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A Driving Simulator-Based Assessment of Traffic Calming Measures at High-to-Low Speed Transition Zones

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Highlights

What are the main findings?

- Physical traffic calming measures, such as chicane and road narrowing, reduced speeds and altered the deceleration behaviors at high-to-low speed transition zones.
- Psychological traffic calming measures such as avenue planting and transverse markings have minimal standalone effects on speed and deceleration but can support smoother transitions when combined with physical interventions.

What is the implication of the main finding?

- Integrating gateway designs into urban entry zones can enhance smart mobility strategies by reducing reliance on enforcement and promoting self-explanatory roads.
- The study offers actionable insights for integrating simulator-based testing in traffic engineering, allowing early-stage evaluation of road design interventions.

Abstract

Effective speed management at urban entry points is essential for ensuring traffic safety and supporting sustainable mobility in smart cities. This study contributes to urban mobility planning by using a high-fidelity driving simulation to evaluate gateway designs that enhance safety and behavioral compliance at built-up entry zones. Seven gateway configurations, comprising physical (i.e., chicanes, road narrowing) and psychological (i.e., transverse markings, avenue planting) speed calming measures, were evaluated against a reference scenario. A total of 54 participants completed a 14 km simulated route under standardized conditions, with vehicle speed, acceleration/deceleration, and lateral position continuously recorded. The strongest effects were observed in designs featuring chicanes, which achieved the largest speed reductions but also induced abrupt deceleration. In contrast, the combination of road narrowing and transverse markings resulted in a smoother and more gradual deceleration, minimizing driver discomfort and lateral instability. Psychological measures alone, such as avenue planting, had a limited impact on speed behavior. These findings highlight the importance of combining physical and psychological traffic calming measures to create effective, perceptually engaging transitions that promote safer and more consistent driver responses.

Keywords: speed transition zones; gateway design; traffic calming measures; driving simulator; urban mobility

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1. Introduction

Managing vehicle speed during transitions from high-speed to low-speed zones is a critical challenge in the design of urban mobility systems. These transition zones, commonly situated at the entry to urban areas, often experience elevated crash risks due to immediate changes in driver expectations and insufficient adaptation to posted speed limits [1,2]. Traditional reliance on traffic signage alone has proven inadequate, as studies show that many drivers fail to perceive or comply with speed limit changes when entering built-up areas [3,4]. Addressing this challenge is essential for smart cities that prioritize traffic safety and sustainable urban mobility.

To enhance safety and compliance, policymakers have increasingly adopted gateway treatments, with physical and perceptual interventions designed to prompt earlier deceleration and improve driver awareness at the urban threshold [5]. These include physical (e.g., chicane, road narrowing) as well as psychological (e.g., transverse marking and avenue planting) traffic calming measures (TCMs) [6]. Such treatments aim to shape driver behavior through spatial constraints and the manipulation of visual and cognitive cues, aligning with the principles of behavioral design in urban systems [7,8].

Smart cities provide an opportunity to rethink the planning and evaluation of such interventions through data-driven approaches and simulation-based tools [9,10]. Driving simulators, in particular, enable the controlled testing of infrastructure layouts under repeatable conditions, offering detailed insight into driver behavior without real-world risks [11]. They are increasingly integrated into smart urban planning workflows, including digital twin platforms and scenario-based decision support systems.

This study contributes to this emerging direction by using a high-fidelity driving simulator to evaluate seven gateway designs, comprising both physical and psychological elements, for their effectiveness in moderating driver speed, acceleration/deceleration, and lateral positioning during the transition from rural to urban zones. A reference scenario without any TCMs serves as a baseline. In addition to objective behavioral metrics, subjective driver evaluations were collected to assess comfort and perceived effectiveness.

The aim is to identify which configurations most effectively promote safe and consistent deceleration before entering lower-speed zones, without inducing abrupt or uncomfortable maneuvers. By embedding these findings within the context of smart city planning and simulation-driven infrastructure design, this research offers practical insights for policymakers, engineers, and mobility planners seeking to enhance safety at critical urban thresholds.

2. Background and Related Works

Urban mobility highlights the importance of ensuring traffic safety on different road segments and transportation networks, specifically focusing on challenging conditions [12]. The transition from high-speed to low-speed road environments presents a critical challenge for traffic engineers seeking to enhance road safety and ensure drivers' compliance with posted speed limits. Various speed calming strategies have been developed and evaluated to address this, ranging from physical interventions to psychological treatments [13]. This section discusses three principal types of TCMs: vertical, lateral, and psychological. Emphasis is placed on how these measures influence driver behavior at transition zones and their comparative effectiveness in reducing speed and improving lane discipline under simulated conditions.

2.1. Vertical Traffic Calming Measures

Vertical TCMs play a central role in managing speed reduction at transitions from high-speed (e.g., 70 km/h) to low-speed (e.g., 50 km/h) road zones [14]. These interventions rely on physical elevation changes in the roadway to prompt deceleration. The most commonly applied vertical measures include speed humps, speed tables, and raised pedestrian crossings or intersections. Speed humps and bumps are short, abrupt elevations that force drivers to reduce speed to avoid discomfort or vehicle damage [15]. In contrast, speed tables offer a broader, flat-topped design that moderates speed while preserving ride comfort [16]. Raised crosswalks serve the dual function of enhancing pedestrian safety and reducing vehicle speed [17]. In practice, these devices are often deployed in combination with horizontal elements or visual markings to amplify their impact.

Driving simulator studies have extensively assessed the effectiveness of these vertical measures in speed transition zones. The results consistently demonstrate significant reductions in mean vehicle speed and notable changes in driver behavior at the location of vertical interventions. However, a common observation across studies is that drivers frequently accelerate after passing the calming device, diminishing the long-term effectiveness unless additional measures are implemented downstream [18]. To address this, simulations have tested vertical elements in series, spaced strategically to maintain reduced speeds over longer road segments. For example, placing speed humps or raised platforms every 75 to 200 m can prevent drivers from regaining high speeds too quickly [19].

The effectiveness of vertical measures is further enhanced when combined with other types of TCMs, such as road narrowing, horizontal deflections, or changes in pavement texture. Driving simulator studies have shown that such combinations lead to more sustained reductions in speed, as they increase cognitive load and force drivers to remain attentive throughout the transition zone. Even low-cost or temporary vertical treatments, such as portable crash barriers or marked elevations, have demonstrated meaningful impacts in simulator-based experiments, particularly at intersections or gateways into urban areas [20].

Design considerations derived from simulator-based research are crucial for optimizing the deployment of vertical calming devices [21]. Appropriate spacing between successive devices is essential to sustain the desired speed profile, with a recommended maximum distance of 200 m for maintaining speeds below 50 km/h, and closer spacing (around 75 m) for zones targeting 40 km/h or lower speeds. Additionally, differences in vehicle type significantly influence the perceived impact of vertical measures, emphasizing the need for tailored designs based on the expected traffic mix [14]. Overall, driving simulator studies affirm the utility of vertical speed calming devices in transition zones and offer empirical guidance for their strategic implementation to ensure both safety and effectiveness.

2.2. Lateral Traffic Calming Measures

Lateral TCMs aim to reduce vehicle speeds by modifying the horizontal alignment of the roadway or creating visual cues that alter a driver's perception of the driving environment. These interventions compel drivers to adjust their lateral path, thereby promoting speed reduction through steering adjustments and increased cognitive demand. Common lateral measures include chicanes, gate constructions, horizontal curves, and visual narrowing through pavement markings [22]. Driving simulator studies offer valuable insights into how these designs influence driver behavior during speed transitions from high-speed to low-speed zones.

