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Evaluating a Low-Cost Forward Collision Warning System for Motorcycles: An Exploratory Naturalistic Riding Study in Urban Indonesia

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Abstract: Motorcycle rider safety remains a critical issue, particularly in developing countries where two-wheeled vehicles are disproportionately involved in crashes. This study evaluates the Motorcycle Collision-Alert and Management System (MCAMS), a low-cost aftermarket forward collision warning system, using a Naturalistic Driving Study with six riders in Jakarta, Depok, and Bogor, Indonesia. MCAMS continuously recorded kinematics, headway, time-to-collision, and front-view videos. Eighteen types of Safety-Critical Events (SCE) were identified, Pooled SCE counts were lower after system activation (205 vs. 113), but the prespecified rider-level exact Wilcoxon signed-rank test across the six paired riders was not statistically significant, and the exposure-adjusted rate ratio was imprecise. Descriptively, lower counts were concentrated in scenarios such as tailgating and overtaking, whereas intersection and lateral conflicts showed little change, a pattern consistent with the system's forward-facing design. These results should be interpreted with caution, because this study used the small sample of six riders and the sequential pre–post design without a control group or randomized exposure. These preliminary findings support further investigation with larger samples, longer observation periods, and controlled exposure conditions to establish generalizability and causal inference.

Keywords: Motorcycle; Motorcycle Collision Alert and Management System (MCAMS); Road Safety; Safety Critical Events (SCE); Warning System

1. Introduction

Motorcycles are the most widely used mode of transportation globally, particularly in developing countries. In Southeast Asia, motorcycles serve as a primary means of transport due to their compact size, which allows for greater mobility and easier navigation of congested urban areas[1–3]. Additionally, motorcycles are more economical and have lower maintenance costs than other vehicles. In regions with underdeveloped transportation infrastructure, motorcycles also provide an effective solution for accessing remote areas.

Statistics from the Central Bureau of Statistics (BPS)[4] indicate a significant increase in motorcycle registrations, reaching 132.4 million units in 2023, which accounts for 84.31% of all motor vehicles. Globally, the World Health Organization estimated approximately 1.19 million road-traffic deaths in 2021[5]. In Indonesia, BPS recorded 150,906 road crashes and 26,839 deaths in 2024[6]. Separately, Indonesian National Police recorded 1,258,252 motorcycle units among vehicles involved in police-recorded crashes in 2024, representing 76.47% of vehicle-involvement records[7]. This percentage describes vehicle-involvement records and should not be interpreted as the proportion of unique crashes involving motorcycles.

Given this context, motorcycle safety has become an urgent public concern. In addition to fatal crashes, near-miss incidents are increasingly recognized as valuable

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indicators of road safety risk. Though they do not always result in actual collisions, near misses often reflect hazardous behavior that could lead to future crashes. Schaaf et al.[8] argue that Near misses occur more frequently than actual crashes and can, therefore, serve as a reliable statistical measure for detecting safety trends. This principle has since been formalized within naturalistic driving research, where near crashes have been shown to serve as statistically valid crash surrogates that permit reliable risk estimation when observed crash counts are too small for direct analysis[9].

Efforts to prevent road crashes are central to enhancing traffic safety. Numerous approaches have been adopted, including national government initiatives such as Indonesia's General Plan for Road Traffic and Transport Safety (RUNK LLAJ), introduced through Presidential Regulation No. 1 of 2022[10]. This 20-year strategy (2021-2040) focuses on five safety pillars: safe systems, safe roads, safe vehicles, safe road users, and post-crash response. Other national campaigns, such as the Indonesian Youth Road Safety Warriors (IYRSW)[11] and National Road Safety Week (PNKJ)[12] aim to raise awareness, particularly among young people, through public education and the promotion of sustainable transport. These efforts are complemented by digital enforcement systems, such as Electronic Traffic Law Enforcement (ETLE), and by regular police operations. Technology offers a promising avenue for enhancing motorcycle safety. Innovations such as Anti-lock Braking Systems (ABS), Combined Braking Systems (CBS) and Automatic Headlights On (AHO) have already made significant contributions to improving motorcycle safety [13]. More recently, the focus has expanded to include warning systems that alert riders to potential hazards.

Globally, a variety of driving safety systems have been developed to assist motorcyclists and other road users, including adaptive cruise control, blind-spot detection, lane-departure warning, and vehicle-to-vehicle (V2V) communication systems. These technologies vary in complexity and cost but share the goal of improving situational awareness and reducing the likelihood of crashes. In the motorcycle domain, these technologies are collectively described as Advanced Rider Assistance Systems (ARAS). A systematic review by Savino et al.[14] catalogued nine categories of ARAS, which are spanning antilock braking, autonomous emergency braking, collision warning, and intersection support, while noting that most remain at prototype or early-testing stages and that comparatively few have been evaluated with real-world data. More recent crash-database analyses have begun to quantify their potential benefit: Ait-Moula et al.[15] examined in-depth crash records and estimated that ARAS could have influenced approximately 61.5% of the powered two wheeler crashes analyzed, with anti-collision alerts and automatic braking among the most influential functions, while Terranova et al.[16] compared the applicability of five active systems (ABS, motorcycle autonomous emergency braking, collision warning, curve warning, and curve assist) using population-based crash data across Australia, Italy, and the United States. Complementing these effectiveness estimates, Huth and Gelau[17] found that rider acceptance of such systems depends strongly on interface design and social norms, underscoring the need to evaluate low-cost, forward-facing warning devices under authentic riding conditions rather than in simulation alone. Understanding how these systems operate provides valuable context for evaluating MCAMS within the broader spectrum of motorcycle safety innovations. One of the most notable innovations is the Motorcycle Collision Alert and Management System (MCAMS), developed by Virginia Tech (USA). This system leverages data-driven safety management and artificial intelligence to monitor risk factors and deliver real-time alerts, aiming to significantly reduce crash risk. The potential of such systems to revolutionize motorcycle safety is indeed promising. Figure 1 illustrates the MCAMS technology.

To evaluate the effectiveness of such systems in real-world riding conditions, the Naturalistic Driving Study (NDS) offers a valuable framework. The NDS involves collecting behavioral data directly from the rider's perspective without experimental interference[18]. It enables the observation of interactions between rider behavior and external factors, such as traffic conditions, weather, and road types. A core element of the NDS is the identification of Safety Critical Events (SCE), Near-misses, or potentially hazardous events, such as sudden braking or loss of control. Monitoring these events enables researchers to analyze crash precursors and develop targeted safety interventions.

