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Speed and Lane Change Characteristics of Motorcycles at Priority Junction

Benidiktus Susanto, Siti Malkhamah*, Latif Budi Suparma, Arumdyah Widiati
Department of Civil and Environmental Engineering, Universitas Gadjah Mada, Yogyakarta, INDONESIA
*Corresponding author: malkhamah@ugm.ac.id

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ABSTRACT Motorcycles are Indonesia's predominant mode of transportation and contribute to a substantial share of road traffic accidents. The research aims to identify key behavioural factors contributing to motorcycle-related conflict risks at intersections and to propose evidence-based safety interventions. This study analyzed speed characteristics with varying degrees of disruption that motorists would experience at the intersection. These disruptions were categorized into high, low, no disruption, and left-turn movements. High disruption was defined as vehicles stopping in the middle of the intersection as motorcyclists approached, while low disruption was defined as vehicles preparing to enter the intersection from minor roads. In addition to speed characteristics, this study also observed lane-changing behavior when disruptions occurred at the intersection. To obtain detailed data, drone-based cameras were used for observations, and the results were validated against radar speed measurements. The results show that 67.94% of riders exceed the 60 km/h speed limit during the morning period, while 33.27% exceed it in the afternoon, indicating clear temporal differences in operating speeds. Approximately 85 per cent of lane-changing manoeuvres occur within 20 metres of the conflict point, reflecting short decision distances that increase collision risk. Riders also exhibit assertive gap-acceptance behaviour, often requiring main-road vehicles to adjust their speed. Statistical validation confirms that there is no significant difference between drone-derived and radar-based speed measurements, demonstrating the reliability of the drone-based methodology. Based on these findings, the study recommends targeted speed management measures, including automated enforcement and the use of traffic-calming devices; improved lane discipline through more precise road markings and selective physical separation; and junction design enhancements, such as motorcycle waiting areas and advanced stop lines. These measures can improve motorcycle safety at priority junctions and support more efficient and predictable urban traffic operations.

KEYWORDS Motorcycle; Speed; Lane-changing behaviour; Priority junction; Traffic safety.

1 INTRODUCTION

Motorcycles dominate Indonesia's crash statistics and consistently emerge as the most vulnerable mode of transportation. National data show that up to 74% of all road-traffic fatalities involve motorcycle users, while broader accident records indicate that 87.36% of reported crashes involve motorcycle riders. These patterns align with evidence that Indonesia loses one life on the road every 20 minutes, with a substantial share of victims consisting of young and inexperienced riders (Irawan et al., 2022; Anggraini et al., 2024; Lumba et al., 2024). Taken together, these figures indicate not only the scale of motorcycle-related safety problems but also the need to prioritise behaviour-based safety interventions rather than solely expanding infrastructure. Furthermore, speeding or exceeding the speed limit appears to be a major problem for drivers in many countries, even in developed countries like the UK. This condition underscores the urgent need to address motorcycle safety in urban environments, particularly in mixed-traffic systems where interactions between motorcycles and other vehicle types are highly complex. Such conditions create highly dynamic conflict patterns that differ significantly from those of car-dominated traffic systems, especially in Southeast Asian cities (Mokhtar et al., 2023).

Speed is widely recognised as a significant factor influencing the occurrence and severity of crashes, as higher speeds reduce reaction time and increase impact forces (Tanishita and van Wee, 2017; Abdul Manan et al., 2018). In motorcycle-dominated traffic, speed selection and behavioural adjustments become crucial, particularly near conflict-prone locations such as intersections.

Furthermore, in dense urban environments, intersection safety is significantly compromised by constrained sight distances, often exacerbated by physical obstructions such as buildings or vegetation, as well as changes in road infrastructure over time. Moreover, the complexity of urban intersections leads to decreased perception–reaction windows and variable vehicle behaviours, thereby increasing the likelihood of crashes

(Intini et al., 2021; Kilani et al., 2021). At priority junctions, where right-of-way rules place greater decision-making responsibility on minor-road users, motorcyclists face heightened exposure to near-conflict situations due to limited stopping distances and lateral manoeuvring space.

This relationship suggests that relatively small reductions in speed near intersections can significantly improve safety, particularly for vulnerable road users such as motorcyclists (International Transport Forum, 2018; Torrão, 2022).

Intersections are among the most hazardous points in urban networks due to multiple potential conflict zones. A type of intersection often found in urban areas is the priority intersection. At priority intersections, where traffic on the main road has the right of way and vehicles from the minor road must yield, there are a high number of vehicle-related conflicts and crashes, particularly involving motorcyclists.

Previous studies have discussed vehicle-specific speed reduction behaviour at intersections; however, limited attention has been given to motorcycle behaviour at priority intersections under local traffic conditions (Rusli et al., 2020; Shafie et al., 2022; Amegah et al., 2023). In the Indonesian context, most existing studies focus either on general traffic safety, signalised intersections, or aggregated vehicle classes, leaving motorcycle-specific speed and lane-changing behaviour at priority intersections largely unexplored. In Indonesia, aggressive riding habits, narrow lane widths, and the absence of physical lane separators further exacerbate these safety challenges. Local geometric constraints and mixed-traffic characteristics often lead to unpredictable lateral movements and shorter decision-making distances, thereby elevating crash exposure around conflict points (Kurniati, Afyendo and Putri, 2020; Kurniati, Purnawan, Yosritzal and Putri, 2020; Anggraini et al., 2024; Pujiantoro and Manullang, 2025). This condition highlights a research gap in understanding how motorcycle speed adjustments and lane-changing behaviour interact simultaneously at priority intersections under mixed traffic conditions.

Previous studies have also highlighted a strong relationship between speed reduction and crash severity; however, empirical research on motorcycle behaviour, particularly regarding lane changes and perceived conflicts at priority intersections, remains limited (Elvik, 2005; Cameron and Elvik, 2010; Mohan, 2016).