Among the most prominent lateral interventions, chicanes have demonstrated consistent effectiveness in both simulator and field studies [23]. By introducing alternating shifts in road alignment, chicanes force drivers to reduce speed and maneuver carefully through the deflections [24]. Their efficacy is highly dependent on geometric design factors such as curvature, spacing, and deflection angle. Horizontal curves similarly sustain speed reductions over longer distances, as they increase driver workload and attentiveness. Simulator results suggest that although these features may slightly increase lateral position variability, they contribute meaningfully to lower speeds across the transition zone [22,25].

Gateway constructions, physical or visual structures placed at the boundary of speed zones, are another proven lateral measure. These gateways serve as strong psychological signals that cue drivers to decelerate upon entering a lower-speed area. Driving simulator studies indicate that gate constructions lead to localized speed reductions and modest increases in lateral movement, but these do not pose significant safety risks [26]. Similarly, peripheral hatched markings, which visually narrow the perceived width of the road, encourage drivers to maintain a central lane position while decreasing travel speed [27]. These visual treatments have been shown to reduce lateral wandering and enhance lane discipline, especially in transition zones where abrupt speed changes are expected.

In sum, lateral speed calming measures, particularly when designed with attention to human perception and roadway context, offer a powerful set of tools to manage driver behavior in speed transition zones. Empirical findings from simulator studies should guide the selection and placement of such measures to ensure optimal effectiveness and safety.

2.3. Psychological Traffic Calming Measures

Psychological TCMs are non-physical interventions that rely on visual stimuli and perceptual manipulation to influence driver behavior. Unlike vertical or lateral speed calming devices, these measures alter how drivers perceive the road environment rather than the road itself. They are instrumental in high-speed to low-speed transition areas where subtle yet effective cues can encourage earlier and more consistent deceleration. Driving simulator studies provide a controlled environment to isolate and assess the impact of such psychological interventions on speed regulation and lane discipline.

One of the most studied psychological interventions involves modified road signage. These include larger, more vividly colored, or uniquely shaped signs that draw the driver's attention to upcoming speed reductions [28]. Simulator experiments have shown that such signs can be as effective as physical road markings in reducing vehicle speeds at the entry to lower-speed zones [29]. Enhanced signage functions by capturing the driver's cognitive focus earlier, enabling smoother deceleration and greater compliance with posted limits. The early engagement it prompts is particularly important in transitions where conventional signage might otherwise be overlooked or filtered out cognitively. In addition, strategically placed vegetation along the roadway creates an optical narrowing effect [30], contributing to a reduction in driving speed. The amount of vegetation and its distance from the road are important factors [31].

Another set of psychological interventions includes road surface markings, such as transverse lines, colored pavement sections, and peripheral hatched markings. These visual cues create the illusion of speed or narrowing, which in turn prompts drivers to reduce their speed. Though technically tactile, transverse rumble strips contribute visually by emphasizing deceleration zones [32]. Driving simulator research has shown that these markings not only reduce average speed but also improve lateral control, particularly when peripheral markings are used. Gateways, whether painted or physically framed, also serve as strong psychological indicators of a changing traffic environment, leading to immediate deceleration at the transition threshold. Additionally, optical pavement treatments, such as converging lines, gradient markings, or brightness-modulated textures, have proven effective in manipulating speed perception [33]. These techniques rely on visual illusions that suggest acceleration or narrowing, prompting drivers to slow down reflexively. Simulator studies confirm that these markings successfully reduce speeds without compromising lateral control [34].

While psychological measures consistently produce significant reductions in speed at the point of transition, their effects tend to diminish once drivers pass beyond the treated zone. Simulator studies indicate that although drivers slow down in response to visual cues, many begin accelerating again shortly afterward. This rebound effect highlights the importance of continuity or repetition in applying psychological calming strategies. These measures are best used in conjunction with physical devices or as part of a sequenced intervention plan that maintains driver attention and reinforces speed regulation across the transition area to achieve more sustained impact.

Despite extensive research on TCMs, notable gaps persist in the literature regarding the combined effects of physical and psychological interventions in high-to-low speed transition zones. Previous studies have predominantly examined isolated TCMs without evaluating their synergistic potential when implemented in coordinated gateway designs. Moreover, there is limited empirical understanding of how such combinations simultaneously influence longitudinal (speed, acceleration) and lateral (deviation) driving behavior. This study addresses these gaps by systematically testing seven distinct gateway configurations that integrate both physical and psychological elements using a high-fidelity driving simulator. This research offers insights into the effectiveness of combined TCM strategies by capturing a wide range of behavioral indicators, including speed, acceleration/deceleration, and lateral positioning. The findings directly inform the design of smarter, more self-explanatory urban entry points, aligning with the broader objectives of sustainable and data-informed urban mobility.

3. Materials and Methods

The primary aim of this study was to assess the effectiveness of seven distinct gateway designs using a driving simulator. Each gateway design comprises a combination of physical and psychological TCMs. These designs were evaluated by analyzing participant driving behavior in terms of speed, acceleration/deceleration, and lateral position. This allowed for a comprehensive assessment of how each design influenced driver responses and maneuver execution. To determine the impact of each gateway design, comparisons were made against a reference scenario without any intervention. The systematic collection and analysis of relevant data enabled a direct comparison of each design's performance and behavioral effects.

3.1. Overview of Gateway Designs

Figure 1 provides a general overview of all gateway designs implemented in this research. It shows the distances within each design and the position of the 'built-up area' sign, which signals the drivers that they are entering the low-speed zone.

The transition zone is designed with a fixed length of 100 m, allowing for a smooth and comfortable deceleration from 70 km/h to 50 km/h [35,36]. Based on existing literature, this distance effectively facilitated the intended speed reduction [37]. In four of the tested configurations, transverse road marking and avenue planting were implemented before the transition zone. In all seven designs, physical TCMs (i.e., chicane, road narrowing, or a combination of both) were employed in the transition zone. Additionally, a reference design without any intervention served as the baseline condition.

Each design scenario comprised a total roadway length of 650 m and simulated driving in the direction from a rural to an urban environment. Both the 70 km/h and 50 km/h segments were configured as two-way roads with one lane per direction and equipped with a centerline and edge markings. The minimum required pavement widths for these zones were 6.40 m and 6.10 m, respectively, with corresponding lane widths of 3.00 m and 2.85 m.

For simulation purposes, a uniform pavement width of 7.00 m was applied to the 70 km/h zone, and 6.50 m to the 50 km/h zone. The edge markings were 0.15 m wide, and the centerline consisted of broken segments measuring 2.5 m in length and 0.15 m in width, spaced at 10 m intervals. A continuous curb, measuring 10 cm in height and 50 cm in width, was added along the transition zone, as prior studies indicated its potential to double the speed-reducing effect compared to zones without curbs [26]. The built-up area sign was positioned precisely at the end of the 100 m transition zone. All driving scenarios were performed under daytime conditions with good visibility to ensure consistency across all experimental designs.

