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Gateway Design for Transition from High-Speed to Low-Speed Areas: A Driving Simulator Study

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Abstract

This research analyzes various gateway designs aimed at reducing vehicle speeds during the transition from 70 km/h (outside urban areas) to 50 km/h (within urban areas) to identify the most effective combinations of physical and visual measures. Seven gateway designs were developed, along with a reference design. These scenarios utilized either transverse road markings or avenue planting before the transition zone and a road narrowing, chicane, or a combination thereof within the transition zone. Using a driving simulator, 54 participants each drove a 14 km route in which all designs appeared in randomized order under standardized conditions. Objective driving data (speed, lateral position, acceleration, etc.) were recorded with STISIM Drive 3 and analyzed using Python, Excel, and IBM SPSS Statistics. Subjective experiences and preferences were collected via Google Forms. Avenue planting showed no significant effect, whereas transverse road markings, road narrowing, and chicanes effectively reduced speed. Chicanes caused the most considerable speed reduction but led to the most abrupt braking. The combination of transverse road markings and road narrowing enabled a smooth deceleration before the "urban area" sign, ensuring drivers entered below the speed limit. After passing the gateways, vehicle speeds within the urban zone were similar across all designs.

Keywords: gateway design; driving simulator; chicane; road narrowing; avenue planting; transverse road markings

1. Introduction

This study analyzes various gateway designs intended to reduce vehicle speeds during the transition from high-speed to low-speed zones. Such transitions typically occur when entering an urban area from a non-urban environment.

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Gateway designs aim to enhance road safety within built-up areas by implementing speed-reducing measures, as Torbic et al. (2012) outlined.

Physical speed-reducing measures are applied in the studied transition zones, as traffic signs alone have proven insufficient in influencing driver behavior. Research indicates that only 32.06% of speed limit signs are noticed by drivers, according to Lantieri et al. (2015). Speed limit violations are more common in these zones, as drivers must adjust their speed to changing conditions. Speed is a key factor in traffic accidents: as vehicle speed increases, so does the likelihood of a crash and its consequences.

The central research questions of this study focus on several key aspects of gateway design and its impact on traffic behavior and safety. Specifically, the study seeks to identify which factors influence the functionality and effectiveness of a gateway, as well as to understand the impact of a gateway on driver speed. It explores whether drivers tend to decelerate or accelerate when approaching a gateway and examines the effects of combining different speed-reducing measures. Additionally, the study investigates whether placing multiple speed-reducing elements in succession positively or negatively affects traffic flow and safety. The role of vegetation within gateway designs is also considered, particularly regarding its influence on driver behavior. Furthermore, the research addresses concerns about whether gateways create obstacles for emergency services and whether such designs may prompt drivers to perform maneuvers that could endanger other road users.

Two types of traffic calming measures can be implemented as part of gateway designs: vertical and lateral speed-reducing elements, according to Schermers & van der Kint (2019). Vertical elements include speed bumps, raised platforms, and chicanes, while lateral measures consist of lane shifts and central islands. These concepts have been the subject of previous studies and are incorporated into the framework of this research. It should also be taken into account that traffic-calming measures must be designed to avoid obstructing the movement of all road users, especially emergency vehicles, so as to ensure uninterrupted access for essential and emergency services.

The gateway designs will be tested using a prototypical driving simulator. A prototypical simulator comprises a vehicle mock-up and a visual projection system, according to van der Horst (2008). The mock-up is equipped with standard vehicle controls, enabling a semi-realistic yet safe simulation of the influence of traffic design on driver behavior.

2. Literature review

For speed reductions to 50 km/h, physical measures such as road narrowing, raised crossings, and changes in road surface are most suitable. For reductions from higher speeds (>50 km/h), visual or psychological measures, such as markings and roadside greenery, are preferred. Since the 50 km/h speed limit within built-up areas applies to both cases, this study investigates both physical and visual measures.

2.1. Vertical Measures

A speed bump is a raised element designed to slow down vehicles. Recommended dimensions are 12 cm in height and 4.5 m in length. Variants include raised junctions (plateaus), humps, ridges (3 cm to 5 cm), and dome-shaped markers (2.5 cm height, 25 cm diameter). Speeds can be reduced to 25 km/h on average, according to Kraay (1980). However, bumps can damage vehicles or impair emergency response access if not visible or properly designed.

