significant ($W = 0.77$, $p = .47$). In general, behavioural data suggest possible directional benefits for visual and multimodal cueing, but not robust evidence of improved performance.

3.2 Subjective Experience

The questionnaire results, summarised in Figure 5, are clearer for design refinement and follow-up investigation than for performance claims. Cue clarity was rated positively by 92.3% of participants, and 69.2% disagreed or strongly disagreed that alerts were overwhelming; no participant reported strong cognitive overload. Trust and reliability were moderate, with 60% agreeing or strongly agreeing that they trusted the system to warn accurately and 60% rating the warnings as reliable. Realism was also acceptable for an exploratory simulator probe, with 70% agreeing that traffic situations felt realistic compared to their riding experience.

The weaker subjective findings are equally important. Only 23.1% of participants agreed that MOTEX made them feel more aware of their surroundings, while 61.5% were neutral and 15.4% disagreed. This suggests that the cues often confirmed hazards participants had already noticed rather than creating a strong awareness gain. Timing was the main design limitation: 69.2% disagreed that alerts appeared early enough to take action. This supports moving the trigger earlier than the current 2.0 s TTC threshold, for example toward a 3.0–4.0 s window, so that the system can support search and anticipation rather than only confirm imminent danger.

4 Discussion

This exploratory study evaluated whether a helmet-integrated multimodal feedback system can support anticipatory hazard awareness for motorcyclists in time-critical urban scenarios. The results provide understanding of how predictive feedback influences rider behaviour beyond simple reaction speed.

For **RQ1**, which asked whether proactive visual, auditory, or multimodal cues influence riders' physical response metrics, the pilot provides no conclusive evidence of a reliable behavioural effect. The feedback modality did not significantly affect reaction time or minimum TTC, although the descriptive pattern in Figures 3 and 4 suggests numerically faster responses and larger safety margins for visual and multimodal signals than for audio and control. The reaction-strategy results also suggest that MOTEX did not substantially change how the participants responded: braking remained the dominant evasive action under the conditions.

For **RQ2**, which concerned perceived utility, clarity, and subjective situation-awareness gains across feedback modalities, the evidence is more useful for design refinement than for strong effectiveness claims. Participants generally evaluated the cues as clear and non-overwhelming, and trust and reliability ratings were moderate. However, perceived benefits in situation-awareness were mixed: only a minority reported greater awareness, while most participants were neutral. This pattern suggests that MOTEX was often experienced as a confirmation cue rather than as a cue that newly revealed unseen hazards. The questionnaire overview in Figure 5 also highlights timing as the main subjective limitation, with many participants indicating that alerts did not appear early

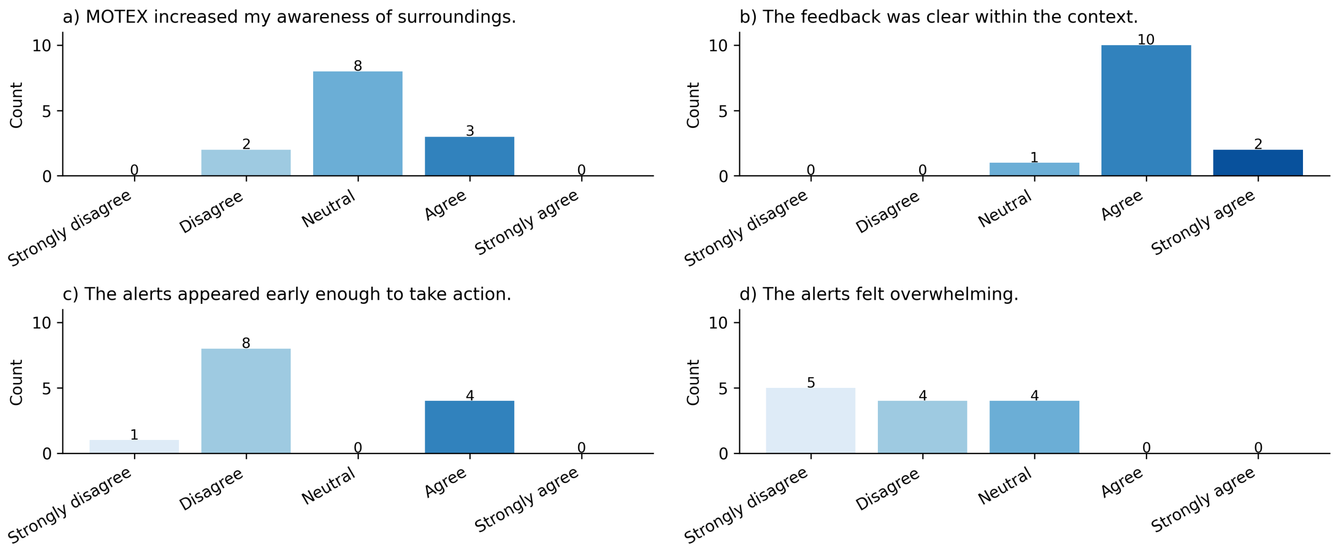

Figure 5: Post-test questionnaire responses for awareness, clarity, timing, overload, trust, and realism.

enough to support action. Thus, the perceptual contribution of MOTEX appears to lie in spatial confirmation and reassurance, not in a strong subjective transformation of awareness.