Therefore, this study aims to analyse motorcycle speed characteristics and lane-changing behaviour at priority intersections in Yogyakarta using drone-based observations validated by radar measurements. This study contributes by providing an integrated behavioural analysis of speed compliance, deceleration patterns, and lane-changing distances under mixed traffic conditions, thus offering empirical evidence to support targeted safety interventions in motorcycle-dominated urban environments.

Yogyakarta was chosen as the research location because it represents a medium-sized city in Indonesia. This condition is reflected in its heavy reliance on motorcycles and mixed traffic, making it suitable for analysing motorcycle behaviour at priority intersections.

2 METHODS

2.1 Field Procedures

The study took place along Adisucipto Street in Yogyakarta, Indonesia—an arterial corridor that carries a high volume of motorcycles and experiences frequent instances of speeding behaviour. This location was selected because it represents a typical urban arterial in a medium-sized Indonesian city, characterised by high motorcycle dependency and mixed-traffic conditions.

The selected segment represents a priority junction, where vehicles on the main road have the right of way, and those entering from the minor road must yield to them. This corridor typifies the mixed-traffic conditions commonly observed in Indonesian urban areas, making it an ideal site for analysing real-world motorcycle operating behaviour under priority-control conditions.

Field observations took place during two peak-hour periods: 8:00–9:00 a.m. and 3:00–4:00 p.m., representing commuting and return-flow conditions, respectively. Preliminary traffic counts identified the highest motorcycle flows and the behavioural contrast between morning urgency and afternoon relaxation, which defined the observation times. All data collection occurred under clear and dry weather conditions to ensure consistent visibility and to minimise potential measurement errors caused by rain, glare, or wind.

An observation segment approximately 150 metres in length was located upstream of the priority junction to ensure that recorded speeds represented free-flow conditions unaffected by deceleration near the intersection. Drone cameras and radar speed guns covered the same segment simultaneously, enabling synchronised measurement and cross-validation between aerial and ground-based data. The observation segment length was selected to ensure sufficient distance for capturing stable operating speeds while avoiding speed changes induced by intersection approach behaviour.

Field instruments underwent calibration prior to data collection, and each observation was assigned an in-

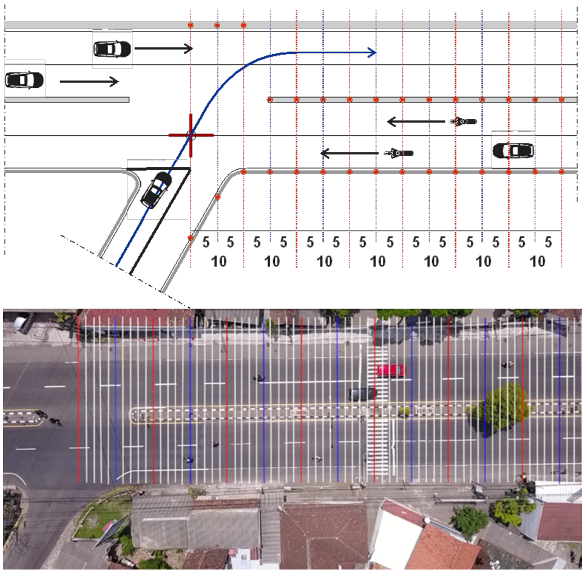


Figure 1. Drone Camera Setup for Speed Measurement

dividual timestamp to facilitate precise alignment between datasets. The collected data formed the basis for analysing speed variation, lane-changing distance, and the influence of surrounding traffic conditions under mixed-traffic environments.

2.2 Data Collection Instruments

This study relied on two primary instruments to obtain motorcycle operating data: drone cameras and radar speed guns. Both instruments monitored the same 150-metre observation segment to maintain consistent spatial coverage and to enable cross-validation of the recorded speeds.

The drone cameras captured continuous aerial footage from an altitude of approximately 50 metres, providing an unobstructed view of motorcycle trajectories. This perspective enabled the accurate extraction of longitudinal movement, lateral displacement, and lane-changing behaviour.

Owing to battery constraints, the research team conducted drone flights in consecutive 15-minute intervals, with observation periods scheduled back-to-back to ensure uninterrupted data collection during peak-hour windows.

The research team adjusted the camera angle during each flight to maintain image stability under varying wind conditions. Figure 1 illustrates the drone's operational configuration, including altitude, viewing angle, and field of coverage.

The drone camera footage was processed by adding lines to the video to facilitate speed determination. The lines were used to create observation segments. The distance between red lines was 10 meters, between

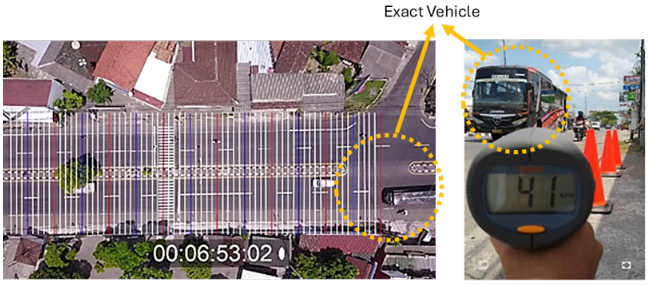


Figure 2. Speed Gun Measurement Setup

blue lines and blue lines was 10 meters, between red and white lines was 1 meter, and between white and blue lines was 1 meter. Speed was calculated by dividing the distance traveled by the desired segment distance. In this study, the segment length used was 5 meters.

Radar speed guns served as ground-based reference instruments to verify the speed values extracted from the drone footage. The team positioned each radar device 150 metres upstream of the priority junction so that all recorded speeds reflected free-flow conditions unaffected by deceleration near the conflict zone. Each radar reading included an embedded timestamp, which enabled precise synchronisation with the corresponding drone-derived observations. Figure 2 illustrates the placement and operating position of the radar speed gun.