These are increasingly used in urban settings to enhance pedestrian safety by slowing vehicles using a ramped platform. This infrastructure improves neighborhood walkability and reduces collisions with vulnerable road users, as Singh et al. (2019) stated.

2.2. Lateral Measures

A chicane introduces artificial curves using raised islands, requiring drivers to steer or brake. Two types exist: overridable and non-overridable. The former offers flexibility in heavy traffic or for emergency vehicles. Studies show that 57% of drivers brake without oncoming traffic, increasing to 85% when traffic is present. Chicanes are most effective at optimal positions and widths (≥30% of lane width). Consideration must be given to pavement durability and potential noise and vibration for nearby residents from Roelofs (2014).

Reducing lane width leads to slower driving due to limited space, according to Bobermin et al. (2019). This effect is positive under low traffic conditions but may reduce safety when volumes are high. Longer narrowing reduces traffic flow but has a limited additional effect on speed unless exceeding 10 m in length, as Melman et al. (2020) highlighted.

2.3. Psychological Measures

Examples include wide edge lines, chevrons, transverse rumble strips, and fishbone patterns. These create a perception of narrowness, encouraging lower speeds, according to Hussain et al. (2021). Transverse road markings (painted at 3 mm thickness) provide both visual and tactile cues. As strips increase in frequency near the built-up area sign, they produce a gradual speed reduction from Martindale & Urlich (2010) and Cornu (2016). Each group of strips adds one more stripe, placed every 4 m, with central breaks to allow motorcycle safety from Agentschap Wegen en Verkeer (2022). Strategically placed greenery narrows the driver's visual field, promoting slower speeds. Dense planting closer to the road leads to lower speeds and wider lateral distances, while open spaces encourage faster driving.

3. Materials and Methods

This section describes the methodology applied, the sample characteristics, the driving simulator used, the simulation scenario and its development, and the primary data frame used for the analysis.

3.1. Driving simulator and participants

The simulation was conducted using a medium-fidelity driving simulator provided by the Transportation Research Institute (IMOB) of Hasselt University. It features a vehicle mock-up and a three-beamer projection system onto a spherical screen, offering a wide field of view and high visual immersion. The setup is integrated with the validated STISIM Drive® 3 operating system, which records multiple driver behavior parameters—including speed, lateral position, and acceleration—commonly used in this type of research. Further details of the simulator are available in Pirdavani et al. (2025). In total, 54 participants (13 women and 41 men) participated in the experiment. All participants completed a short familiarization drive to get used to the simulator before proceeding with the test scenarios. Eligibility requires at least a provisional category B driving license and a minimum of 20 hours of driving experience. Participants were excluded in cases of pregnancy, illness, or excessive use of alcohol or drugs. Participation was entirely voluntary and could be discontinued at any point. The test drives consisted of successive gateway designs presented in different sequences along a 14 km route, interspersed with neutral road segments ("filler pieces"). Four scenario variants with randomized order were used to minimize learning effects and maintain natural driving behavior. This variation reduced predictability, limited habituation, and helped ensure the reliability of the results.

3.2. Data processing

The data were collected using the STISIM Drive 3 program and an online questionnaire via Google Forms. The collected data were processed using Python, Excel, and IBM SPSS Statistics.

3.3. Selection of Measurement Points

Specific measurement points were selected for each parameter (speed, acceleration, lateral position) analyzed, without combining them, to ensure the relevance of the data and avoid inaccurate results.

For speed, measurements were taken at six locations: at the beginning of the modified section, at the end of the speed bump before the transition zone, at three points within the transition zone (beginning, middle, end), and at 100 meters after the start-of-built-up-area sign to observe any prolonged effect of the device.

For acceleration, five points were chosen: in the middle of the previous speed bump, just before the one located in the transition zone, in the middle and at the end of this zone, and 20 meters after the device to verify whether drivers accelerate after passing it.

Avoidance behavior at the traversable chicane was assessed by analyzing the vehicle's lateral position. This position was observed over three consecutive cushions to understand the strategy used (deviation, straight trajectory, etc.).

4. Results

4.1. Speed

When a traffic-calming measure is implemented, vehicle speeds are generally lower (Fig. 1). The results clearly show that all tested gateway designs significantly reduce driving speed compared to the reference scenario without any intervention. This reduction occurs primarily before the 'start of built-up area' sign, particularly between measurement points 4 and 5, which is critical for safety in transition zones.