For **RQ3**, which asked whether a decoupled helmet interface can influence rider confidence and hazard detection independently of overt response behaviour, the pilot supports a cautious interpretation of the "second pair of eyes". MOTEX did not produce a statistically reliable behavioural advantage, but the combination of clear cue ratings, low reported overload, and descriptive advantages for visual and multimodal feedback suggests that peripheral helmet cues may support hazard checking without being intrusive or prescriptive [11, 14]. Motorcycle HMI should be evaluated not only as a display problem, but as an embodied, time-critical interaction in which riders must maintain balance, monitor the road surface and coordinate gaze, braking, steering, and body posture.

The study also clarifies what a stronger follow-up evaluation requires. Broad scenario coverage improves ecological breadth, but when each participant experiences each scenario only once, scenario difficulty can become confounded with modality. The figures in the appendix (Figures 7 and 8) make this issue visible by showing the scenario-level variability that is hidden in the modality averages. The next study should therefore recruit primarily active riders, report riding frequency and annual mileage transparently, improve counterbalancing or use a smaller fully crossed scenario set, manipulate cue timing systematically, and analyse the data with models that account for participant, scenario, order, and missingness. In summary, this work contributes a concrete prototype, preliminary numerical evidence for the three research questions, and a clearer path toward a confirmatory evaluation of helmet-integrated proactive rider assistance.

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A Supplementary Material

In line with current open science practices and recommendations for transparency in automotive user research [3], the authors openly provide these research artefacts to support reproducibility, collaboration and further advancements in the field. The simulator and analysis code, the anonymised data and the materials used in the experiment are available at https://doi.org/10.4121/3ba4edd4-6158-41d6-aa2d-2727f25467b9. The maintained version of the code is available at https://github.com/T-vH/motex.