Several studies have employed the NDS to examine motorcycle rider behavior and safety. For instance, Aupetit et al.[19] identified 248 risk scenarios faced by novice riders, aiming to improve training and licensing systems. Using in-vehicle video, logbooks, and interviews, they found that



Fig. 1: Motorcycle Collision-Alert and Management System (MCAMS)

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lane changes in dense traffic were among the most frequent situations. Chung[20] analyzed injury severity using video evidence, revealing that crash speed, helmet use, and weather conditions significantly influence crash outcomes. Omar and Lamin[21] conducted a statistical review of fatal motorcycle crashes in Malaysia and recommended technologies such as anti-lock braking systems (ABS) and blind spot detection. Al Haddad et al.[22] proposed a standardized protocol for data collection to improve consistency and quality in future studies. In Indonesia, Halim et al.[23] analyzed Safety Critical Events (SCE) across six cities using the NDS. They found that traffic violations and risky maneuvers were among the most common triggers of crashes, and emphasized the importance of education, infrastructure improvements, and law enforcement in addressing these issues. Glaser et al.[24] evaluate various motorcycle-car conflict topologies as well as the corresponding prevalence based on an NDS study.

While previous research has made significant contributions to understanding rider behavior and crash causations, few studies have directly examined the role of alert-based safety systems, such as the MCAMS, in reducing near-miss incidents. Previous studies primarily focused on behavior and injury outcomes[19,20], whereas Omar and Lamin[21] did not evaluate the direct impact of such technology. Particularly in Indonesia, empirical studies exploring the effectiveness of these systems remain limited. The most existing evaluations of ARAS and collision-warning systems have relied on crash-database reconstruction, riding simulators, or controlled trials conducted in high-income countries with lane-disciplined, predominantly car-based traffic[14-16], rather than on real-world data from riders. Second, the urban traffic environment of Indonesian cities differs fundamentally from these settings: motorcycles constitute most of the vehicle fleet and operate within dense, heterogeneous, weak-lane-disciplined traffic, where filtering, overtaking, and weaving generate frequent lateral and side-swipe conflicts in addition to rear-end conflicts[25]. Warning strategies validated under regulated, lane-disciplined conditions may therefore not transfer directly to this context, making urban Indonesia a scientifically distinct and largely underexamined setting for evaluating forward collision warning. Taken together, the research gap is as follows: the real-world effectiveness of low-cost aftermarket forward collision warning for motorcycles has rarely been assessed using naturalistic riding data, and there are limited studies that undertaken in the mixed, motorcycle-dominated traffic of urban Indonesia.

Therefore, this exploratory study evaluates whether SCE frequency differs between matched OFF and ON phases among a small sample of commuting motorcyclists under naturalistic riding conditions. Given the limited sample size and the non-randomized, sequential OFF-then-ON design, the study does not aim to provide a definitive assessment of system effectiveness but rather to establish feasibility and generate preliminary evidence to inform larger, adequately powered trials.

2. Methods

2.1. Materials

2.1.1. Participants

This study involved six participants in Jakarta, Depok, and Bogor, Indonesia, and data were collected for three months. Participants were selected through convenience sampling, targeting individuals who met specific inclusion criteria to ensure data validity. Subjects were required to hold a valid motorcycle license, actively ride within the past 12 months, use motorcycles as their primary commuting mode, and be free from alcohol or drug influence. The sample consisted of motorcycle-commuting staff from the Faculty of Engineering, Universitas Indonesia, deemed appropriate for evaluating the real-world impact of MCAMS on SCE. Because all participants were drawn from a single institutional setting (Faculty of Engineering, Universitas Indonesia) through convenience sampling, this should be regarded as a small pilot sample rather than a representative cross-section of riders; accordingly, the findings are not intended to generalize to urban motorcyclists in Indonesia as a whole or to other rider populations.

The six riders were motorcycle commuting staff from the same faculty. They comprised of 6 men, with ages ranging from 31 to 54 years (40±7.82 years). Self-reported riding experience ranged from 14 to 37 years, and participants commuted by motorcycle on approximately 5 days per week, covering typical one-way commuting distances of about 10-15 km. Their habitual routes ran through Jakarta, Depok, and Bogor and consisted predominantly of urban arterial and residential roads characterized by dense mixed traffic and frequent signalized intersections.

Jakarta, Depok, and Bogor were selected as study locations because they represent high-density urban areas with complex traffic patterns, diverse road conditions, and a high prevalence of motorcycle use, making them suitable for evaluating MCAMS performance in challenging real-world environments. The decision to involve only six participants was based on the intensive data collection and manual video review required by the NDS methodology, as well as the availability of MCAMS devices. Although small, the data collected by each individual was extensive because this study was conducted over three months. It allowed for detailed monitoring and high-quality data collection within the study's resource constraints. In this study, we measured the commuting time to and from work for each participant, so that road type, time of day, and intersection frequency were treated as constant each day.

The crash intervention used in this research was the

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MCAMS, a technology-based warning system designed to enhance motorcycle rider safety by providing real-time alerts about potential road hazards. The system aims to reduce the frequency of SCE that riders experience in everyday commuting environments.

2.1.2. Instruments

This study used a visual data-recording system to support the naturalistic driving methodology, enabling unobtrusive observation of rider behavior under actual road conditions. The primary instrument used was a video camera mounted on the motorcycle, which enabled continuous documentation of both the traffic environment and rider interactions throughout the study period. In addition to the video, the MCAMS collects critical driving information, including 3-dimensional acceleration, speed, headway distance relative to leading objects, and time-to-collision (TTC). The MCAMS is designed to enhance rider safety by combining LiDAR-based safety management with an on-board video recorder. It continuously monitors riding risks and issues real-time early warnings intended to reduce the likelihood of collisions on the road. The device incorporates two cameras: one mounted on the dashboard and oriented toward the rider, and a second positioned at the front of the motorcycle and directed at the roadway, which together capture clear footage of the riding environment. Video data from each respondent were stored on an Innovv K6 dashcam fitted with a 256 GB memory card. This camera offers a 140-degree forward field of view that records the rider's real-world riding conditions. It requires no manual operation: because it is wired directly to the motorcycle's battery, it powers on and begins recording automatically whenever the motorcycle is started. The warnings issued by the system were visual, which are a red indicator light.