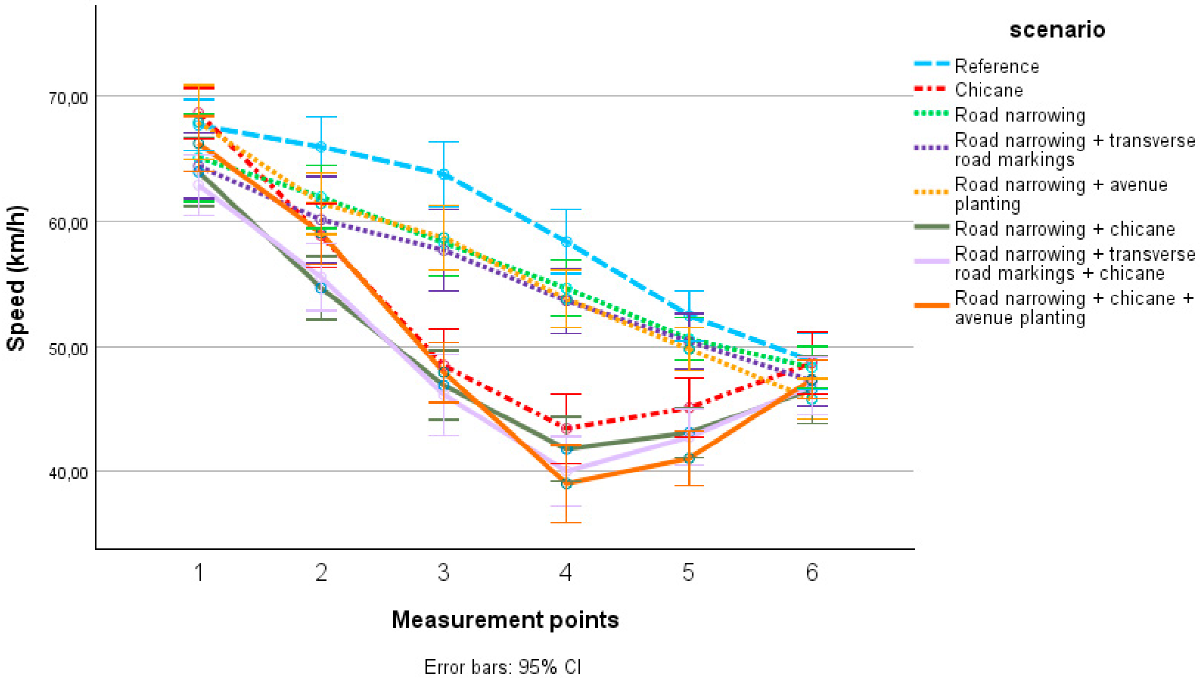

Fig. 1. Variation in speed across measurement points under different scenario conditions.

The chicane is the most effective among the various individual traffic-calming elements, with an average speed of 45.66 km/h. It causes drivers to reduce speed significantly before reaching the urban boundary, well below the legal limit of 50 km/h. The chicane also leads to the only instance where speeds remain under the 50 km/h threshold exactly at the speed sign. In contrast, in both the reference design and the road narrowing scenario, speeds still exceed the limit at that point. Road narrowing also produces a noticeable speed reduction, averaging 54.17 km/h. Though less pronounced than the effect of a chicane, this measure promotes a more gradual and predictable deceleration, avoiding sudden braking.

Transverse road markings demonstrate the strongest effect ahead of the transition zone, serving as an effective early signal to drivers. However, this effect is relatively moderate unless combined with physical measures. On the contrary, roadside avenue planting shows no statistically significant impact on driving behavior. Average speeds in these cases remain high and comparable to the reference condition, suggesting minimal perceptual influence.

The most substantial reductions in speed are observed in designs that combine multiple measures, particularly the combination of a chicane and road narrowing. In such configurations, the average speed is over 9 km/h lower than in the reference design, reinforcing the value of integrated interventions. Interestingly, the presence of an oncoming vehicle in the chicane-and-narrowing configuration does not significantly affect average speed. The speed profiles in both the with- and without-oncoming-traffic scenarios are nearly identical, suggesting that the chicane's effectiveness is robust and consistent, regardless of traffic conditions. Subjective feedback from participants supports the objective findings. Most drivers reported a strong sense of needing to reduce speed in designs that combined measures (82.35%) and in chicane-based layouts (76.47%). In contrast, only 9.80% of drivers indicated a perceived need to slow down when avenue planting was used, confirming its limited psychological influence.