The research team calibrated both instruments before field deployment, and the analysis synchronised all measurements through timestamp matching across devices. The combined use of drone footage and radar speed guns ensured the accurate estimation of motorcycle operating speeds, consistent measurement across platforms, and reliable identification of lane-changing characteristics under mixed traffic conditions.

2.3 Speed Measurement Procedure

This subsection explains the procedure used to measure motorcycle speeds along the 150-metre upstream observation segment. The research process extracted speed values from drone footage and radar speed gun recordings and synchronised the two datasets through timestamp matching to maintain consistency across instruments.

The team employed a time–distance approach to determine speeds from the drone recordings. Analysts tracked motorcycle positions at 5-metre intervals using the 50 frames-per-second video feed, which allowed for the precise calculation of travel time between consecutive reference points. The analysis computed instantaneous speed values by dividing the measured distance by the corresponding travel time. Only motorcycles travelling under free-flow conditions, without interference from surrounding vehicles, were included in the dataset to preserve the validity of the speed profiles.

Radar speed guns supplied complementary point-speed measurements at a fixed location 150 metres upstream of the priority junction. Each radar reading included an embedded timestamp, enabling direct alignment with the drone-derived trajectories and supporting validation of the calculated speeds.

Following the extraction, the research team compiled all speed observations into a unified dataset and classified them by morning and afternoon periods. The team conducted descriptive statistical analyses, including minimum and maximum speeds, mean speed, standard deviation, and the distribution of observations across defined speed ranges. The team quantified speed reduction near the junction by comparing upstream free-flow speeds with those measured in the conflict zone, thereby capturing behavioural adjustments during junction approach.

2.4 Video Review and Data Extraction

This subsection explains the procedure used to extract speed and lane-changing information from the drone recordings. The research team reviewed all video footage recorded at 50 frames per second, which provided sufficient temporal resolution to track motorcycles at 5-metre intervals. Analysts identified motorcycles travelling under free-flow conditions and traced their longitudinal positions frame by frame to determine travel time between reference points.

The review process also identified lateral movements relevant to lane-changing behaviour. Analysts recorded the point at which each motorcycle initiated a lane change, the lateral displacement pattern, and the distance from the conflict zone at the time of manoeuvre. The analysis excluded any motorcycle trajectories influenced by surrounding vehicles, pedestrian movement, or side friction to maintain the accuracy of the extracted behaviour.

The extraction procedure produced a structured dataset containing position, time, speed, and lane-changing attributes for each valid motorcycle trajectory, which formed the basis for the obstacle classification and subsequent statistical analysis.

2.5 Obstacle Classification

This subsection describes how the study classified traffic conditions on the minor road to analyse their influence on motorcycle behaviour. The classification relied on the presence and movement of vehicles on the minor approach observed in the drone footage. Additionally, this classification was applied to a consistent observation window of 50 metres upstream of the stop line to ensure that all traffic conditions were evaluated within the same visual detection zone. This operational boundary improves the consistency and repeatability of the classification process. The analysis assigns each motorcycle trajectory to one of four categories:

1. No obstacle: No vehicles are on the minor road within 50 metres of the stop line. This condition indicates uninterrupted traffic flow with no visible interaction or conflict from the minor road.
2. Low obstacle: One or more vehicles are stopped behind the stop line on the minor road. This condition reflects passive interaction where vehicles are present but do not directly interfere with the motorcycle's path.
3. High obstacle: One or more vehicles are crossing the intersection from the minor road. This condition indicates an active conflict situation where movement through the intersection directly affects the speed and decision-making of approaching motorcycles.
4. Left turn: A motorcycle is executing a left turn manoeuvre at the intersection. This category indicates manoeuvre-based conditions that require adjustments in speed and lateral movement due to geometric and operational constraints.

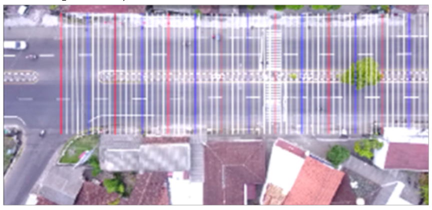
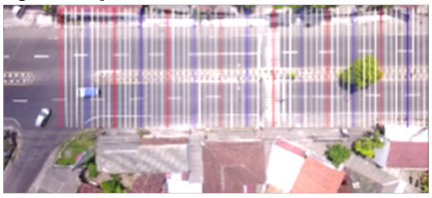
The research team defined these categories to represent increasing levels of potential conflict and decision-making complexity at the priority junction. These classifications were used as categorical variables in the analysis to compare speed distributions, deceleration patterns, and lane-changing behaviour across different traffic interaction conditions.

Table 1 summarises the four obstacle categories used to classify minor road conditions. The table also provides operational definitions and visual illustrations to support consistent interpretation and reduce subjectivity during data extraction from drone observations.

2.6 Statistical Validation

This subsection outlines the procedure used to validate drone-based speed measurements against radar speed gun data. A total of 30 paired observations were selected, each consisting of a drone-derived speed value and a corresponding radar measurement recorded at the same time via time synchronisation. This paired approach ensures that both instruments capture identical traffic conditions, enabling meaningful comparisons.

Table 1. Minor-Road Conflict Classification

No	Category	Definition, Characteristics and Illustration
1	No obstacle	• No vehicle is present on the minor road within 50 m upstream of the stop line. • No conflict. • Motorcycles operate under free-flow conditions without interaction. 
2	Low obstacle	• One or more vehicles are stationary behind the stop line on the minor road without entering the junction. • Passive conflict. • Minor speed adjustment with limited interaction. 
3	High obstacle	• One or more vehicles from the minor road are entering or crossing the junction. • Active conflict. • Significant speed reduction and reactive manoeuvres. 
4	Turning left	• The motorcycle performs a left-turn manoeuvre toward the minor road. • Manoeuvre-based interaction. • Speed reduction and lateral repositioning due to geometric constraints.