To fully characterize the intervention, the operating specifications of the MCAMS are summarized as follows. Sensing is provided by a single-point (one-point) laser LiDAR with a detection range of up to 150 meters, complemented by a front-facing camera with a 140° field of view and a rear-facing camera with a 120° field of view. The front camera records at 1440p and the rear camera at 1080p, both at 30 frames per second, while the LiDAR data are sampled at 100 Hz. For object selection, the system relies on single-point distance measurements from the laser LiDAR to compute the relative speed of obstacles within its direct forward line of sight. The forward-collision warning is issued based on time-to-collision (TTC), with the alert threshold nominally set to 2 seconds; when triggered, the warning is presented for a duration of approximately 2 seconds. The warning itself is a red visual indicator mounted directly above the instrument cluster, positioned to remain within the rider's peripheral vision without drawing attention away from the road ahead. To limit false positives in dense, slow-moving traffic, warnings are disabled below a low-speed threshold, and a suppression algorithm reduces repeated alerts during sustained conflicts. Sensor calibration was performed manually using a laser alignment tool to ensure that the LiDAR and cameras were aligned with the motorcycle's central longitudinal axis. Finally, installation required no permanent modification to the motorcycle and left no lasting effects; the system draws minimal power while operating and no power when the motorcycle is switched off.

The study employed a within-subject, fixed sequential design in which each rider served as their own control across two consecutive phases. Immediately after the recording equipment and the MCAMS unit were installed, the system was held in an inactive state (OFF) for the first two weeks to capture each rider's habitual, unassisted commuting behavior as a baseline. The device then activated automatically and remained active (ON) for the remainder of the three-month period. Because each rider is compared only against their own baseline, the analysis is a within-rider pre–post contrast rather than a randomized controlled comparison. The MCAMS operated in an inactive state (OFF) during the first 2 weeks post-installation to establish a behavioral baseline, followed by continuous activation (ON) for the remainder of the 3-month period. To ensure exposure equivalence, exposure was matched within each rider rather than pooled across the sample: for every rider, ON-phase riding was accumulated to the same travel distance that the same rider had covered during their own OFF phase, over a comparable two-week window. Across the six riders this matched exposure in total 209.8 km for six riders (per-rider distances, durations, and trip counts are reported in Table 3). Participants rode fixed weekday commuting routes that maintained consistent road types, times of day, and intersection frequencies across both phases.

The video data obtained from the camera were systematically analyzed to identify SCE, defined as incidents with a high potential for collision or near misses. In total, approximately 70.5 hours of video data were recorded across all participants. The analysis window was defined by exposure, not by events: for each rider it comprised every commuting trip recorded during the two-week OFF phase and the distance-matched set of ON-phase trips described in the next paragraph. This window contained 20.7 hours of video (10.7 h OFF and 10.0 h ON; approximately 29.4% of the total recorded), and the remaining ON-phase footage recorded after each rider's matched distance had been reached was not reviewed and contributed to neither the SCE counts nor the exposure denominators. Within the window, screening was exhaustive rather than event-centered: analysts viewed the footage of every included trip continuously from trip start to trip end and flagged candidate SCE prospectively during this pass, using the two-stage procedure described below.

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Candidate flagging relied on video cues in both phases and was not triggered by MCAMS alerts, so the same ascertainment procedure was applied to OFF and ON footage. Some trips contained recording gaps because of dashcam file-segment loss or power interruption, during which no usable video was available. Trip distance and duration were derived from the dashcam's GPS track, so the matched distances and the durations in Table 3 refer only to riding covered by usable video; riding that fell within a gap contributed neither SCE nor exposure in either phase.

To make the two phases as comparable as possible, participants rode their usual fixed weekday commuting routes throughout the study, so that road type, intersection frequency, and the morning and evening time-of-day windows were held approximately constant across the OFF and ON phases for each rider. Exposure was equated by distance rather than by calendar time. For each rider, the ON phase sample comprised the commuting trips recorded from the start of the ON phase, accumulated in chronological order until the cumulative ridden distance matched that same rider's own OFF-phase distance.

Although this fixed route, distance matched approach holds the more stable exposure variables (route, road type, and time of day) approximately constant, other conditions could not be fully equated. Traffic density and weather were not recorded as covariates and were not statistically controlled, so day-to-day fluctuations in congestion and road surface conditions may differ between phases. Because the OFF and ON windows were separated in time, any seasonal drift in weather, daylight, or traffic patterns across the study period is confounded with phase and cannot be disentangled from the effect of the system in the present design.

Participants were informed that a warning device had been installed on their motorcycle, but they were not told the activation schedule in advance and were not instructed to alter their riding behavior; they were also blinded to the specific behavioral parameters and SCE categories used to score their riding. During the OFF phase the device produced no alerts, so riders experienced ordinary, unassisted commuting. During the ON phase, which began automatically after two weeks, the system delivered real-time alerts, which meant riders necessarily became aware that the system was active whenever an alert was issued.

The selection of two weeks' data ensured consistency when comparing the two riding conditions while still capturing a representative sample of commuting behavior. A consistent set of predefined criteria was used to determine whether an event is qualified as a Safety Critical Event (SCE). These criteria included, but were not limited to, abrupt braking, sudden lane changes, loss of control, and near-miss incidents with other road users or obstacles. These events were then meticulously categorized into 18 distinct scenarios, a process that was informed by prior studies and rigorous observational criteria, as summarized in Table 1.

The scenarios were created based on previous studies[19,24], however, several scenarios were obtained from field events according to the situation in Indonesia, namely SCE 14 (tailgating when the rider follows too closely to the vehicle in front), SCE 15 (Near-miss due to another rider losing control and nearly colliding with the rider), SCE 16 (loss of control due to damaged road), SCE 17 (near-miss due to a blind spot, failing to see another rider at an intersection or turn), and SCE 18 (near-miss caused by an oncoming vehicle driving too close at high speed). The items listed in Table 1 represent specific traffic and environmental conditions observed during the study, each of which can be considered a distinct scenario reflecting potential hazards for riders. The identification of SCE was conducted through manual review of video data, applying predefined criteria derived from previous studies, particularly Aupetit et al.[19], complemented by additional categories observed in the Indonesian traffic context. While MCAMS automatically records kinematic data and potential event triggers, final categorization was performed using these established criteria to ensure consistent classification.