4.2. Lateral deviation

Fig. 2 presents the distribution of participants' driving strategies across three scenarios involving a chicane. The scenarios include chicane exclusively, a chicane combined with road narrowing, with or without the presence of oncoming traffic. In the chicane, combined with road narrowing and the presence of oncoming traffic configuration, an oncoming vehicle approaches while the participant navigates the chicane, creating an added layer of complexity.

Most participants chose to drive straight over both bumps on the right side, especially in the scenario with only the chicane (68.63%). This percentage decreases when road narrowing is introduced (50.98%) and remains relatively high when an oncoming vehicle is present (61.76%). These results suggest that the basic chicane design is the least likely to trigger evasive maneuvers, whereas the addition of narrowing prompts more deviation from a straight path. The slalom strategy, in which drivers steer between the bumps, increases noticeably with the introduction of road narrowing (35.29%). This indicates that the narrowing acts as a stronger visual or physical cue, encouraging evasive behavior. However, in the chicane combined with road narrowing with the presence of oncoming traffic scenario, the presence of an oncoming vehicle significantly reduces slalom maneuvers (10.78%), as it likely restricts the available space and discourages such movements. Driving in the center of the road was most common in the chicane combined with road narrowing condition (7.84%) and less frequent in the other two scenarios. This may reflect a compromise strategy, where participants attempted to balance between slaloming and driving directly over the bumps. Rather than both, driving over only the first or second bump was observed most frequently. This is likely due to the limited maneuverability caused by the oncoming vehicle, forcing drivers to make partial evasive movements instead of full slalom. It reflects a degree of adaptive avoidance behavior under constrained conditions. Lastly, outlier behavior, those not fitting within the defined strategy categories, was present to a limited extent in all scenarios. These outliers highlight instances of non-standard or unpredictable driving patterns that may warrant further investigation.

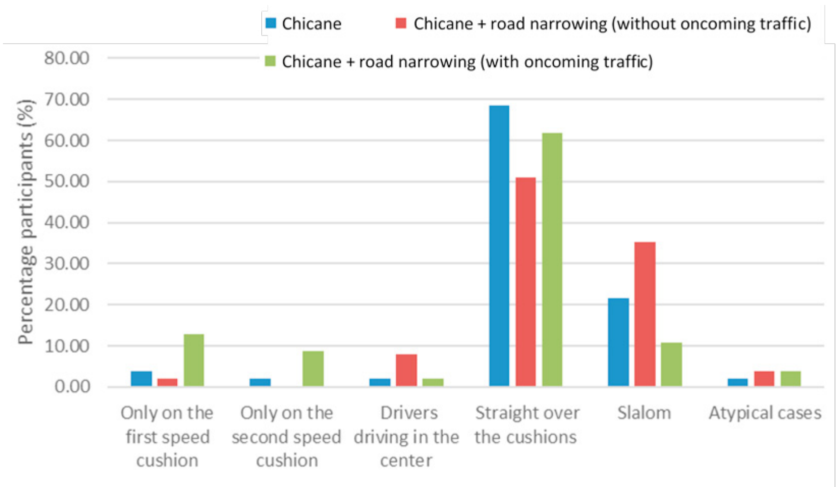

Fig. 2. Overview of vehicle navigation strategies at the chicane across the different scenarios.

Overall, the presence of narrowing and, especially, oncoming traffic clearly influences driver behavior, reducing slaloming and encouraging more direct passage, often over one bump. This suggests realistic traffic conditions suppress evasive actions and create more predictable driving patterns.

4.3. Acceleration

The analysis reveals that gateway designs incorporating a chicane produce more pronounced deceleration and acceleration values, indicating more abrupt and dynamic driving behavior. This is particularly evident immediately after passing the chicane, where a noticeable increase in positive acceleration is observed, suggesting that drivers tend to quickly resume speed. In contrast, designs with only road narrowing or reference design (without physical measures) exhibit a smoother and more gradual acceleration pattern with minimal fluctuations.