A two-tailed Z-test was used to compare the average speeds obtained from both measurement methods. Because the sample size (n= 30) of this test meets the assumptions of the central limit theorem, and the paired observations are synchronized in both time and location, allowing the sample distribution of mean differences to approximate normality. Furthermore, the Z-test provides a simple and widely accepted approach for comparing two measurement systems under controlled observation conditions.

The analysis used a significance level of α = 0.05, and the test statistic was calculated using the pairwise mean differences, pooled standard deviations, and sample sizes. Descriptive statistics and validation results are presented in the Results section to provide a clearer interpretation of the comparison between the measurement methods.

This validation procedure ensures that this study relies on accurate, internally consistent speed measurements before conducting further behavioural analysis.

Statistical validation techniques, including the Z-test, ensure the reliability and consistency of data across different measurement methods. In transportation studies, similar validation approaches have been widely applied to assess the consistency between different speed measurement techniques, such as video-based and sensor-based systems, ensuring that alternative methods accurately represent actual traffic conditions without introducing systematic bias (Losa et al., 2013).

The selection of an appropriate statistical method should consider factors such as sample size, data distribution, and the analysis's purpose. In this study, the Z-test was deemed appropriate given the sample size (n = 30) and the paired nature of the observations, which meet the assumptions for statistical testing (Gulati, 2025).

Furthermore, applying this validation approach strengthened the robustness of the data collection framework by confirming that there were no statistically significant differences between drone and radar-based speed measurements. This consistency indicates that the drone-based method can reliably represent actual field conditions and can be used with confidence for further analysis of speed behaviour and lane-changing characteristics in mixed traffic environments.

3 RESULTS AND DISCUSSION

3.1 Speed Distribution and Acceleration

Figure 3 presents the distribution of operating speeds for both the morning and afternoon observation periods. The morning distribution shows a wider spread, with several riders travelling at noticeably higher speeds. This pattern reflects the increased urgency associated with morning commuting, when riders tend to maintain higher cruising speeds and accelerate more aggressively along arterial corridors. In the Indonesian urban context, this urgency is often linked to work-related travel constraints, limited schedule flexibility, and perceived time pressure, which collectively encourage higher risk-taking behaviour.

Previous studies have also reported similar temporal variation patterns, where morning peak periods are associated with higher average travel speeds and more aggressive acceleration behaviour among motorcycle commuters in urban Southeast Asian traffic environments (Ibrahim et al., 2024; Firmansyah et al., 2025). These findings suggest that temporal demand characteristics play a critical role in shaping motorcycle operating behaviour, particularly in mixed-traffic corridors with limited enforcement presence.

Table 2 summarises the descriptive statistics for both

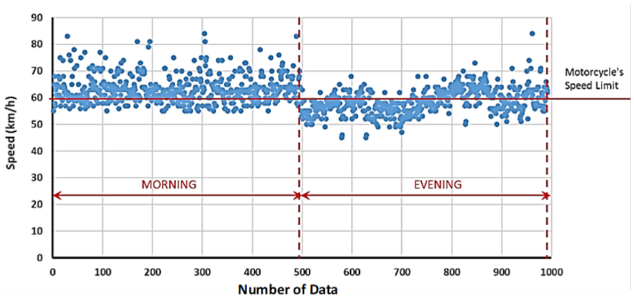


Figure 3. Motorcycle's Speed Distribution and Speed Limit (km/h)

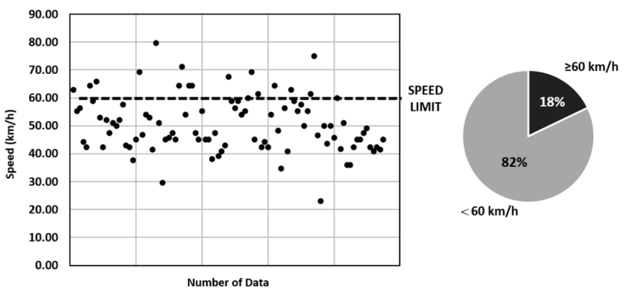


Figure 4. Motorcycle speed distribution approaching a priority junction (km/h)

periods. The morning mean speed reaches 63.45 km/h, and 67.94% of riders exceed the posted speed limit of 60 km/h. Several riders accelerate to 84 km/h, indicating a strong preference for higher speeds during the morning peak. Such high speeds substantially increase kinetic energy and reduce available reaction time, thereby increasing the potential severity of crashes when conflicts occur near priority junctions.

In contrast, the afternoon mean speed decreases to 58.53 km/h, and the proportion of speeding riders declines sharply to 33.27%. The minor variations and lower peak speeds in the afternoon suggest more stable operating behaviour and reduced acceleration intensity. This shift indicates a behavioural transition from goal-oriented commuting to more relaxed return-flow travel, in which riders exhibit greater speed compliance and smoother acceleration patterns.

This pattern aligns with previous findings that peak-hour trip purpose significantly influences operating speed. Specifically, work-related commuting produces higher speed variance and a greater likelihood of speeding violations compared to discretionary or return-flow travel (Tseng, 2013; Wang et al., 2025). From a safety perspective, higher variance, combined with elevated mean speeds, increases both crash likelihood and injury severity, particularly for motorcycles approaching unsignalized conflict points.

Table 2. Motorcycle Speed Distribution

Statistics Value	Morning (8:00 - 9:00 AM)	Afternoon (3:00 - 4:00 PM)
Sample size (*n*)	496	496
Mean (km/h)	63.45	58.53
Standard Deviation (km/h)	5.37	4.91
Min (km/h)	55	45
Max (km/h)	84	84
Speed > 60 km/h (speed limit)	67.94% (337)	33.27% (165)
Speed ≤ 60 km/h (speed limit)	32.06% (159)	66.73% (331)

Beyond overall speed levels, acceleration patterns along the 150-metre upstream segment also differ between the two periods. Morning riders tend to sustain higher acceleration over a longer distance, producing a steeper speed–distance profile. This sustained acceleration suggests limited anticipation of downstream conflicts and a stronger tendency to prioritise travel time over safety margins.