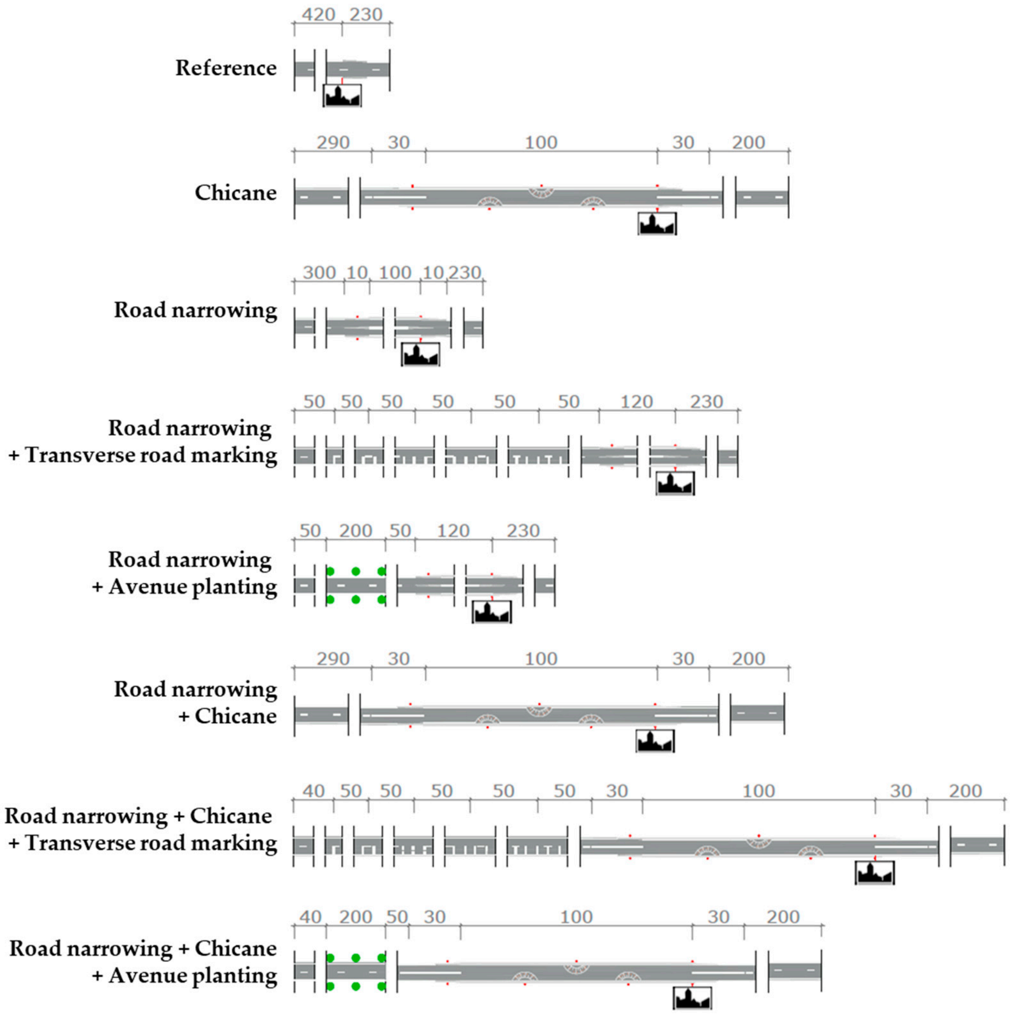

Figure 1. General overview of all gateway designs.

In the road narrowing design, the roadway width was visually and physically reduced. The total pavement width was narrowed to 6.70 m, with each lane measuring 2.85 m, corresponding to the minimum allowable lane width for a speed zone of 50 km/h [36]. This layout preserved sufficient paved space to accommodate wider vehicles while maintaining the narrowing effect. The construction was reinforced through road markings, enhancing its visual impact. Appropriate signage was implemented to inform drivers: a warning sign for the upcoming narrowing was placed 200 m in advance, followed by a "no overtaking" sign at 100 m before the narrowing. At 100 m beyond the end of the narrowed road section, a final sign indicated that overtaking was once again permitted.

3.2. Overview of Interventions

In this study, the term 'chicane' refers to a staggered arrangement of three half-circle speed cushions that primarily function as a lateral deflection measure. Figure 2 provides further clarification and shows the dimensions within the transition zone. The cross-section AA′ shown in this figure is further elaborated in Figure 3.

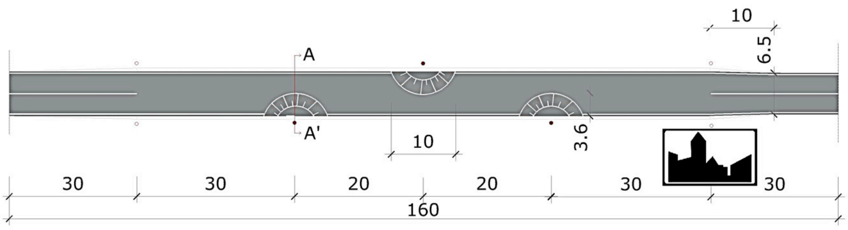

Figure 2. Dimensions of the chicane in meters with indication of cross-section AA′.

Each speed cushion features a linear incline, sloping upward from the center toward the edge of the roadway, reaching a maximum height of 14 cm at the outer edge. This configuration slightly deviates from the conventional standard, typically consisting of a uniform elevation of 12 cm across the full roadway width [38]. Due to technical constraints within the simulation software, it was not feasible to implement a consistent 12 cm height across the entire surface. The cushions were constructed in each single passing lane with a 4% slope along the cross-section to accommodate this. To enhance visibility and alert drivers, delineator posts were placed 75 cm from the edge of the paved surface at the location of each raised element. A cross-section of the roadway at the location of a cushion is shown in Figure 3.

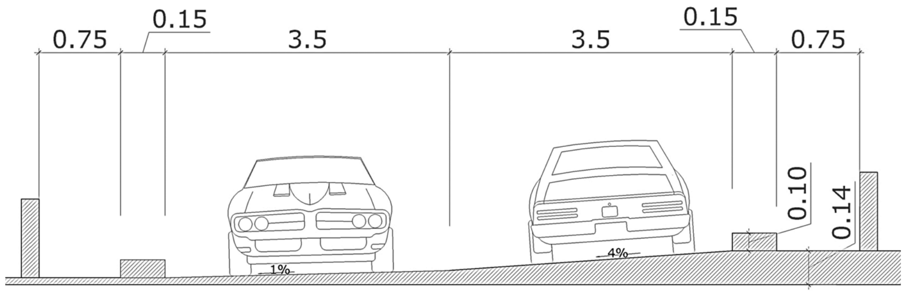

Figure 3. Cross-section AA′ with dimensions of the chicane (in meters).

In the road narrowing with a chicane design, the narrowing was applied exclusively as a physical constraint, without providing additional pavement width to accommodate wider vehicles, as such an addition would undermine the intended effect of the chicane. The lane width was reduced to 2.85 m per lane. A chicane was integrated into the narrowing to introduce lateral vehicle displacement.

The designs incorporating transverse road markings were applied over a 200 m stretch, with a new group of markings every 50 m. Each marking measured 0.5 m in width, with a minimum spacing of 4 m between successive lines [39]. The number of markings per group increased progressively, starting with one and culminating in five transverse lines in the final group.

Finally, visual narrowing was introduced in designs that included avenue planting by placing tall trees with high trunks, approximately 13 m in height. These were spaced at 10 m intervals along a 200 m stretch and planted at a distance of 2 m from the edge of the roadway. This configuration was intended to enhance the psychological narrowing effect and reinforce the perception of entering a lower-speed environment.

3.3. Simulator Setup

Simulations were conducted using an in-house fixed-base driving simulator (STISIM Drive® 3; Systems Technology Inc., Hawthorne, CA, USA). The simulator consisted of a Ford Mondeo chassis, integrated with a 180-degree projection system (utilizing three projectors) and Fanatec hardware components, which provided a wide field of view and high visual immersion. The simulator is shown in Figure 4.