2.2. Methods

2.2.1. Data Collection

Data for this study were collected for three months, focusing on real-world motorcycle riding behavior during participants' daily commutes. The study was conducted in accordance with the Declaration of Helsinki and approved by the Research and Community Engagement Ethical Committee of the Faculty of Public Health, Universitas Indonesia (Ethical approval number: Ket-94/UN2.F10.D11/PPM.00.02/2025). All participants met the inclusion criteria and provided informed consent before data collection. Following the consent process, video recording equipment was installed on each participant's motorcycle. Participants received practical guidance on using recording devices and the associated procedures. Data collection was conducted during regular weekday commuting hours, Monday to Friday, encompassing both morning and evening trips. This schedule was designed to reflect typical urban traffic conditions and riders' habitual behavior, ensuring the findings are directly applicable to real-world motorcycle commuting scenarios.

Analysts screened the complete 20.7 h distance-matched analytic sample and recorded candidate SCE on a standardized observation sheet with event time and contextual details. The same academic analysts conducted the initial screening and final classification. Review files used coded names that did not reveal recording dates, phase order, or OFF/ON status; the warning indicator and

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MCAMS activation/status channel were not visible in the material used for classification. Analysts therefore did not know the condition when screening or adjudicating events. To operationalize this combination, video review and MCAMS kinematic data were integrated sequentially rather than treated as independent classifiers. In the first pass, each analyst screened the front-view footage to flag candidate events and assigned a provisional category from directly observable cues. In the second pass, the MCAMS forward-facing channels, which are time-to-collision (TTC), headway, and 3-axis acceleration, were queried within a fixed time window bracketing each candidate event (approximately 3 s before to 3 s after the flagged frame) to confirm, reject, or re-assign threshold-sensitive categories. Because MCAMS senses only forward and longitudinal/vertical dynamics and does not capture lateral or rear-facing motion, kinematic corroboration was applied to frontal closing-conflict categories, whereas lateral-conflict, intersection, filtering, and third-party categories were resolved from video evidence alone. The complete set of operational definitions, the distinguishing feature used to separate each category from adjacent categories, and the classification basis (kinematic-corroborated versus video-based) for all 18 SCE types are provided in Table 1.

Objective kinematic thresholds were applied where a relevant forward-facing signal was available. SCE 5, 6, 7, 14, and 18 required TTC < 3 s. SCE 6 required a discrete lead-vehicle deceleration that produced the short-TTC conflict, whereas SCE 14 required TTC < 3 s to be present before visible lead-vehicle deceleration. The revised label describes the rule that was applied during the original adjudication more accurately than the previous label; no recorded event was reclassified, and the category counts are unchanged from the previously submitted version. Loss of control categories (SCE 3, 4, 11, 13, and 16) were identified from video. When scenarios overlapped, the event was assigned to the earliest observable precipitating hazard. A discrete maneuver or event took precedence over a background traffic condition; rider-initiated and other-initiated conflicts were distinguished; and an occlusion category was used only when impaired visual detection was the proximal cause and no more specific maneuver-based category applied.

Table 1: Operational definition, distinguishing feature, and classification basis for each of the 18 SCE categories

SCE ID	Operational definition, distinguishing feature, and classification basis
1	**Near-miss while changing lanes in dense traffic.*** Rider initiates a lateral movement between adjacent streams of traffic and must brake, swerve, or abort to avoid contact. Distinguished from SCE 7 in that no complete pass of a vehicle is achieved. Basis: video.
2	**Near-miss when another user does not give way at an intersection.**** Another road user enters the rider's path at an intersection without yielding, requiring evasive action by the rider. Other-initiated; mirrors SCE 8 by the actor who fails to yield. Basis: video.
3	**Loss of control on a sharp bend.** Rider loses traction or the intended line while negotiating a curve. Curved geometry is the proximal cause, and no other road user is involved. Basis: video.
4	**Loss of control on a slippery road.** Rider loses traction on the surface of reduced friction such as water, oil, or spillage. Distinguished from SCE 16 in that surface condition rather than road defect is the proximal cause. Basis: video.
5	**Near-miss after an unanticipated lane change by a user in front of the rider.** A vehicle ahead moves laterally into the rider's path with TTC below 3 s. Other-initiated lateral entry ahead; distinguished from SCE 6 in that the lead vehicle does not decelerate. Basis: kinematic-corroborated.
6	**Near-miss after unanticipated slowing of traffic ahead.** The lead vehicle decelerates unexpectedly, producing TTC below 3 s with visible deceleration on video. The precipitating event is a discrete deceleration ahead of the rider. Basis: kinematic-corroborated.
7	**Near-miss during an overtaking maneuver performed by the rider.***** Rider initiates a full pass of another vehicle and a conflict arises during the maneuver, with TTC below 3 s. Rider-initiated complete pass; distinguished from SCE 1, where no pass is completed, and from SCE 12, which is other-initiated. Basis: kinematic-corroborated.
8	**Near-miss when the rider does not give way at an intersection.****** Rider enters an intersection without yielding, requiring evasive action by the rider or another user. Rider-initiated; mirrors SCE 2 by the actor who fails to yield. Basis: video.
9	**Near-miss during filtering when another road user begins to turn.** Rider filters alongside stopped or slow traffic and another user begins a turn across the rider's path. Filtering combined with another user's turning movement, with no complete pass by the rider. Basis: video.
10	**Near-miss during route-finding in dense traffic.** Rider's attention is diverted to route-finding in dense traffic, producing a delayed response to a developing conflict. Applied only when no discrete precipitating maneuver by another user was present. Basis: video.
11	**Loss of control while turning immediately after starting.** Instability during a low-speed turn executed immediately after pulling away from a standstill. Distinguished from SCE