Designs incorporating a chicane show more extreme deceleration and acceleration values, indicating more abrupt driving behavior (Fig. 3). In contrast, designs with only a road narrowing or the reference design display more gradual deceleration and virtually no acceleration. Notably, in the reference design, the most substantial deceleration is observed at measurement point 4 (at the 'start of built-up area' sign). This suggests that, in the absence of prior speed-reducing cues, drivers apply abrupt braking when entering the urban zone. Conversely, gateway designs tend to prompt earlier and smoother deceleration, thereby improving speed adaptation.

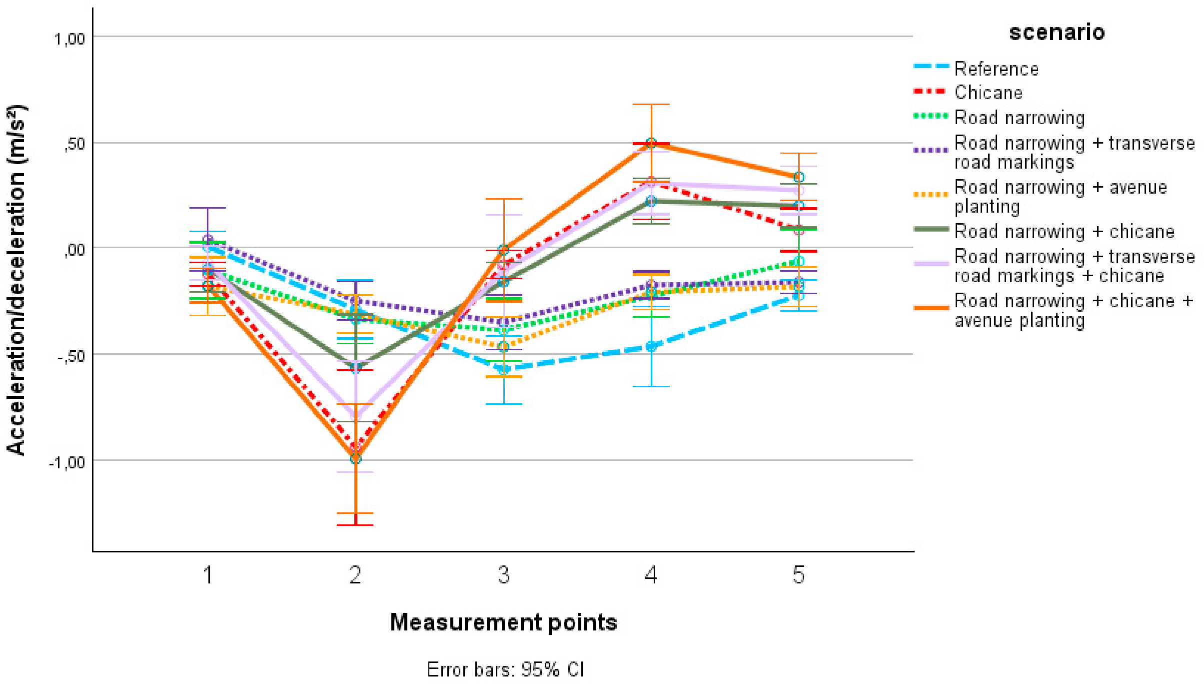

Fig. 3. Variation in acceleration/deceleration across measurement points under different scenario conditions.

The results further indicate that most chicane-based designs produce significantly higher average acceleration values compared to the reference scenario. Among these, combining a chicane and road narrowing leads to the highest acceleration levels, followed by designs that integrate chicanes with transverse road markings or avenue planting. On the other hand, designs using only visual measures, such as road narrowing or avenue planting, show minimal differences in acceleration behavior compared to the reference, suggesting a limited influence on driver response regarding speed variation. Importantly, the acceleration values associated with chicane designs also display a significant 95% confidence interval, implying greater variability in driver response. This wide range indicates that chicanes elicit more unpredictable vehicle maneuvers, which in turn can contribute to potentially unsafe traffic situations, especially in mixed-traffic environments with vulnerable road users. Lastly, the presence of an oncoming vehicle within a chicane, combined with a narrowing, did not significantly impact the overall acceleration behavior. This suggests that the effect of the chicane itself remains relatively robust regardless of environmental traffic factors.