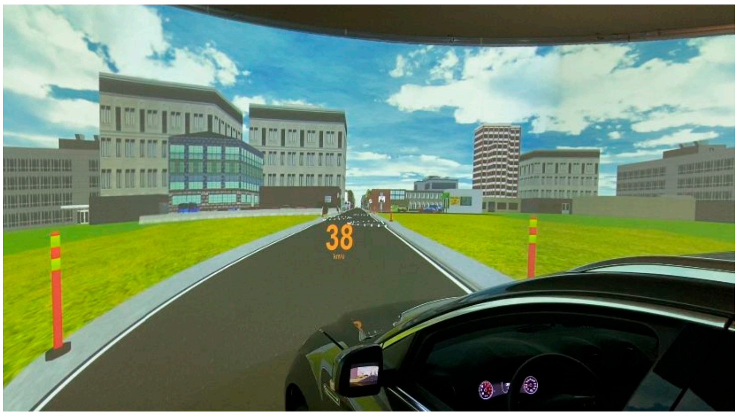

Figure 4. Driving simulator with 180° projection system.

3.4. Participants and Procedure

A total of 54 participants (13 women and 41 men) took part in the experiment. Before participation, all individuals signed an informed consent form and completed a pre-survey. Before starting the experimental trials, each participant performed a brief familiarization drive to become accustomed to the simulator environment. Eligibility criteria included possessing at least a provisional category B driving license and a minimum of 20 h of driving experience. Participants were excluded in cases of pregnancy, illness, or substance impairment (e.g., alcohol or drug use). Participation was entirely voluntary and could be withdrawn at any time. The experimental drives comprised sequential gateway designs distributed across a 14 km driving route. Each scenario featured a combination of TCMs interspersed with neutral road segments, referred to as filler pieces, to mitigate carryover effects. The scenarios specifically targeted the transition from rural to urban environments.

In total, four unique driving scenarios were developed, each presenting the gateway designs in a different order. This variation was intended to minimize the learning effect—the potential change in driving behavior due to increasing familiarity with the simulation environment. By alternating both the structure and sequencing of scenarios across participants, predictability was reduced, and habituation was effectively minimized. Although these steps reduced the likelihood of behavioral learning unrelated to the interventions, it cannot be ruled out entirely that repeated exposure influenced some responses.

The present study did not perform subgroup analyses by age, gender, or driving experience, as the main objective was to isolate the effects of gateway designs rather than demographic variability. While informative, such analyses would have extended the scope considerably beyond the intended focus of this research. We aim to identify relative differences between gateway designs under controlled conditions, not to estimate population-level effects for all driver groups. It should also be noted that with 54 participants, our sample size is relatively large for driving simulator experiments, which typically involve fewer participants due to the resource-intensive nature of such studies.

3.5. Data Collection and Processing

Data collection was conducted for driving behavior metrics. The collected data were analyzed using IBM SPSS Statistics version 29.0.1.1. Objective variables, including speed, acceleration/deceleration, and lateral position, were recorded at a sampling frequency of 0.014 s across the whole 650 m test trajectory and predefined measurement points. Each gateway design was treated as a separate data block. A comprehensive set of measurements was gathered during the simulation runs and subsequently subjected to parameter-specific analysis to minimize data loss.

The processing of participant data began with identifying and excluding statistical outliers. If a participant was flagged as an outlier for any of the main parameters (i.e., speed, lateral deviation, or acceleration/deceleration), they were excluded from the dataset entirely. Outliers were determined based on the interquartile range (IQR) method, with values exceeding 1.5 times the IQR above the third quartile or below the first quartile classified as extreme [40,41]. These thresholds were consistently applied across all parameters. Participants exhibiting outlier values in more than 15% of the measurement points were excluded from the analysis, which aligned with common practices reported in the literature [42]. As a result, no outliers were detected in the collected dataset, indicating a consistent and reliable data distribution.

4. Results

This section presents the findings of the driving simulator study, structured around three key behavioral indicators: speed, acceleration/deceleration, and lateral deviation. Each parameter was analyzed across the eight gateway designs to assess the effectiveness of individual and combined TCMs. The results are derived from data captured at predefined measurement points throughout the gateway. Measurement points were carefully selected for each parameter to ensure relevance and accuracy so that the influence of each design, as well as each TCM, can be interpreted.

Given the unbalanced design of our driving simulator experiments, we employed a Linear Mixed-effect Model (LMM) approach, which is well-suited for analyzing repeated measures and data structures with unequal group sizes or missing observations. Unlike traditional ANOVA, which assumes a balanced design and homogeneity of variance, LMMs can account for both fixed and random effects, offering greater flexibility and robustness in real-world experimental setups [43,44]. Type III tests of fixed effects were used within the LMM framework to identify statistically significant differences in driving behavior across the tested designs.

The following subsections discuss the results in detail, highlighting where and how the TCMs influenced driver performance. First, speed and acceleration/deceleration data are presented from measuring points across all designs. Then, the effectiveness of each TCM, if implemented as a standalone design, is also statistically studied. Finally, the drivers' behavior when encountering chicanes, as the most influential TCMs, is investigated.

4.1. Speed

Speed data were collected at six fixed measurement points to assess how each gateway design influenced speed. These points include: the beginning of the design segment, the end of any pre-transition measure (e.g., markings or avenue planting), three locations evenly spaced within the 100 m transition zone (i.e., start, middle, and end), and a final point 100 m downstream of the built-up entry sign. Figure 5 shows the locations of the measuring points for speed recording.

Figure 5. Measurement points for speed (distances are in meters).

Table 1 presents the results of the Type III tests of fixed effects with speed as the dependent variable. The analysis reveals that both the gateway's design and the measurement point's location had a statistically significant impact on vehicle speed. Specifically, the design yielded an *F*-value of 82.015 ($p < 0.001$), indicating that the different gateway designs resulted in substantial variations in average driving speed. Similarly, the effect of measurement point was significant ($F = 433.841$, $p < 0.001$), reflecting the expected variation in speed across the transition zone and into the urban segment. The significant intercept ($F = 4777.922$, $p < 0.001$) confirms that the estimated baseline level of the dependent variable—representing the expected value when all predictor variables are set to zero—is significantly different from zero, confirming that the model captures a meaningful starting point for the outcome measure.

Table 1. Type III tests of fixed effects with speed as the dependent variable.

Source	Numerator Df	Denominator Df	*F*	*p*
Intercept	1	52	4777.922	<0.001
Design	7	2409	82.015	<0.001
Measurement Point	5	2409	433.841	<0.001

In the LMM with speed as the dependent variable, the effect of the gateway design on average speed was systematically analyzed. The results are shown in Table 2. The model's intercept was estimated at 53.378 km/h, representing the expected mean speed in the reference design at measurement point 6, which is located within the built-up area where the legal speed limit is 50 km/h. All design-related coefficients were found to be negative and statistically significant ($p < 0.001$), indicating that the implemented measures resulted in significantly lower speeds compared to the reference scenario.

The largest reductions were observed in designs combining chicane and road narrowing. This gateway design led to an average speed decrease of more than 9 km/h relative to the reference. Designs featuring only a chicane produced reductions of over 7 km/h, while a standalone road narrowing yielded a moderate decrease of just over 3 km/h. The positive estimated coefficients for most measurement points, except for point 5 (i.e., the actual start point of the urban zone indicated by the built-up entry sign), reflect higher speeds at those locations compared to the reference point, and the least amount of speed at point 5. Collectively, the values reveal a gradual speed-reduction pattern across successive measurement locations. However, within individual designs, no statistically significant differences in average speed were found between measurement points 4, 5, and 6, suggesting a consistent speed level in that zone.