Afternoon riders accelerate more gradually and stabilise at lower operating speeds. Such behaviour reflects improved hazard anticipation and greater willingness to adjust speed in response to perceived junction risk. Higher acceleration near conflict zones has been associated with increased crash severity potential because elevated kinetic energy reduces perception–reaction time and braking effectiveness (Paul and Ghosh, 2021).

Figure 4 illustrates these differences by showing how riders adjust their speeds along the approach segment.

Overall, these contrasting patterns highlight the significant influence of temporal factors on motorcycle operating behaviour. Morning riders maintain higher speeds and exhibit greater variability, both of which increase the likelihood and severity of crashes, particularly when approaching conflict-prone priority junctions. Afternoon riders tend to demonstrate more moderate and predictable speed profiles, thereby reducing their overall exposure to high-risk conditions.

These findings reinforce the safety implications of targeted speed management during morning peak periods, which may yield substantial benefits in reducing crash risk. Similar findings suggest that even small increases in average speed can significantly amplify the severity of crash injuries, particularly for vulnerable road users such as motorcyclists (Lubbe et al., 2022).

3.2 Speed Reduction near Junction

Figure 5 presents the speed profiles of motorcycles as they approach the priority junction under four distinct traffic conditions: no obstacle, low obstacle, high obstacle, and left-turn manoeuvres. The figure shows that riders adjust their speeds primarily in response

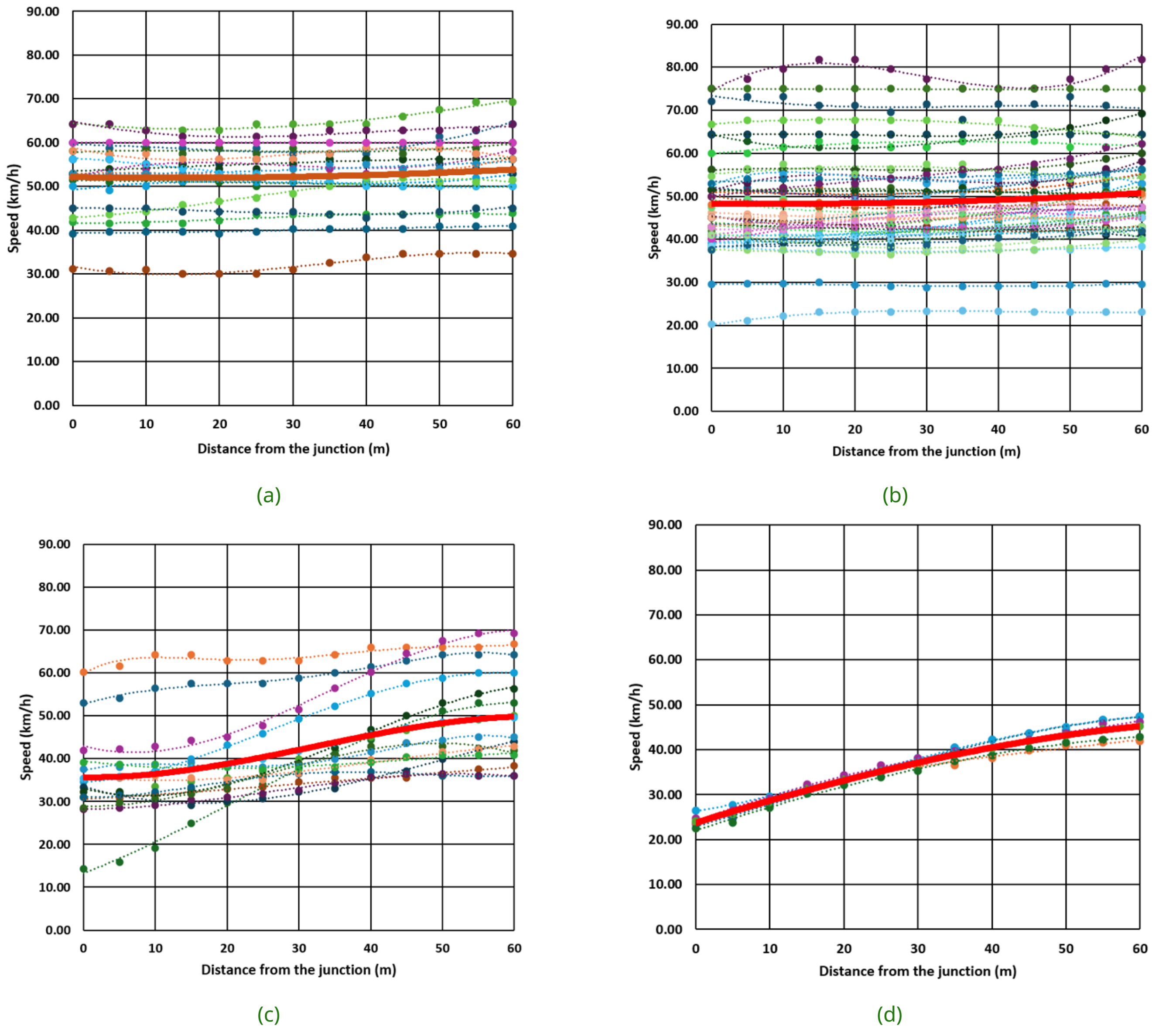


Figure 5. Approaching speed (km/h) profiles under different traffic conditions : (a) No obstacle, (b) Low obstacle, (c) High obstacle, (d) Left turn

to visible, immediate conflicts rather than to passive cues along the minor road. Speed reduction was derived by comparing the upstream free-flow operating speed with the speed observed closer to the conflict point along the approach segment, thereby capturing behavioural deceleration during junction negotiation.