	3 by speed and geometry. Basis: video.
12	**Near-miss when another user overtakes the rider on the wrong side.** Another road user passes the rider on the unexpected side. Other-initiated pass; mirrors SCE 7 by actor. Basis: video.
13	**Loss of control due to wind.** A lateral gust displaces the motorcycle from its intended path. Environmental lateral force with no other road user involved. Basis: video.
14	**Tailgating when the rider follows too closely to the vehicle in front.** The rider was already travelling behind a lead vehicle at TTC < 3 s before the lead vehicle visibly decelerated, and a conflict developed during that deceleration. Distinguished from SCE 6 because the TTC criterion was already met before deceleration; in SCE 6, the discrete deceleration produced the short-TTC conflict. Basis: kinematic-corroborated.
15	**Near-miss caused by another rider losing control and nearly colliding with the participant.** Another rider loses control in the immediate vicinity and nearly contacts the rider. Third-party loss of control is the proximal cause. Basis: video.
16	**Loss of control due to a damaged road surface.** Rider loses control on a defective road surface such as a pothole or broken pavement. Distinguished from SCE 4 in that a road defect rather than reduced friction is the proximal cause. Basis: video.
17	**Near-miss when a blind spot prevents the rider from seeing another rider at an intersection or turn.***** Occlusion prevents the rider from detecting another user before a conflict develops at an intersection or turn. Applied only when occlusion is the proximal cause and no maneuver-based category applies. Basis: video.
18	**Near-miss caused by an oncoming vehicle driving too close at high speed.** An oncoming vehicle closes on the rider's path at speed, producing TTC below 3 s. Opposing direction of travel distinguishes this from all same-direction categories. Basis: kinematic-corroborated.

Note: Scenario labels for SCE 1–13 were adapted from Aupetit et al. (reference 19); their operational definitions and evidentiary rules were specified for this study. SCE 14–18 were identified during the pilot review; the finalized 18-category codebook was then applied to the complete OFF and ON analytic footage. These supplementary categories have not undergone external validation.
**Triggered by the rider's lateral movement in dense traffic*
***Triggered by another user failing to yield at an intersection*
****Triggered by the rider initiating a full overtaking maneuver past another vehicle*
*****Triggered by the rider failing to yield at an intersection*
******Near-miss occurs due to lack of visual detection prior to conflict*

2.2.2. Data Processing

An inter-rater reliability assessment was conducted to evaluate the consistency among raters in reviewing and classifying in-vehicle video recordings. Four raters independently evaluated 20 segments selected by stratified random sampling from the complete reviewed footage. The strata were defined by the presence or absence of an adjudicated SCE, so the reliability sample included both SCE and non-SCE footage and was not restricted to known events. The level of agreement among raters was calculated using the multi-rater version of Fleiss' Kappa coefficient. The result showed a Kappa value of 0.840, which falls within the "Almost Perfect Agreement" category as defined by Landis and Koch[26]. A p-value below 0.05 ($p<0.001$) indicated that the agreement was statistically significant. These findings demonstrate strong reliability in the ratings and confirm that the video assessment data were suitable for further analysis. MCAMS-recorded kinematic data, including time-to-collision (TTC), headway distance, and 3-axis acceleration, were used as objective reference signals to cross-validate video-based classifications, particularly for threshold-dependent SCE such as tailgating (SCE 14) and unanticipated slowing (SCE 6).

The individual rider was the unit of analysis. Each rider contributed one total SCE count for the OFF phase and one for the ON phase, yielding six matched pairs. The 18 SCE categories were not treated as independent experimental units, and category-level comparisons were descriptive only. The primary analysis was a two-sided exact Wilcoxon signed-rank test of the six paired rider totals. A secondary log-linear quasi-Poisson model estimated the exposure-adjusted phase rate ratio, with rider entered as a fixed effect and log ridden distance as an offset: log[E(SCE count)] = rider effect + phase effect + log(distance). Because distance was matched within each rider and recording gaps were excluded from the exposure in both phases (Section 2.1.2), the paired offsets were equal and represent observed rather than nominal ridden distance. The Poisson residual deviance was 20.98 on five residual degrees of freedom (dispersion = 4.20); the model-based standard error was therefore scaled by the quasi-Poisson dispersion. The phase effect is reported as an incidence rate ratio (IRR) with a 95% Wald confidence interval computed on the log scale using a normal approximation. Because the dispersion parameter is estimated from only five residual degrees of freedom, a t-based interval on the same five degrees of freedom is appreciably wider and includes unity (IRR 0.55, 95% CI 0.30-1.02).

3. Results

Analysis of the video recordings showed fewer SCE after activation of the MCAMS. A total of 205 SCE was

identified in the continuously screened footage during the baseline period (with the warning system off), decreasing to 113 during the intervention period (with the warning system on). This pooled count was 44.88% lower during ON, but it is a descriptive contrast rather than a significance test or causal effect estimate. Per-rider distances, durations, and trip counts are reported in Table 2, ensuring a fair, exposure-matched comparison between the two conditions.

Table 3 presents descriptive counts and within-condition percentages for the 18 SCE categories. Because the categories were not independent experimental units and several counts were sparse, no category-level hypothesis tests or causal interpretations were made.

Although most SCE categories showed reductions after MCAMS activation, several event types remained unchanged or increased. In particular, SCE 2, SCE 4, SCE 5, SCE 8, and SCE 12 showed higher frequencies during the warning-system-ON condition. In contrast, SCE 13 remained relatively unchanged. These event types were primarily associated with intersection, lateral, or complex multi-directional traffic interactions.

At the rider level, SCE counts decreased in five of the six paired observations. The primary exact Wilcoxon signed-rank test gave $W = 2$ and $p = 0.09375$ (reported as $p = 0.094$); therefore, the rider-level comparison did not reach the prespecified 0.05 significance threshold. The secondary distance-matched quasi-Poisson model estimated IRR = 0.55 (95% Wald CI 0.34-0.88), corresponding to a 44.88% lower model-estimated SCE rate in the ON phase; the corresponding t-based interval on five residual degrees of freedom is 0.30-1.02 and includes unity. The model estimate describes the magnitude and uncertainty of the observed rate contrast but does not supersede the nonsignificant primary test. Neither analysis identifies a causal system effect because phase order was fixed and no concurrent control group was observed.