Table 2. Estimates of fixed effects with speed as the dependent variable.

	Parameter	Estimate	Std Error	Df	*t*	*p*
	Intercept	53.378	0.937	110.558	56.965	<0.001
Designs	Reference *	0	0	–	–	–
	Chicane	−7.315	0.608	2409	−12.032	<0.001
	Road narrowing	−3.032	0.608	2409	−4.987	<0.001
	Road narrowing + Transverse road marking	−3.925	0.608	2409	−6.455	<0.001
	Road narrowing + Avenue planting	−3.275	0.608	2409	−5.386	<0.001
	Road narrowing + Chicane	−10.020	0.608	2409	−16.481	<0.001
	Road narrowing + Chicane + Transverse road marking	−10.485	0.608	2409	−17.245	<0.001
	Road narrowing + Chicane + Avenue planting	−9.405	0.608	2409	−15.470	<0.001
Points	1	18.417	0.527	2409	34.977	<0.001
	2	12.246	0.527	2409	23.258	<0.001
	3	6.035	0.527	2409	11.461	<0.001
	4	0.636	0.527	2409	1.209	0.227
	5	−0.545	0.527	2409	−1.035	0.301
	6 *	0	0	–	–	–

* Baseline categories.

Figure 6 presents the speed profiles across the six measurement points for each gateway design. The graph demonstrates that the presence and type of TCMs significantly influence how drivers adapt their speed while approaching and traversing the transition zone. Designs incorporating a chicane have formed a cluster, associated with the most pronounced speed reductions, with average speeds dropping below 45 km/h before the built-up entry sign. In contrast, configurations lacking a chicane, such as the reference design or those featuring only visual cues or road narrowing, exhibit a more gradual decrease pattern, with speeds typically remaining above the 50 km/h threshold until after the transition is completed.

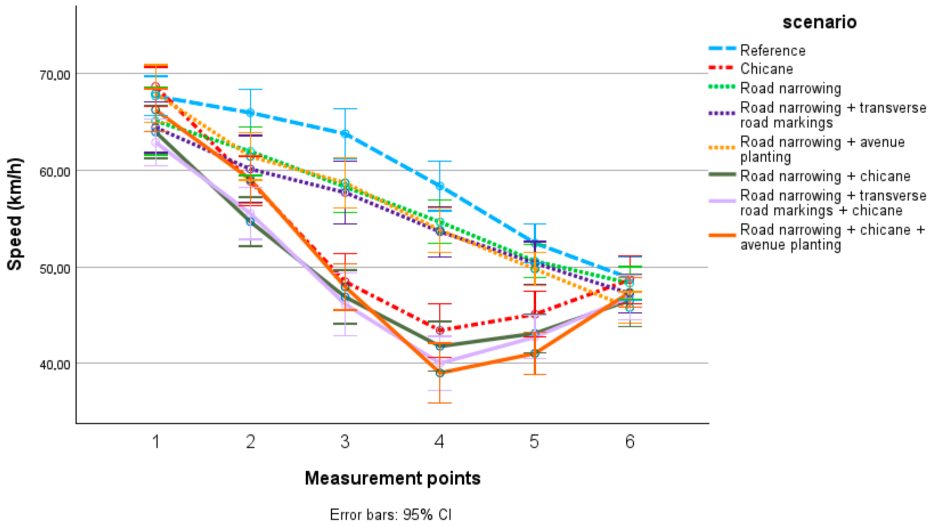

Figure 6. Speed at measurement points in different designs.

4.2. Acceleration/Deceleration

This section analyzes the effects of the different gateway designs on drivers' longitudinal acceleration and deceleration behavior. Acceleration/deceleration was measured at five specific points in each gateway design, capturing the dynamics before, during, and after the TCM. The spatial distribution of these measurement points is shown in Figure 7.

Figure 7. Measurement points for acceleration/deceleration (distances are in meters).

Table 3 presents the outcomes of the Type III fixed effects tests with acceleration/deceleration as the dependent variable. The results indicate that all three examined factors, intercept, design, and measurement point, have statistically significant effects on acceleration behavior. The design factor yielded an F-value of 6.355 with a p-value below 0.001, confirming that the specific gateway configuration has a meaningful influence on how drivers accelerate or decelerate. An even more substantial effect was observed for the measurement point, with an F-value of 75.909, reflecting a substantial variation in acceleration as drivers progress through different segments of the test environment. Additionally, the intercept was highly significant, confirming that the baseline acceleration/deceleration level, corresponding to the condition when all predictors are zero, is statistically different from zero.

Table 3. Type III tests of fixed effects with acceleration/deceleration as the dependent variable.

Source	Numerator Df	Denominator Df	F	p
Intercept	1	50	156.646	<0.001
Design	7	1978	6.355	<0.001
Measurement Point	4	1978	75.909	<0.001

Table 4 presents the fixed effects estimates for acceleration and deceleration behavior across various gateway design configurations and measurement points. The reference design showed a slight deceleration (-0.107 m/s^2), serving as the baseline. Designs featuring a chicane, either alone or in combination with road narrowing and psychological measures, demonstrated significantly higher positive estimates, indicating more pronounced acceleration events. The strongest effects were observed in configurations combining chicanes with transverse markings or avenue planting, each producing acceleration estimates around 0.23 m/s^2 ($p < 0.001$). This pattern reflects a rebound effect where the acceleration following the gateway can outweigh the earlier deceleration, resulting in net positive values. To avoid this potential bias, the analysis in Section 4.3 focuses only on zones where the gateway design is located, thereby excluding the post-gateway segment from consideration. This allows the impact of each individual TCM to be assessed more directly. Moreover, road narrowing alone (0.086 m/s^2) was not statistically significant (p = 0.095), and the combination with avenue planting (0.04 m/s^2) showed no meaningful effect (p = 0.442).

Measurement point analysis revealed that points 1, 2, and 3 show significant negative estimates, with point 2 exhibiting the most pronounced deceleration (estimate = −0.594, p < 0.001), while points 4 and 5 (i.e., the reference point) do not significantly differ.

Table 4. Estimates of fixed effects with acceleration/deceleration as the dependent variable.

	Parameter	Estimate	Std Error	Df	*t*	*p*
	Intercept	−0.107	0.045	1699.260	−2.390	0.017
Designs	Reference *	0	0	–	–	–
	Chicane	0.161	0.051	1978	3.124	0.002
	Road narrowing	0.086	0.051	1978	1.673	0.095
	Road narrowing + Transverse road marking	0.130	0.051	1978	2.525	0.012
	Road narrowing + Avenue planting	0.040	0.051	1978	0.768	0.442
	Road narrowing + Chicane	0.229	0.051	1978	4.441	<0.001
	Road narrowing + Chicane + Transverse road marking	0.230	0.051	1978	4.468	<0.001
	Road narrowing + Chicane + Avenue planting	0.239	0.051	1978	4.649	<0.001
Points	1	−0.122	0.041	1978	−2.994	0.003
	2	−0.594	0.041	1978	−14.6	<0.001
	3	−0.300	0.041	1978	−7.366	<0.001
	4	0.000	0.041	1978	0.005	0.996
	5 *	0	0	—	—	—

* Baseline categories.