When the minor road is clear and no obstacle is detected, riders reduce their speed by only 3.15 per cent along the final segment of the approach. This minimal reduction indicates that riders maintain a strong desire to preserve cruising speed when they perceive no active conflicts ahead. From a behavioural perspective, this suggests that the absence of visible threats leads riders to prioritise travel efficiency over precautionary deceleration, even when approaching a conflict-prone junction.

Under low-obstacle conditions, when one or more vehicles are stopped behind the stop line on the minor road, riders decrease their speed by approximately 5%. Although this reduction is slightly more pronounced, stationary vehicles still do not trigger substantial deceleration, suggesting that riders view low obstacles as low-risk situations. Such behaviour indicates that passive visual cues alone are insufficient to prompt significant speed adjustment, potentially reflecting an underestimation of latent conflict risks associated with sudden vehicle movements from the minor road.

A significantly sharper decline occurs under a high-obstacle condition, when a vehicle is crossing the junction from the minor road. In this scenario, riders reduce their speed by 29 per cent, demonstrating a marked behavioural response to direct conflict within the inter-

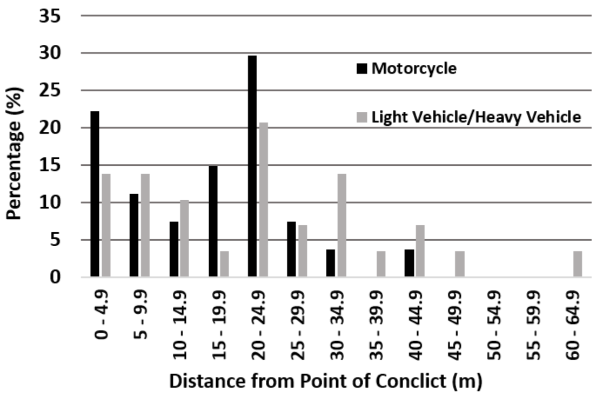


Figure 6. Lane-change distance for motorcycles, light vehicles, and heavy vehicles

section. This substantial deceleration indicates that riders recognise the active obstruction as a serious hazard requiring immediate corrective action. The magnitude of this speed reduction reflects heightened risk perception and a rapid appraisal of hazards when the conflict becomes explicit and unavoidable.

Motorcyclists performing a left-turn manoeuvre display a distinct behavioural pattern. Riders begin to slow down roughly 60 metres before reaching the conflict point and stabilise at an average turning speed of 24 km/h. This behaviour reflects the combined influence of geometric constraints, lane-positioning requirements, and the need for additional steering control during the turning movement. Unlike through movements, left-turn manoeuvres require anticipatory deceleration to maintain balance and manoeuvrability, resulting in earlier and more gradual speed reduction. The pattern also appears at a roundabout, where the driver needs to decelerate to navigate its geometric layout (Aziz et al., 2025).

Overall, the results highlight a clear tendency: motorcyclists decelerate meaningfully only when confronted with active conflicts, such as vehicles crossing the junction. Passive or indirect cues, such as vehicles waiting at the stop line, trigger only marginal adjustments in speed. This pattern suggests that riders may underestimate the risks associated with potential conflicts, thereby increasing their exposure to severe collisions when unexpected movements occur within the conflict zone. From a safety perspective, this behaviour underscores the importance of enhancing visual conspicuity and active warning measures at priority junctions to encourage earlier and more consistent speed reduction.

3.3 Lane Change Behavior

Figure 6 illustrates the distance at which motorcycles, light vehicles, and heavy vehicles initiate lane-change manoeuvres as they approach the priority junction. This analysis includes both light vehicles and heavy vehicles to provide a comparative behavioural context and capture interaction effects under mixed-traffic conditions. At the same time, motorcycles remain the primary focus of safety evaluation.

The results show a distinct behavioural difference between motorcycles and larger vehicles. Motorcycle riders tend to perform their lane-change manoeuvres much closer to the conflict point, with 85 per cent of riders initiating the manoeuvres within 20 metres of the junction. This short decision distance indicates limited anticipation and narrower reaction margins, which heighten the risk of abrupt lateral movements in the conflict zone. Such late manoeuvres reduce the available response time for both riders and surrounding traffic, thereby increasing the likelihood of near-conflict situations.

Light vehicles and heavy vehicles exhibit more predictable behaviour. These vehicles initiate lane changes farther upstream, maintain more stable lateral positioning, and demonstrate a higher level of anticipation. Their behaviour suggests more deliberate planning and slower interaction with the surrounding flow, reducing potential conflicts with adjacent traffic. The larger vehicle size, lower manoeuvrability, and higher perceived crash severity likely encourage earlier decision-making and more conservative lateral movements.

Motorcycles, in contrast, display more reactive and less disciplined lateral movement. Riders often adjust their position only when they encounter slower vehicles, respond to perceived conflicts, or attempt to bypass congestion near the junction. This behaviour leads to rapid lateral shifts, sharper movement angles, and reduced inter-vehicle clearance, which collectively increase the likelihood of rear-end collisions, side-swipe conflicts, and unpredictable manoeuvres within the conflict area. In mixed-traffic environments, such reactive behaviour can propagate instability in the traffic stream and amplify the severity of conflicts at priority junctions.

Figure 7 provides the cumulative distribution of lane-change distances for motorcycles. The steep curve indicates that most lane-change activity occurs within a short upstream segment. More than half of all lane-change manoeuvres occur within 15 metres of the conflict point, and nearly 85 per cent of riders complete their manoeuvres within 20 metres, consistent with the findings shown in Figure 6. This cumulative representation highlights the compressed nature of motorcycle lane-change decision-making as riders approach the junction.

This cumulative pattern reinforces the conclusion that motorcycle lane-change behaviour is heavily compressed and highly concentrated near the junction. Such behaviour reduces the available reaction time for surrounding traffic, increases crash exposure, and underscores the need for improved lane guidance, more precise upstream markings, and better lateral-movement management approaches for mixed-traffic conditions on arterial corridors. From a safety perspective, interventions that encourage earlier lane positioning, such as advance lane assignment, more precise pavement markings, or channelisation, may help mitigate abrupt lateral movements near conflict points.