Table 2: Per-rider exposure by phase (distance, duration, and trip counts)

Respondent	Matched distance per phase (km)	OFF screened (h)	ON screened (h)	OFF trips (n)	ON trips (n)
1	34.6	0.81	0.76	18	18
2	30.5	1.34	1.26	20	20
3	29.7	0.94	0.85	16	16
4	40.3	2.36	2.21	20	20
5	36.1	2.24	2.22	18	18
6	38.6	3.01	2.70	20	20
Total	**209.8**	**10.7**	**10**	**112**	**112**

Note: Distance, screened duration, and trip counts refer to the same matched analytic sample. Distance was matched within each rider, so 209.8 km applies to each condition (419.6 km across OFF and ON combined). The 10.7 h (OFF) and 10.0 h (ON) values are the complete footage screened from start to finish, not event-centered clips. Matching by distance permits screened duration to differ between conditions. The OFF and ON duration columns report the total duration of distance-matched trip footage in each phase, all of which was screened continuously from trip start to trip end for candidate SCE; they are not limited to segments around SCE occurrences. They exclude recording gaps and the later ON-phase footage that was not reviewed, and together they sum to the 20.7 h analysis window.

Table 3: Summary of SCE

ID	SCE scenario	Warning System OFF		Warning System ON		% changes
		Occurrences	Percentage	Occurrences	Percentage	
1	Near-miss while changing lanes in dense traffic	18	9%	6	5%	-66.67%
2	Near-miss when another user does not give way at an intersection	6	3%	10	9%	66.67%
3	Loss of control on a sharp bend	1	0%	0	0%	n.r.
4	Loss of control on a slippery road	0	0%	1	1%	n.r
5	Near-miss after an unanticipated lane change by a user in front of the rider	13	6%	15	13%	15.38%
6	Near-miss after unanticipated slowing of traffic ahead	52	25%	21	19%	-59.62%
7	Near-miss during an	31	15%	12	11%	-61.29%

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	overtaking maneuver performed by the rider					
8	Near-miss when the rider does not give way at an intersection	5	2%	6	5%	20%
9	Near-miss during filtering when another road user begins to turn left	4	2%	1	1%	n.r.
10	Near-miss during route-finding in dense traffic	14	7%	7	6%	-50%
11	Loss of control while turning immediately after starting	1	0%	0	0%	n.r.
12	Near-miss when another user overtakes the rider on the wrong side	8	4%	14	12%	75%
13	Loss of control due to wind	0	0%	0	0%	—
14	Tailgating when the rider follows too closely to the vehicle in front	36	18%	17	15%	-52.78%
15	Near-miss caused by another rider losing control and nearly colliding with the participant	3	1%	0	0%	n.r.
16	Loss of control due to a damaged road surface	2	1%	1	1%	n.r.
17	Near-miss when a blind spot prevents the rider from seeing another rider at an intersection or turn	5	2%	2	2%	n.r.
18	Near-miss caused by an oncoming vehicle driving too close at high speed	6	3%	0	0%	n.r.
	Total	**205**	**100%**	**113**	**100%**	**-44.88%**

Note: Counts are pooled across the six riders. Percentage changes are not reported (n.r.) for categories with fewer than 10 events across both phases, because a difference of one or a few events would yield large percentages that overstate their importance.

The decrease in the number of SCE is best interpreted as an observed association rather than as evidence of improved rider safety or a direct effect on rider awareness, neither of which was measured in this study. Notably, the most pronounced reductions were observed in SCE 6 (Near-miss after an unanticipated slowing of the traffic), SCE 14 (tailgating), and SCE 7 (near-miss during an overtaking maneuver performed by the rider).

Five riders had fewer SCE during ON, whereas one rider had more (15 OFF and 23 ON).

Table 4: Summary of SCE by participants

Respondent	OFF	ON	% Change
1	24	18	-25.00%
2	15	23	53.33%
3	59	29	-50.85%
4	48	14	-70.83%
5	26	6	-76.92%
6	33	23	-30.30%
Total	**205**	**113**	**-44.88%**

The within-rider differences were heterogeneous, ranging from −34 to +8 events (Table 4). Given the small sample, this pattern is reported descriptively and does not show that individual riders responded consistently to MCAMS.

4. Discussion

In this study, fewer SCE were observed during the system-ON phase than during the system-OFF phase among riders in Jakarta, Depok, and Bogor. Because the study used a within-rider design without a control group or randomized exposure, this reduction is best read as an observed association rather than as definitive causal evidence of system effectiveness. The primary rider-level test was not statistically significant, and the 95% confidence interval from the supportive quasi-Poisson model included no difference. The result is therefore potentially meaningful in magnitude but statistically uncertain. The fixed sequence, absence of concurrent control, and small convenience sample prevent attribution of the observed contrast to MCAMS.

Compared to Aupetit et al.[19], who identified 13 types of

SCE in France, this study highlights the more complex traffic dynamics in Indonesia, influenced by road conditions and interactions among road users. Dangerous behaviors such as tailgating, risky overtaking maneuvers, and loss of control due to damaged roads have emerged as additional SCE that reflect local traffic characteristics. Furthermore, Halim et al.[23] identified traffic violations and risky maneuvers as the leading causes of SCE. This study aligns with these findings and makes additional contributions to understanding physical environmental variables, such as road conditions and traffic dynamics. This study strengthens the argument that SCE are triggered not only by the rider's internal factors but also by the road environment and interactions with other road users.