Figure 8 illustrates acceleration/deceleration patterns across the measurement points for gateway designs. A distinct variation in how drivers respond can be observed depending on the type of TCM encountered. Designs incorporating a chicane exhibit sharp deceleration just before the chicane, followed by a noticeable acceleration immediately afterward, highlighting a rebound effect. This rapid deceleration–acceleration sequence reflects a more abrupt and reactive driving style. In contrast, designs with road narrowing show a more gradual and linear deceleration behavior with a modest and delayed recovery in acceleration, suggesting a smoother and more predictable driver response. The reference design and those with only visual cues, such as transverse road markings or avenue planting, demonstrate relatively steady acceleration/deceleration profiles, indicating minimal behavioral adaptation.

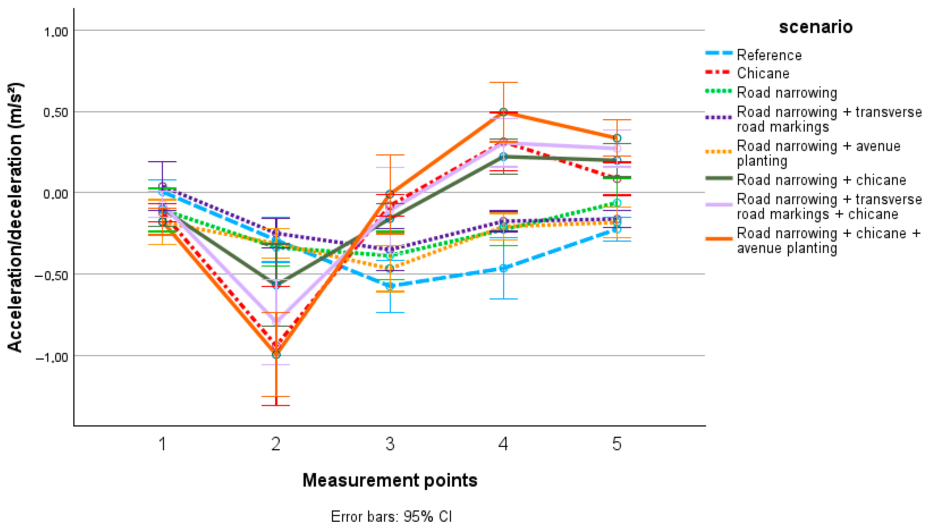

Figure 8. Acceleration/deceleration at measurement points in different designs.

4.3. Impact Assessment of Individual Traffic Calming Measures

We extended our analysis by performing additional LMM to gain a deeper understanding of how each individual TCM affects driving behavior. While the initial LMMs reported in previous sections focused on combined TCMs, these subsequent models isolate the independent impact of each treatment. The analysis was restricted to the segment where the gateway design was located to ensure that the observed effects reflect the direct influence of the TCMs rather than downstream driving responses. By excluding post-gateway segments where behavioral rebound effects may occur, this focused approach improves the precision of our estimates and allows for a more precise evaluation of each TCM's local effect. This enables us to identify which individual TCMs exert the most influence when controlling for other factors.

Table 5 presents the results of the Type III tests of fixed effects for speed, focusing on the independent contribution of each TCM. The chicane intervention had a statistically significant impact on driving speed ($F = 246.286$, $p < 0.001$), confirming its strong influence in reducing speed. The impact of road narrowing is also statistically significant ($F = 22.745$, $p < 0.001$), suggesting a less pronounced but still meaningful impact. In contrast, avenue planting ($F = 1.364$, $p = 0.243$) and transverse road markings ($F = 1.354$, $p = 0.245$) did not show statistically significant effects.

Table 5. Type III tests of fixed effects of individual TCMs with speed as the dependent variable.

Source	Numerator Df	Denominator Df	*F*	*p*
Intercept	1	84.976	3618.853	<0.001
Chicane	1	1585	246.289	<0.001
Road narrowing	1	1585	22.745	<0.001
Avenue planting	1	1585	1.364	0.243
Transverse marking	1	1585	1.354	0.245

Table 6 provides parameter estimates for the fixed effects with speed as the dependent variable. For each TCM, the reference category is where the intervention was present, while the effect estimate represents the mean difference in speed when the TCM is absent. The presence of a chicane corresponds to a significant reduction in speed, with an estimated increase of 8.122 km/h when the chicane is removed ($p < 0.001$), underscoring its strong traffic calming effect. Similarly, removing road narrowing results in a 3.491 km/h speed increase ($p < 0.001$), confirming its moderate but significant role in reducing speed. In contrast, the absence of avenue planting yields a negligible and non-significant effect (estimate = −0.855 km/h, $p = 0.243$), as does the removal of transverse markings (estimate = 0.852 km/h, $p = 0.245$).

Table 6. Estimates of fixed effects with speed as the dependent variable for each TCM.

Parameter	Estimate	Std Error	Df	*t*	*p*
Intercept	51.847	1.233	224.459	42.037	<0.001
Chicane = 0	8.122	0.518	1585	15.694	<0.001
Chicane = 1 *	0	0	—	—	—
Road narrowing = 0	3.491	0.732	1585	4.769	<0.001
Road narrowing = 1 *	0	0	—	—	—
Avenue planting = 0	−0.855	0.732	1585	−1.168	0.243
Avenue planting = 1 *	0	0	—	—	—
Transverse marking = 0	0.852	0.732	1585	1.163	0.245
Transverse marking = 1 *	0	0	—	—	—

* Baseline categories.

Table 7 presents the Type III fixed effects analysis outcomes using acceleration/deceleration as the dependent variable. The chicane exhibits the most substantial effect (F = 4.155, p < 0.042), indicating its influence on driving behavior by inducing deceleration. In contrast, all other TCMs, including road narrowing (F = 1.197, p = 0.274), avenue planting (F = 2.344, p = 0.126), and transverse road markings (F = 0.134, p = 0.715), did not significantly impact acceleration.

Table 7. Type III tests of fixed effects of individual TCMs with acceleration/deceleration as the dependent variable.

Source	Numerator Df	Denominator Df	*F*	*p*
Intercept	1	2.028	0.751	0.476
Chicane	1	1177	4.155	0.042
Road narrowing	1	1177	1.197	0.274
Avenue Planting	1	1177	2.344	0.126
Transverse marking	1	1177	0.134	0.715

Table 8 offers parameter estimates to further interpret the effect of each TCM on acceleration/deceleration. A negative estimate indicates stronger deceleration compared to the reference condition (i.e., presence of TCM). The presence of a chicane results in significantly higher deceleration, with a mean increase of 0.077 m/s^2 when the chicane is removed (p = 0.042). Road narrowing (estimate = −0.058 m/s^2, p = 0.274), avenue planting (estimate = 0.081 m/s^2, p = 0.126), and transverse markings (estimate = −0.019 m/s^2, p = 0.715) did not significantly differ from their reference conditions.

Table 8. Estimates of fixed effects with acceleration/deceleration as the dependent variable for each TCM.

Parameter	Estimate	Std Error	Df	*t*	*p*
Intercept	−0.377	0.392	2.115	−0.960	0.434
Chicane = 0	0.077	0.038	1177	2.038	0.042
Chicane = 1 *	0	0	—	—	—
Road narrowing = 0	−0.058	0.053	1177	−1.094	0.274
Road narrowing = 1 *	0	0	—	—	—
Avenue planting = 0	0.081	0.053	1177	1.531	0.126
Avenue planting = 1 *	0	0	—	—	—
Transverse marking = 0	−0.019	0.053	1177	0.366	0.715
Transverse marking = 1 *	0	0	—	—	—

* Baseline categories.