5. Discussion

All tested gateway designs resulted in a significant speed reduction before the 'start of built-up area' sign compared to the reference design without any intervention. Among these, the design incorporating a chicane proved the most effective, producing the greatest decrease in speed. The speed reduction effect was further amplified when combined with other measures, such as a road narrowing. However, speeds converged across all designs after passing the built-up area (measurement point 6). This aligns with existing literature indicating that drivers typically resume their initial speed within approximately 120 meters of a gateway.

Regarding specific speed-reducing measures, chicanes were highly effective at lowering speed but also caused more abrupt braking and acceleration. This behavior may negatively impact driver comfort and the safety of vulnerable road users. Road narrowing also contributed to speed reduction, albeit to a lesser extent than chicanes, but they offered a smoother and more predictable deceleration profile, which is preferable for traffic safety. Transverse road markings helped maintain a more uniform speed profile, particularly when combined with physical measures. In contrast, avenue planting showed no significant impact on driving speed and is considered less effective.

Analysis of driver behavior and maneuvering strategies revealed that most drivers passed straight over both bumps in the chicane. The incidence of slalom maneuvers increased when a road narrowing was added, but decreased sharply when oncoming traffic was present. This suggests that realistic traffic interactions, such as encountering oncoming vehicles, promote more predictable and safer driver behavior.

Designs featuring chicanes exhibited not only the highest acceleration levels but also the greatest variability in driver response, as indicated by wider 95% confidence intervals. This unpredictability may lead to more erratic driving and an increased risk of hazardous situations. In contrast, road narrowing showed narrower confidence intervals, reflecting more consistent and controlled driver reactions.

This study has some limitations. Using a driving simulator means that participant behavior might differ from real-world driving. Additionally, the sample was not fully representative of the general population, with an overrepresentation of young male drivers. The use of fixed measurement points may also have missed certain behavioral changes occurring between these points.

Based on the findings, for an effective and controlled transition from 70 km/h to 50 km/h, it is recommended to implement a combination of transverse road markings and road narrowing. This combination facilitates smooth speed reduction without causing abrupt maneuvers or risky evasive actions. While chicanes effectively reduce speed, they are not recommended where driver comfort or interactions with vulnerable road users are key priorities.

6. Conclusion

This study concludes that physical traffic-calming measures with an obstructive character significantly influence driving behavior more than purely visual or landscape-based interventions. Aesthetic or visual measures, such as transverse road markings or avenue planting, are insufficient to sustain a sustained vehicle speed reduction. A combination of transverse road markings placed before the transition zone and a road narrowing at the transition itself emerges as the safest design in this study. This configuration facilitates a gradual deceleration without abrupt braking, enhancing road safety and driving comfort. Although the chicane triggered the most pronounced speed-reducing effect, this benefit is accompanied by safety drawbacks. The sharp deceleration is experienced through sudden braking and evasive maneuvers around physical obstacles, which increases the risk of unsafe traffic situations. Nevertheless, chicane can be a valuable tool in specific contexts where a strong speed-reducing effect is essential, provided it is carefully designed and appropriately implemented. In contrast, adding avenue planting does not significantly affect driving behavior and is not recommended as a standalone speed-reduction measure.

An essential contribution of this study lies in combining objective simulator data with subjective feedback from participants. Including both perspectives provides a more nuanced understanding of how drivers respond to different gateway designs. For example, designs that produced the most substantial speed reductions—such as the chicane and road narrowing—also received the highest ratings from participants regarding perceived need to slow down. Conversely, avenue planting failed to reduce speed objectively and was rarely perceived by drivers as an effective speed reduction measure. This consistency between behavioral and perceptual responses strengthens the reliability of the findings and supports the practical recommendations derived from the study.

Based on these findings, road authorities should prioritize physically perceptible and tangible measures, such as transverse road markings and road narrowing, when designing speed transition zones. Caution is warranted when implementing obstacle-rich measures like chicanes unless the traffic context explicitly demands a strong braking effect. This approach maximizes design effectiveness while minimizing the risk of unintended safety consequences.

While this study provides valuable insights under controlled daylight conditions, further field measurements are necessary to validate the results. Future research could explore the influence of environmental factors such as night-time visibility, weather conditions, and road surface quality. Additionally, the effectiveness of alternative visual measures, such as glow-in-the-dark road markings or reflectors, warrants further investigation. Finally, it is recommended to compare simulation results with real-world measurements to assess their alignment with actual driving behavior.

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