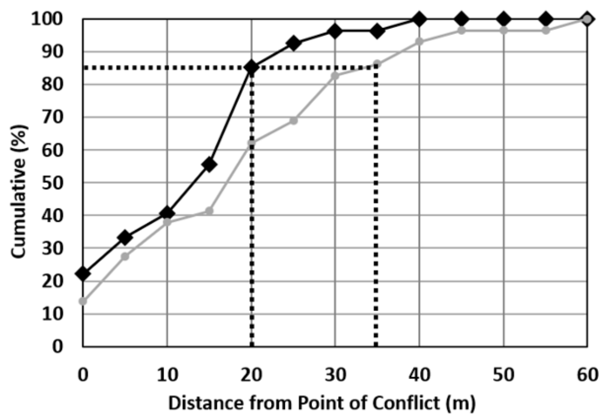


Figure 7. Cumulative distribution of motorcycle lane-change distances

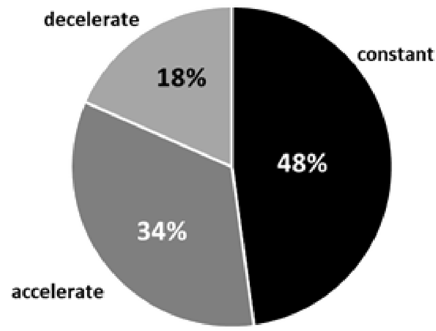


Figure 8. Motorcycle speed change before and after speed limit sign

3.4 Obstacle-Based Behaviour

This subsection examines the influence of minor-road conditions on motorcycle operating behaviour based on the four obstacle categories defined in Table 1, namely no obstacle, low obstacle, high obstacle, and left-turn manoeuvres. These categories represent progressively increasing levels of conflict potential and offer a structured framework for analyzing speed responses and lateral positioning near priority junctions. They emphasize quantitative profiles to reduce speed. This subsection synthesizes behavioral patterns across various obstacle types to elucidate how motorcyclists perceive and respond to differing levels of conflict risk.

Motorcycles display the highest operating speeds under no-obstacle conditions, with riders maintaining their desired cruising speed up to the final segment of the approach. The absence of visible conflict leads riders to treat the upstream segment as an uninterrupted corridor, resulting in only minimal adjustments to their speed. This behaviour indicates reliance on visual confirmation of immediate threats rather than proactive risk anticipation when approaching priority junctions.

Under low-obstacle conditions, riders reduce their speed slightly when they observe vehicles waiting at the minor road stop line. This modest deceleration suggests that riders perceive stopped vehicles as low-risk cues, which are insufficient to prompt significant adjustments in speed. Behaviourally, this response implies that stationary vehicles do not substantially elevate perceived conflict unless movement into the junction becomes imminent.

The high-obstacle condition triggers a markedly stronger behavioural response. When a vehicle crosses the junction, riders demonstrate substantial deceleration and more cautious forward positioning. This behaviour reflects heightened hazard perception and the need for additional reaction time to avoid conflict with crossing vehicles. The findings align with field observations, which show abrupt speed drops and greater lane stabilisation in the presence of active crossing movements. This contrast highlights a threshold-based response, where behavioural adaptation intensifies only when conflicts become explicit and unavoidable.

Riders executing left-turn manoeuvres exhibit a distinct behavioural pattern influenced by geometric constraints and the need for lateral repositioning. These manoeuvres require early preparation and tighter turning angles, prompting riders to reduce speed significantly and stabilise their trajectory before entering the turning path. Unlike through movements, left turns necessitate anticipatory control rather than reactive deceleration, resulting in earlier and more consistent speed adjustment.

Overall, obstacle-based observations indicate that motorcyclists respond primarily to active conflicts, such as vehicles crossing the junction. In contrast, passive or indirect cues, such as vehicles merely waiting at the stop line, trigger only limited behavioural change. This behavioural asymmetry suggests that reliance on passive cues alone may delay risk recognition, increasing exposure to sudden conflicts. From a safety and design perspective, this finding supports the need for enhanced warning cues, improved visibility on minor roads, and junction treatments that encourage earlier speed adjustments before conflicts become apparent.

3.5 Speed Sign Effectiveness

Figure 8 illustrates the change in motorcycle speeds before and after passing the posted speed limit sign on the arterial segment. The distribution shows that the majority of riders do not reduce their speed in response to the regulatory sign. Instead, a considerable proportion continue to accelerate even after passing the sign, suggesting that compliance with the posted limit is low. This pattern suggests that the presence of the speed limit sign alone does not sufficiently influence riders' speed choices along the arterial approach.

The analysis shows that only a small segment of riders demonstrates effective compliance. A notable share of motorcyclists maintain their existing speed, indicating minimal behavioural adjustment. More critically, a substantial proportion continue to accelerate after passing the sign, reinforcing the conclusion that riders perceive the posted limit as a weak regulatory cue rather than an enforceable constraint. This response suggests that riders prioritise perceived roadway conditions and personal judgement over formal regulatory instructions when approaching priority junctions.

This behavioural pattern highlights the limited influence of static roadside signage on rider decision-making in mixed-traffic environments. The visibility of the sign, the absence of enforcement, and the prevailing speed culture on arterial roads contribute significantly to low compliance. Additionally, site-specific factors, such as the sign's placement distance relative to the junction, potential visual clutter from roadside elements, and reduced conspicuity during high-speed travel, may further diminish the sign's effectiveness. Riders often rely on situational cues, such as traffic density, obstacle presence, or perceived police enforcement, rather than the regulatory instruction provided by the sign.