4.4. Lateral Deviation Behavior

Since scenarios without chicanes showed negligible differences in lateral deviation among themselves, including the reference condition, the analysis of lateral behavior was focused only on gateway designs including chicanes. While the chicane intervention was found to reduce vehicle speeds significantly, it also led to a notable increase in deceleration rates. Although speed reduction is generally associated with improved road safety, the accompanying sharp deceleration may reflect abrupt driver responses or discomfort, potentially introducing new safety risks. This seeming contradiction highlights the need for a more detailed examination of how drivers physically navigate the chicane. In particular, understanding lateral avoidance behavior is essential for interpreting whether drivers are swerving or adjusting their path abruptly in response to the physical constraints imposed by the chicane.

To further analyze the drivers' behavior when encountering chicanes, the lateral avoidance strategies of drivers at the location of the chicane were studied based on measurement points indicated in Figure 9. Each measurement point was taken at the center of the cushion, spaced 20 m apart.

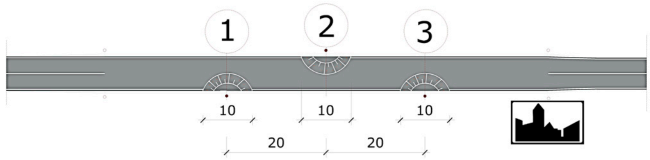

Figure 9. Measurement points for lateral deviation (distances are in meters).

Figure 10 visually illustrates the percentage of participants who used each driving strategy across the three chicane designs. Across all configurations, driving straight over the cushions remained the most prevalent behavior, indicating a general tendency among drivers to prioritize path continuity over evasive maneuvering. In a chicane design without road narrowing or oncoming traffic, almost 70% of participants drove straight over both cushions, making it the most dominant strategy, and only around 20% chose to perform a chicane maneuver. When the chicane was combined with road narrowing, the chicane maneuver strategy became more frequent, with 35%, and fewer drivers passed straight over both cushions. This indicates that the presence of a narrowed roadway heightens spatial awareness and prompts more lateral avoidance. On the other hand, when an oncoming vehicle is added to the design, the majority of participants (over 60%) again choose to drive over the cushions. This may reflect a reluctance to perform lateral maneuvers when facing dynamic conflict, possibly due to uncertainty or perceived risk.

Overall, these findings reveal that while physical or visual constraints can partially influence driver behavior, the tendency to drive over the cushions persists, even under more complex traffic conditions, raising questions about the chicane's actual effectiveness in enforcing safe lateral maneuvers. The combination of road narrowing and oncoming traffic, rather than encouraging evasive behavior, results in a reduction in maneuvering, with more participants choosing either to go straight over both cushions or only partially avoid them. However, although the chicanes did not consistently induce the expected lateral deviation, they still led to a noticeable reduction in speed, often accompanied by abrupt deceleration. This suggests that chicanes may function more effectively as speed-reducing elements than as tools for guiding smooth lateral repositioning, potentially affecting driver comfort and reaction patterns.

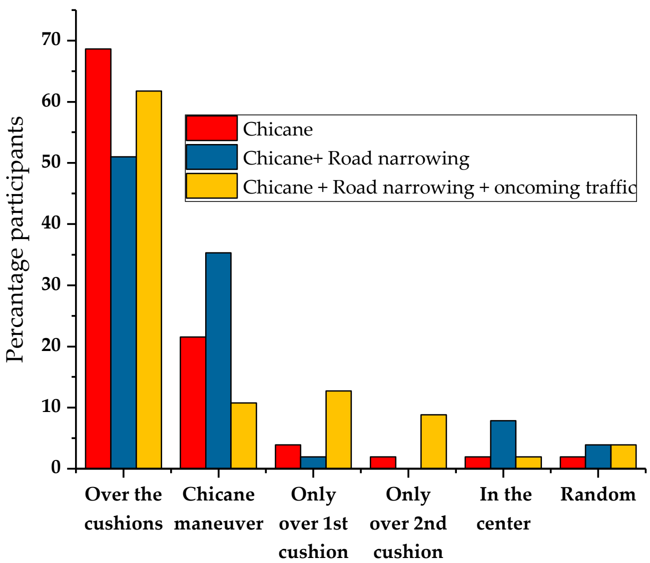

Figure 10. Overview of driving strategies at the chicane across different designs.

5. Discussion

The simulator results revealed a clear pattern: physical TCMs were substantially more effective at reducing vehicle speed during high-to-low speed transitions than psychological measures. Chicanes, both alone and in combination with road narrowing, consistently produced the most substantial speed reductions. These findings corroborate those of Sołowczuk et al. [22], who emphasized the efficacy of lateral deflections like chicanes in maintaining lower travel speeds in transition zones. Similarly, Lantieri et al. [26], demonstrated that curbs and lateral constraints significantly increase driver awareness and reduce approach speeds.

On the other hand, avenue planting and transverse markings failed to produce significant speed reductions when applied independently. This aligns with findings from Hussain et al. [34], who reported that while perceptual markings can influence speed momentarily, their effects dissipate quickly unless combined with physical features. However, Pazzini et al. [8], demonstrated that psychological TCMs, such as smart lighting at pedestrian crossings, can significantly reduce vehicle speeds and enhance yielding behavior. It should be noted that although Section 2 reviewed vertical traffic calming devices such as speed humps, tables, and raised crossings, these were not included in the tested designs. The raised cushions used in the chicane were primarily configured to enforce lateral deflection. As such, the findings of this study should be interpreted as focusing on lateral and psychological interventions rather than vertical ones.

Moreover, the speed data suggested that drivers only respond meaningfully to cues that demand cognitive and physical engagement. Designs that paired physical and perceptual elements, such as road narrowing combined with transverse markings, achieved smoother deceleration profiles without abrupt braking. This finding echoes Doomah and Paupoo [32], who noted that multimodal gateway treatments balance effectiveness with comfort and user acceptance.

Acceleration/deceleration profiles further reinforced the primacy of physical interventions. Chicanes led to abrupt deceleration followed by an immediate acceleration, creating a rebound effect. While this confirms their effectiveness in enforcing deceleration, it also raises concerns about driving comfort and consistency. Pérez-Acebo et al. [14] warned that such reactive maneuvers could lead to unpredictable driver behavior post-intervention, especially in mixed-traffic environments. In contrast, road narrowing designs prompted more gradual deceleration and less aggressive recovery in acceleration, indicating a smoother transition. These results are consistent with the findings of Melman et al. [45], who found that road narrowing, while not as forceful as chicanes, induces moderate but sustained deceleration through perceptual narrowing and steering tension.

The failure of avenue planting and transverse markings to produce significant changes in acceleration/deceleration confirmed earlier reports by Wu et al. [30], and Fitzpatrick et al. [31], who showed that vegetation and visual cues alone lack the tactile urgency to alter driver kinematics meaningfully. These measures might influence lane positioning or perceived safety, but are insufficient to alter longitudinal behavior without supporting physical constraints. The weak performance of psychological traffic calming measures in the present study may be attributed to several factors. First, the absence of tactile feedback (e.g., vibration from transverse rumble strips) likely reduced the salience of the markings. Second, the visual stimuli used in the simulator were uniform and predictable, potentially reducing their novelty effect. Third, the absence of other traffic participants or environmental variability limited the extent to which drivers needed to rely on perceptual cues. Such psychological measures may prove more effective in real-world settings, where drivers encounter multisensory feedback and more complex environmental contexts.

Therefore, simulator results should be interpreted cautiously when generalizing the impact of psychological interventions.