Pooled across both phases, the three most frequently observed SCE types were SCE 6 (near-miss after an unanticipated slowing of traffic; 73 incidents), SCE 14 (tailgating when the rider follows too closely; 53 incidents), and SCE 7 (near-miss when overtaking another vehicle; 43 incidents). Prior studies have described abrupt overtaking and tailgating as high-risk maneuvers that motorcyclists commonly perform under high congestion and limited road space[27,28], and have linked such maneuvers to the dangers faced by riders in high-density traffic environments[29,30]. The present study, however, cannot establish that these conditions explain the prevalence of SCE 6, 14, and 7: traffic density was not recorded for the observed trips, and riders' motives for individual maneuvers were not assessed, so whether these maneuvers functioned as responses to congestion or commuting pressure remains an interpretation drawn from prior literature rather than a finding of this study. SCE 6, 14, and 7 also showed the largest decreases in pooled counts between the OFF and ON phases. This pattern is consistent with a possible association between MCAMS activation and reduced forward-conflict SCE, particularly those involving unanticipated traffic slowdowns, tailgating, and overtaking maneuvers; however, because phase was confounded with calendar time and traffic density, weather, and rider responses to alerts were neither measured nor controlled, the design does not permit attributing these decreases to the system. The persistence or increase in SCE associated with intersection, lateral, and complex multi-directional interactions warrants particular attention. SCE 2 (near-miss when another user does not give way at an intersection) and SCE 8 (near-miss when the rider does not give way at an intersection) both increased during the warning-system-ON condition. Similarly, SCE 12 (a near-miss in which another user overtakes the rider on the wrong side) showed the largest proportional increase at 75%, while SCE 5 (a near-miss after an unanticipated lane change by a user in front of the rider) rose by 15.4%. SCE 4 (loss of control on a slippery road) also appeared for the first time during the ON condition. SCE 13 (loss of control due to wind) remained at zero occurrences in both phases. These findings are consistent with the known limitations of forward-facing collision alert systems: MCAMS is designed primarily to detect longitudinal conflicts by monitoring headway distance and time-to-collision in the forward direction, and it does not capture threats originating from lateral, rear, or perpendicular approaches. Within the broader academic literature, this study extends prior NDS-based investigations by directly measuring the effect of an aftermarket warning system on SCE reduction in a dense, mixed-traffic environment. While earlier studies primarily focused on behavioral analysis or crash severity, this research provides preliminary, observational data on the use of a low-cost aftermarket warning system in an urban Southeast Asian context. Interestingly, the results of this study align with the findings of Omar and Lamin (2025)[21]. It is important to note that some studies have reported different contributing factors to Safety Critical Events than those reported in the present study. For instance, Chung[20] found that extreme weather conditions, such as rain, snow, and fog, were major contributors to SCE severity in South Korea[20]. In contrast, weather did not emerge as a dominant factor in the current study, likely because most data collection occurred during clear or mild rainy conditions, and Indonesian riders are generally accustomed to operating motorcycles in varied weather year-round. These differences underscore the importance of considering local traffic environments when evaluating the effectiveness of warning systems, such as MCAMS.

This study has several limitations; they implied that present findings should be regarded as preliminary and hypothesis-generating rather than as evidence of system effectiveness. First, the sample size was small (six participants), which may limit the generalizability of the findings; therefore, this study was designed as a pilot study to evaluate the warning system for Safety Critical Events rather than as a population-level inferential study. Second, data were collected only in Jakarta, Depok, and Bogor, so the results may not fully represent other regions with different traffic conditions. Third, the study used a sequential pre–post observational design in which the warning-system-OFF condition always preceded the warning-system-ON condition; therefore, temporal adaptation or learning effects cannot be fully separated from the potential influence of MCAMS. More specifically, all six riders experienced the OFF phase before the ON phase; the sequence was neither randomized nor counterbalanced, and no concurrent control group of riders with an installed but inactive system was observed. System activation is therefore completely confounded with calendar time and with any other change that occurred between the two observation windows, including riders' learning of the instrumented motorcycle, adaptation to being observed and to the recording equipment, and variation in traffic density, roadworks, weather, daylight, and travel patterns. Because traffic density and weather

were not recorded as covariates, the direction and size of these influences cannot be estimated. The fixed order was chosen deliberately to obtain an uncontaminated baseline, but this choice does not remove the confounding. Future evaluations should include a concurrent control group, randomize or stagger the timing of activation across riders or add a withdrawal (OFF–ON–OFF) phase, and record traffic and weather conditions so that they can be adjusted for. Fourth, statistical power was very limited. The primary analysis comprised only six paired rider totals. With six pairs, the two-sided exact Wilcoxon signed-rank test cannot yield $p < 0.05$ unless all six riders change in the same direction; once a single rider changes in the opposite direction, p cannot fall below 0.063, and the observed result was $p = 0.094$. The sample size was determined by device availability and the workload of manual video review rather than by power calculation. The evidence is therefore statistically inconclusive: the study demonstrates neither a difference in SCE frequency between phases nor rules one out. The rider-level counts and dispersion estimate reported here are intended to inform sample-size calculations for an adequately powered trial. Fifth, the intervention was only partly characterized. Although the hardware, sensing logic, and nominal TTC alert threshold are described, the number of warnings actually delivered to each rider during the ON phase was not extracted, and the relationship between individual warnings and the rider's subsequent behavior (e.g., throttle release, braking, or increased headway in the seconds after an alert) was not examined. Warning accuracy was also not assessed: the proportions of alerts associated with a genuine forward conflict, of alerts issued without a conflict (false alarms), and of forward conflicts for which no alert was issued (missed warnings), including conflicts below the low-speed suppression threshold, are unknown. Because warnings were visual only, alerts may also have gone unnoticed when the rider's gaze was directed away from the instrument cluster. Relating alert exposure, alert accuracy, and rider responses to SCE frequency, after blinded classification has been completed, is a priority for future analysis. Sixth, only the distance-matched portion of the recorded footage (20.7 of 70.5 h) was analyzed; although this portion was screened in full, SCE frequencies during the later, unreviewed ON-phase riding are unknown, and the ON window reflects only the first weeks of system use. The approximately 49.8 h of unreviewed footage was recorded entirely in the ON phase after each rider's matched distance had been reached, so the ON-phase estimate reflects only about the first two weeks of system use. Over longer periods, riders may be able to accommodate to the alerts, experience alert fatigue if false alarms are frequent, or compensate for the perceived protection by accepting shorter headways; conversely, safer following habits might consolidate over time. None of these longer-term processes can be evaluated from the present data, and the observed ON-phase difference may partly reflect a short-term novelty response. Reviewing the remaining ON-phase footage and examining SCE rates across successive weeks of system use would help to characterize longer-term adaptation. In addition, SCE occurring during recording gaps could not be ascertained; these gaps were removed from both counts and exposure, but if their occurrence was related to riding conditions, observed exposure may not be fully equivalent between phases. Finally, although inter-rater reliability was strong, manual classification of SCE may still involve misclassification or subjective interpretation. Fleiss' Kappa result indicates high agreement, but it was derived from only 20 stratified segments and therefore represents a limited internal reliability assessment. There is a limitation because of sparse SCE categories may have been represented by few or no segments, so category-specific agreement could not be estimated; and because the segments were stratified by the presence or absence of an adjudicated SCE rather than by phase, the assessment does not show whether agreement was equivalent for OFF and ON footage. It also does not quantify detection sensitivity, that is, the proportion of true SCE missed during continuous screening, or intra-rater consistency over time. Future research should address these limitations by expanding participant diversity and geographic coverage, adding analysis of traffic density and weather conditions, and incorporating automated classification methods.