Overall, the findings demonstrate that the posted speed limit sign exerts a minimal influence on motorcycle operating behaviour. The dominance of acceleration and speed-maintenance patterns after the sign indicates that static signage alone is insufficient to regulate rider behaviour effectively. From a policy perspective, these results support the integration of complementary measures, including targeted enforcement, dynamic speed-feedback displays, and geometric or perceptual roadway treatments that encourage self-enforcing speed reduction along arterial approaches to priority junctions. These combined strategies offer greater effectiveness than regulatory signage alone in improving motorcycle speed compliance.

Table 3. Drone and Radar Speed Measurements for *Z*-test Validation

	Drone Camera	Speed Gun
Sample size (*n*)	30	30
Mean	55.43	56.73
Min	24.88	25.00
Max	76.84	78.00
Standard Deviation	10.31	10.33
Z statistic		$z = \frac{(\bar{x}_1 - \bar{x}_2) - d_0}{\sqrt{\frac{{\sigma_1}^2}{n_1}} + \sqrt{\frac{{\sigma_2}^2}{n_2}}}$
z score		0.4880
Rejection Region for Two-Tailed *Z* Test ($H_0 : \mu_1 = \mu_2$ and $\mu_1 : \mu_1 \neq \mu_0$) with $\alpha = 0.05$		*Z* < -1.960 or if *Z* > 1.960
Conclusion		Fail to reject $H_0 (\mu_1 \approx \mu_2)$ There is no statistically significant difference between the drone camera and speed-gun measurements.

3.6 Validation (Interpretation of *Z*-test)

Table 3 summarises the paired speed measurements obtained from the drone footage and the radar speed gun. The validation test used 30 matched observations, each synchronised by timestamp to ensure that both instruments recorded the same motorcycle at the exact moment along the upstream segment. The paired design ensures direct comparability between the two measurement methods and minimises temporal and spatial measurement bias.

The analysis employs a two-tailed *Z*-test at a significance level of α = 0.05 to determine whether the two instruments yield statistically significant differences in mean speeds. This test is appropriate because the sample size (*n* = 30) satisfies the central limit theorem and the observations form synchronised pairs, which enables the sampling distribution of the mean difference to approximate normality.

The test statistic was calculated using the paired mean difference, the pooled standard deviation, and the sample size. The resulting *Z*-value falls within the acceptance region, so the difference between the two means does not reach statistical significance.

This outcome confirms that the drone-derived speeds and radar-based speeds are statistically consistent. In practical terms, the drone measurements accurately represent ground-based speed observations. They can be relied upon for analysing speed distribution, speed reduction, and lane-changing behaviour across the upstream segment. The close agreement in mean values and dispersion further indicates that any minor discrepancies between instruments are attributable to measurement noise rather than systematic bias.

Overall, the *Z*-test results indicate that the combination of drone footage and radar speed guns yields a reliable and internally consistent data collection system.

This statistical alignment strengthens the credibility of the subsequent behavioural analyses presented in this study, particularly those involving speed profiles, obstacle responses, and lane-change dynamics. Moreover, the validation supports the use of drone-based observation as a robust, non-intrusive alternative for detailed traffic-behaviour analysis in mixed-traffic environments.

4 CONCLUSION

This study analysed motorcycle operating behaviour along a 150-metre upstream segment of an arterial corridor approaching a priority junction. The combined use of drone footage and radar speed guns enabled reliable measurement of speed profiles, lane-change patterns, and behavioural responses under different minor-road obstacle conditions. The validation test confirmed that both instruments produced statistically consistent speed measurements, strengthening the credibility of the dataset and the analytical results. This methodological integration demonstrates the feasibility of drone-based observation as a robust tool for detailed behavioural analysis in mixed-traffic environments.

The findings show apparent temporal differences in operating speeds, with morning riders exhibiting higher speeds, greater variability, and more aggressive acceleration patterns than afternoon riders. Motorcycle riders also demonstrate limited early deceleration, reducing speed only when confronted with active conflicts such as crossing vehicles. Passive cues, such as vehicles waiting behind the stop line, trigger only minor speed adjustments, suggesting a general underestimation of latent risks at the junction. These behavioural tendencies indicate that risk perception among riders is strongly event-driven rather than anticipatory.

Lane-change analysis reveals that motorcycles initiate most lateral manoeuvres within a short upstream distance, with 85 per cent of lane changes occurring within the final 20 metres before the junction. This compressed decision space reduces reaction time, increases crash exposure, and distinguishes motorcycles from light and heavy vehicles, which typically change lanes earlier and more predictably. Obstacle-related patterns further emphasise that active conflicts influence rider behaviour far more strongly than passive visual cues. Such differences highlight the unique vulnerability of motorcycles in priority-junction settings within mixed-traffic systems.

The assessment of the speed limit sign indicates limited effectiveness, as many riders maintain or even increase their speed after passing it. This result highlights the weak behavioural influence of static roadside signage in mixed-traffic environments with high motorcycle dominance. Without complementary enforcement or perceptual speed-control measures, regulatory signs alone are unlikely to induce meaningful behavioural change.

Overall, the findings underscore the importance of targeted safety interventions, including improved upstream lane markings, enhanced visibility at minor road approaches, dynamic or reinforced speed control measures, and junction redesign strategies that better accommodate motorcycle behaviour. These measures are essential to mitigate the risks associated with high-speed approaches, short-range decision-making, and limited lane-change anticipation near priority junctions.

From a policy perspective, the results support the prioritisation of self-enforcing road design and active speed management over reliance on static signage alone in motorcycle-dominated urban corridors.

This study is subject to several limitations. The analysis focuses on a single priority junction and specific observation periods, which may limit the generalisability of the findings. Future research should examine multiple junction types, longer observation durations, and different urban contexts to validate and extend the behavioural patterns identified. In addition, integrating conflict indicators or surrogate safety measures would further enhance the understanding of risk mechanisms associated with motorcycle speed and lane-changing behaviour.

DISCLAIMER

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work in this article.

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