B Additional Figures

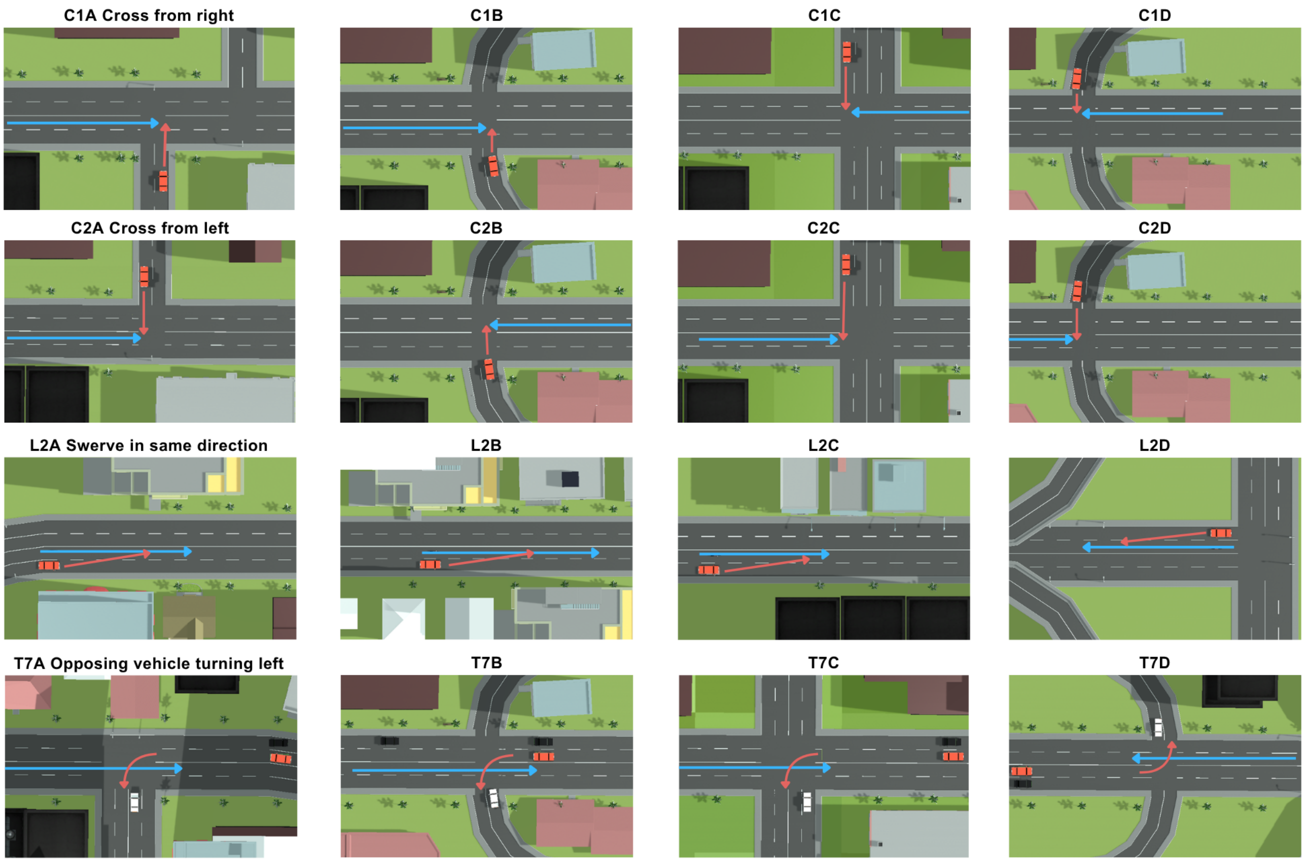

Figure 6: Overview of the 16 hazard scenarios. Rows represent four common accident typologies (C1, C2, L2, T7), and columns (A–D) represent controlled variations in geometry and positioning. Rider trajectory is shown in blue, and conflicting hazard vehicle trajectory in red.

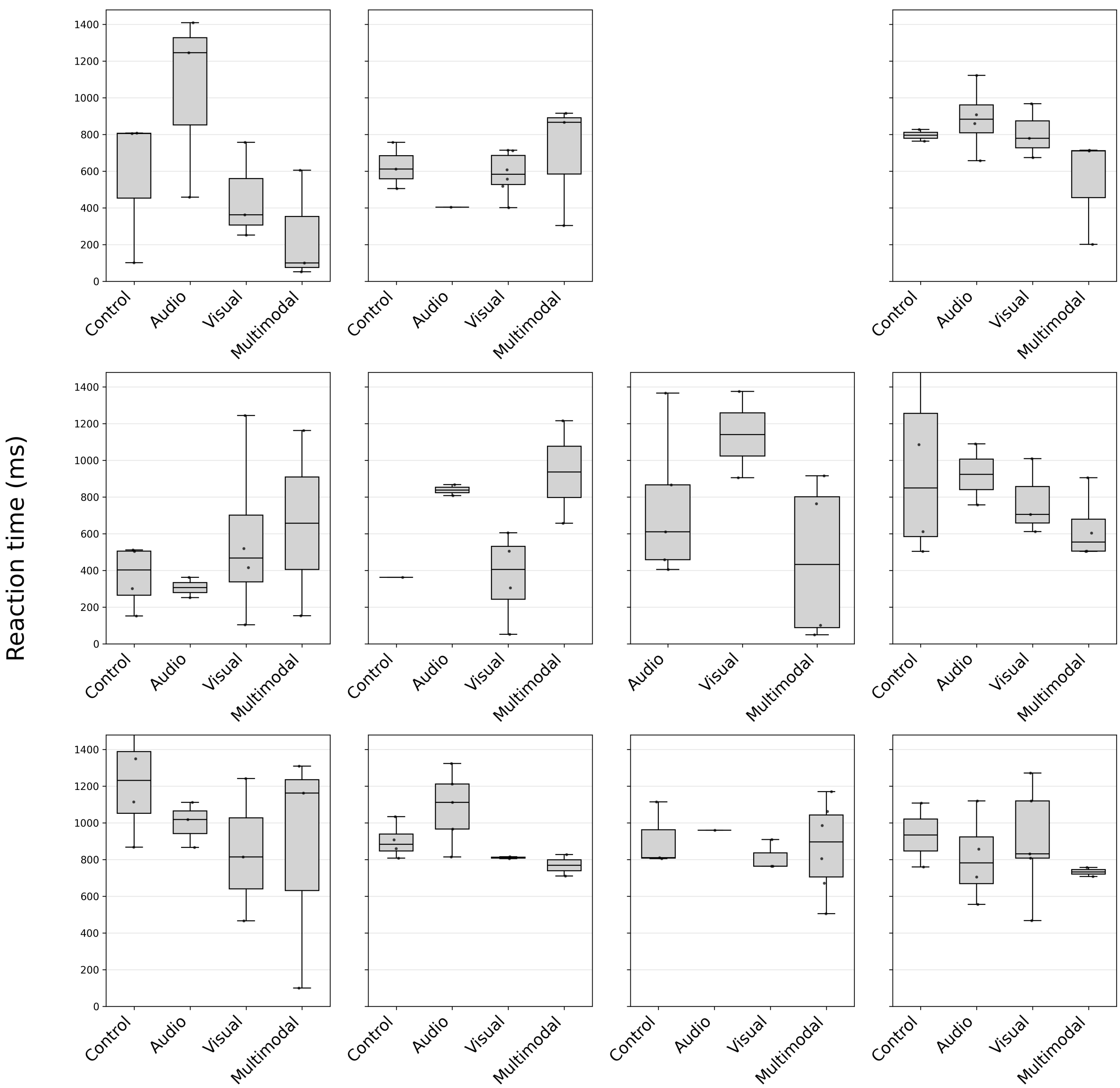

Figure 7: Scenario-level reaction-time distributions.