On the other hand, while chicanes maximized deceleration, their abruptness may compromise ride quality and safety, especially in areas where vulnerable road users might be present. Road narrowing, in contrast, offers a compromise, less dramatic in effect but more stable and predictable. It is important to note that the acceleration/deceleration estimates in the LMMs reflect an average over distinct driving segments; in some cases, the sharp rebound acceleration following a chicane, particularly after passing a gateway, outweighs the initial deceleration, resulting in a net positive estimate. Therefore, these values should be interpreted in conjunction with the full acceleration/deceleration profile, where these segmented patterns are clearly visible.

In addition, the analysis of lateral behavior at chicanes offers nuanced insight into how drivers physically negotiate TCMs. When an oncoming vehicle was added, most participants reverted to driving straight over the chicane cushions, prioritizing collision avoidance over ideal trajectory. This highlights a trade-off between safety and compliance, indicating that driver behavior becomes more risk-averse under perceived conflict conditions. It also aligns with Qin et al. [20], who showed that oncoming traffic can neutralize the behavioral effects of non-exclusive calming features. Therefore, lateral deviation behavior reveals the contextual sensitivity of calming interventions. Unless drivers are given compelling spatial or visual cues, and ideally, both, they tend to revert to default linear strategies. Effective gateway designs should thus limit ambiguity in maneuver paths while preserving options for larger vehicles and emergency access.

6. Conclusions

6.1. Summary

This study evaluated the effectiveness of seven gateway configurations, comprising both physical and psychological TCMs, at transition zones between 70 km/h and 50 km/h speed regimes. Key driving behavior parameters, including speed, acceleration/deceleration, and lateral deviation, were analyzed using a high-fidelity driving simulator and a within-subjects design. The results confirmed that physical interventions, particularly chicanes and their combinations with road narrowing, were the most effective in reducing vehicle speed and inducing significant deceleration. In contrast, when implemented independently, psychological measures such as avenue planting and transverse markings showed minimal behavioral impact. The study also demonstrated that driver response is context-dependent: spatial constraints and traffic presence significantly influence driving strategies and lane behavior at chicanes. Collectively, these findings reinforce the necessity of integrated gateway designs that blend physical constraints with perceptual cues to promote smoother, earlier, and more consistent speed reductions at urban entry points.

6.2. Limitations

While the simulator-based methodology offers controlled testing conditions and rich behavioral data, it also introduces limitations that must be acknowledged [46]. Firstly, the simulated environment may not fully replicate real-world conditions, particularly in terms of sensory input such as vibration, road texture, and dynamic interaction with other traffic participants [47]. This may influence the ecological validity of results, especially for psychological interventions that depend on visual or multisensory perception. Nonetheless, the relative validity of driving simulators for comparing driver behavior across design alternatives has been well established. Given the study's focus on identifying relative differences between gateway designs, the simulator provides a valid platform for this initial investigation. These results can guide future real-world studies to further assess the most promising interventions. Secondly, the participant pool included a diverse range of ages and driving experiences, providing valuable insights into relative effects across different driver profiles. While the sample size was modest, it still allowed us to capture meaningful trends. However, further studies could expand to include additional groups, such as older or professional drivers, to enhance generalizability. Nevertheless, the sample size of 54 participants is comparatively high for driving simulator research, providing a robust basis for detecting relative differences between designs. The findings should therefore be interpreted as relative effects across designs within a controlled environment.

Although the study accounted for learning effects by randomizing scenario sequences, repeated exposure to similar interventions in a controlled environment could still bias participant behavior. Another limitation is that the experiment captured only immediate driver responses during single-drive scenarios. However, examining these immediate effects is an essential first step in identifying the most promising gateway designs for follow-up research. It remains unclear whether the observed speed reductions and deceleration behavior changes would persist after repeated exposure or diminish as drivers become accustomed to the designs. This restricts the ability to generalize findings to long-term driver adaptation, highlighting the need for future longitudinal or field studies to confirm the durability of these behavioral effects.

Moreover, the experimental scenarios excluded other road users, such as pedestrians and cyclists, and higher traffic volumes. This simplification was intentional, as gateway locations are cognitively demanding points on the road network, and the primary focus was on measures to support drivers in adhering to speed changes. While other road users were included in the scenario design to enhance realism, they were not positioned to interact directly with drivers. This approach allowed for isolating the effects of the traffic calming measures. Finally, the simulator's fixed-base platform restricts physical movement, potentially dampening the driver's response to vertical interventions, such as speed cushions. Although no tactile feedback was provided, the raised cushions were visually rendered and perceived by drivers as elevated elements, ensuring that the key visual cue of the intervention was captured. This representation still elicited meaningful speed adjustments because visual information strongly guided driver behavior. While the absence of multisensory feedback may have reduced sensitivity to vertical features, previous research has consistently shown that simulators, even without full physical fidelity, yield reliable outcomes for relative comparisons of design alternatives. For instance, Hussain et al. [11] and Groeger et al. [48] demonstrated that simulators produce reliable behavioral outcomes consistent with real-world observations even when lacking full physical fidelity.

In addition, despite the limitations, the results remain valuable, particularly when analyzing relative differences across design conditions. The relative validity of the findings is strong, as the internal consistency and comparative trends offer meaningful insights into driver behavior in response to different interventions.

6.3. Potential Implications and Future Work

The results carry several inferences for policy and infrastructure design. For policymakers seeking to enhance safety at rural-urban transition points, this study provides clear evidence supporting the implementation of physically constraining measures like chicanes and road narrowing. In addition, the results have implications for smart city safety frameworks such as Vision [49], supporting the design of context-sensitive entry zones that proactively manage driver behavior. Gateway interventions evaluated through simulation can inform urban design guidelines and speed management policies at rural-urban boundaries, improving pedestrian and cyclist safety without relying solely on enforcement. As cities adopt digital twins for infrastructure planning [50,51], the tested gateway interventions can serve as validated modules in city-wide mobility simulations. Integrating behavioral data from simulators into such digital ecosystems supports smarter multi-criteria decision-making, enhances public engagement, and accelerates infrastructure optimization [52].

Future research should extend the findings through on-road experiments or augmented reality simulations that incorporate richer sensory feedback and dynamic traffic scenarios. Longitudinal studies are also needed to assess whether behavioral adaptations persist over time or diminish with driver familiarity. For instance, continuous analysis techniques on simulator time-series data can be employed. Such methods would allow the investigation of full speed and acceleration profiles, rather than discrete measurement points, thereby providing deeper insights into driver behavior dynamics across gateway designs. Moreover, integrating eye-tracking or biometric monitoring (e.g., heart rate variability) could yield more profound insights into the cognitive and emotional responses triggered by different gateway configurations. In addition, as smart city infrastructure evolves, exploring how digital interventions (e.g., in-vehicle alerts or adaptive signage) can complement physical gateways represents a promising direction for next-generation TCMs.

In addition, future studies should complement objective driving behavior data with detailed subjective evaluations, including perceived safety, comfort, and acceptance, to provide a more holistic assessment of gateway interventions. Future research with larger, more balanced samples should investigate whether demographic characteristics moderate design effects; targeted moderator analyses will be more informative once adequately powered. Vulnerable road users and higher traffic densities can also be incorporated into the experiments to better reflect real-world urban conditions and to evaluate the driver behavior in mixed-traffic environments. This was not performed in the current study to maintain focus on drivers' responses to speed changes at cognitively demanding gateway locations. Moreover, this study did not include a cost-effectiveness analysis, which lies beyond its scope, and future work can complement these findings with economic assessments to guide policymakers. Finally, this study can be integrated into a digital twin of the urban mobility infrastructure to design, assess, and iterate transportation policies in real-time.

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