Bearing these limitations, the data are consistent with an exploratory within-rider association between the system-ON phase and a lower frequency of forward-conflict SCE; this association was not statistically significant at the rider level and cannot be separated from changes over time. Accordingly, the directions outlined below are offered as hypotheses for future work rather than as validated recommendations. Because rider responses to individual alerts were not measured, the present data cannot show whether warnings changed how riders responded to unexpected traffic situations such as sudden slowdowns or abrupt maneuvers by surrounding vehicles; linking alerts to rider responses is a priority for future work. Beyond forward warnings, previous studies have suggested several approaches for improving motorcycle safety systems and rider awareness, including the use of lateral detection features, wider sensing coverage, Vehicle-to-Vehicle (V2V) communication systems, and visual traffic-calming measures such as rumble strips and speed-reduction zones[31,32]. In addition, educational programs and strengthened traffic-safety campaigns have also been proposed to improve rider behavior and traffic-rule compliance[33–36]. Although these aspects were not directly evaluated in the present study, they may serve as considerations for future research and development on motorcycle warning systems and urban traffic safety.

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5. Conclusion

In this exploratory study of six riders, fewer SCE were observed during the distance-matched system-ON phase than during the system-OFF phase. Pooled SCE counts were 44.88% lower under the system-on condition (205 vs. 113), but this descriptive figure carries limited inferential weight: the primary rider-level exact Wilcoxon test was not significant ($p = 0.094$), and the t-based 95% CI for the rate ratio included unity (IRR 0.55, 0.30–1.02). Moreover, because rider awareness was not directly measured, this difference cannot be attributed to improved awareness of potential road hazards. The three most dominant SCE identified were SCE 6 (near-miss after an unanticipated slowing of the traffic), SCE 14 (tailgating), and SCE 7 (near-miss during overtaking), which reflect common risk patterns in areas with high vehicle density. SCE 6, 14, and 7 also showed the largest absolute decreases in pooled counts between the OFF and ON phases. Because these are forward-conflict categories that MCAMS is designed to address, they are priority outcomes for future controlled evaluations. The main contribution of this study is to show that a low-cost aftermarket warning system can be evaluated in naturalistic urban riding in Indonesia and to provide preliminary estimates for the design of larger studies. Overall, the findings suggest that MCAMS may help reduce exposure to certain safety critical riding situations. Its potential to adapt to various risk directions, along with the need for educational and regulatory approaches, offers an optimistic outlook for its future development and the maximization of its benefits. However, this study is exploratory, arising and the reported within-subject differences arise from a single, fixed sequential OFF-then-ON design without a control group or randomized exposure. Establishing whether MCAMS confers a genuine safety benefit will require larger, randomized, and longer naturalistic riding studies with matched or controlled exposure across the system-off and system-on conditions. Until such evidence is available, the findings reported here should be regarded as preliminary and hypothesis-generating rather than confirmatory.

Based on the findings of this study, it is recommended that future research not only evaluate the number of SCE but also examine rider behavior. The involvement of a larger number of participants with diverse route characteristics, age groups, and traffic conditions is essential for improving the generalizability of the results. Additionally, the use of supplementary measurement methods, such as physiological data or subjective rider perceptions, could enrich the analysis of the safety system's effectiveness. If confirmed by controlled studies, such evidence could inform the development of active safety systems suited to urban traffic conditions.

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Nomenclature

Symbol	Description
ABS	anti-lock braking system
AHO	automatic headlights on
ARAS	advanced rider assistance system
CBS	combined braking system
CI	confidence interval
FOV	field of view
IRR	incidence rate ratio
LiDAR	light detection and ranging
MCAMS	Motorcycle Collision-Alert and Management System
NDS	naturalistic driving study
SCE	safety critical events
TTC	time to collision
V2V	vehicle-to-vehicle

CRediT authorship contribution statement

M.A.P.: Conceptualization, methodology, supervision, funding acquisition, and writing – original draft. J.R.S.: Investigation, data curation, formal analysis, and writing – review and editing. R.J.H.: Resources and writing – review and editing. F.G.: Methodology, formal analysis, and writing – review and editing. D.H.S.: Investigation, project administration, and writing – review and editing. H.I.: Validation and writing – review and editing. D.A.F. and R.A.W.: Investigation, data curation, and writing – review and editing. All authors reviewed and approved the submitted manuscript.

Competing interests

R.J.H. is affiliated with Motorcycle Safety Solutions, LLC, the company that developed and supplied the MCAMS units evaluated in this study and supported participant funding; this relationship constitutes a potential competing interest. The remaining authors declare no known competing financial interests or personal relationships that could have influenced the work. The contribution of each author is reported in the CRediT statement.

Role of the commercial supporter

Motorcycle Safety Solutions, LLC supplied the MCAMS devices, supported participant funding, provided technical

information about the device, and reviewed the manuscript. The academic investigators retained access to the study data and responsibility for the protocol, footage screening, SCE adjudication, statistical analysis, interpretation, and decision to submit. The commercial supporter had no unilateral authority to alter the results or veto publication.

Data availability

De-identified rider-level SCE counts, exposure summaries, and analysis code supporting the reported results are available from the corresponding author on request, subject to institutional approval. Raw video cannot be shared because it contains identifiable images of participants and third-party road users who did not provide consent for public data release.

Data privacy and protection

Video files were transferred from device memory cards to an external hard drive that was password-protected and encrypted. Files were labelled with participant codes rather than names, and access was restricted to authorized research-team members involved in data processing. Both forward-roadway and rider-facing video channels were recorded; only footage required for SCE classification and quality control was reviewed. Third-party road users were not identified, and no image containing an identifiable face or license plate is reproduced in this article. Raw footage is not publicly shared. Recordings will be securely and permanently deleted when the retention period specified in the institutional ethics approval (Ket-94/UN2.F10.D11/PPM.00.02/2025) is reached.

Declaration of generative AI use

During revision, Claude AI was used to support language editing, and consistency checking. The authors reviewed and verified all AI-assisted text and took full responsibility for the manuscript. Generative AI was not used to collect or alter study data, classify SCE, or determine the reported statistical results.

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