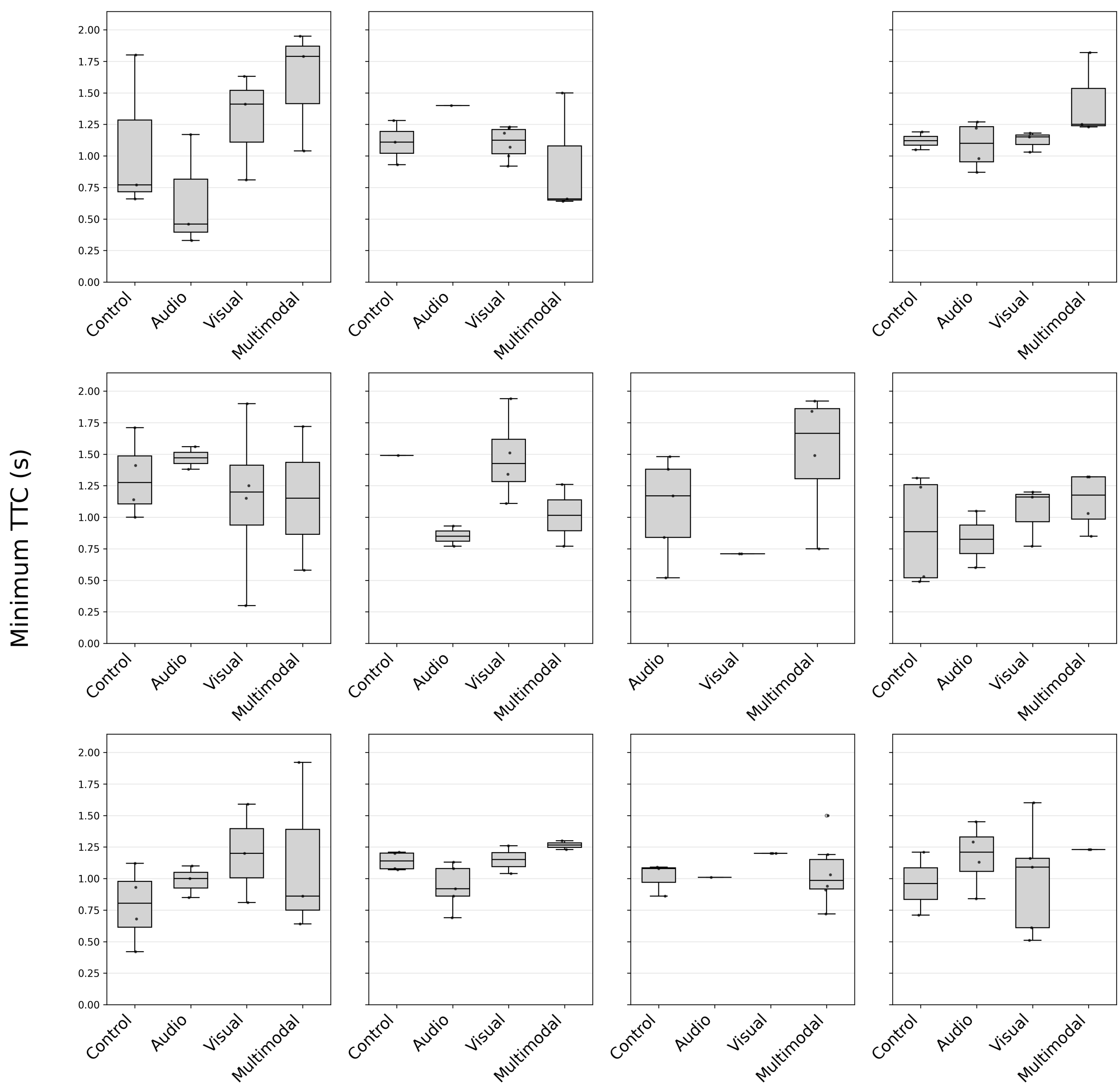

Figure 8: Scenario-level minimum-TTC distributions. These plots illustrate the scenario variability that motivates a stronger mixed-effects design in the follow-up study.