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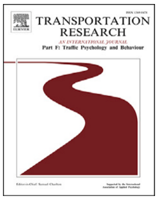

Quantifying the effect of road design on urban road driving speed

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ABSTRACT

Background: Reducing driving speed is a key factor in improving road safety and combating noise emissions. As a result, an increasing number of cities worldwide are lowering speed limits on urban roads. However, main urban roads differ from residential streets in several ways, including their appearance, type of trips they accommodate, mix of vehicles and the presence of public transport. These differences limit the design options available for speed reduction.

This paper examines the impact of continuous road design measures on drivers' preferred speed, safe speed and actual driving speed on urban main roads, as well as the psychological processes influencing these choices.

Methods: A virtual reality (VR) study was conducted using a driving simulator. Participants drove through a series of main roads in VR with varying speed limits and road designs. Speed and lateral position were recorded; in a follow-up survey, participants stated their preferred - as well as the considered 'safe' - speed along different road designs. They were also asked about driving style, perceived complexity and safety of each treatment.

Results: Simulator results indicated that only specific road designs result in slightly lower driving speeds. Survey results revealed that certain measures influenced preferred and safe speed. Specifically, those with effectiveness linked to the presence or absence of other road users (cyclists, pedestrians, or other cars). Moreover, the study showed that perceived safety and complexity moderated the effectiveness of these road design measures.

Conclusion: Overall, road design measures investigated in this study provided evidence on the impact of road design on driving behavior, but also demonstrated the need for further investigations to include dynamic human factors, as well as combinations of measures to achieve the goal of lower speeds on urban roads.

1. Introduction

Speed reduction has significant positive consequences. Reducing driving speed plays a crucial role in promoting road safety; it not only lowers the likelihood of traffic accidents, but - according to the Power Model - also decreases both frequency and severity of crashes (e.g. Elvik, 2013). Speed reductions result in lower noise emissions, reduced annoyance and sleep disturbances (Brink et al., 2022). Lower speeds can also result in reduced emissions, leading to improved air quality and a healthier living environment

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(Transport for London, 2018). Traffic flow can be improved due to reduced acceleration and braking (Transport for London, 2018). Given the already low driving speeds typically observed in urban environments, lowering speed limits from 50 km/h to 30 km/h has only a minimal impact on travel times (Umweltbundesamt, 2016). Traffic calming generally enhances the livability of urban environments (Zein et al., 1997; Yannis & Michelaraki, 2025).

To this end, many European cities and countries have lowered the speed limits of residential and neighborhood roads from 50 km/h (30 mph) to 30 km/h (20 mph) or even 20 km/h (12.4 mph). At the same time, discussion is underway to reduce speed limits on main roads in urban areas in Germany, the Netherlands, Switzerland, the United States and several other countries (Dijkstra & van Petegem, 2019; Häfliger et al., 2019). In Helsinki, Finland, maximum driving speed throughout the city is set at 40 km/h (City of Helsinki, 2018). Several cities in the United States have lowered speed limits on urban roads to 25 mph as part of their Vision Zero initiatives aimed at eliminating traffic-related fatalities and severe injuries (District Department of Transportation, 2022; Seattle Department of Transportation, 2022).

Conventional measures such as speed limits and law enforcement have their merits in ensuring traffic safety and lowering driving speeds. However, adherence to speed limits on urban roads is generally low (e.g. Adminaité-Fodor & Jost, 2019; Niemann, 2020) and effective speed management remains challenging.

A complementary measure to achieve speed reduction is to reconsider road design, which has been found to be a critical factor in determining drivers' speed and their adherence to speed limits. An explanation for this observation is found in the concept of self-explaining roads (SER) (Theeuwes & Godthelp, 1995; Theeuwes, 2021). The SER-approach suggests that if road designs convey that reduced speeds are expected, safe driving speed is lower.

Previous research on road design's speed impact is still sparse and is mostly limited to investigating the influence of road design on rural roads, transition between urban roads and rural roads and main urban roads with a higher speed limit. Hence, research that quantifies the impact of road design on main urban roads with lower speed limits can contribute to a better understanding of the relationship between road design and speed.

Two types of road design measures can be differentiated: point-specific and continuous traffic calming measures. Research has shown that point-specific traffic calming measures such as speed bumps (Johnson & Nedzesky, 2004), digital information boards (Walter & Broughton, 2011) or chicanes (Johnson & Nedzesky, 2004; Molino, 2009) can result in local speed reductions, but do not lead to overall lower driving speeds. Continuous traffic calming measures such as side markings, or different types of center lines, have not been investigated to the same extent. These measures are especially relevant for main urban roads because these roads function as places, but also as corridors for public transport, logistics and emergency services. For these reasons, the present study focuses on continuous road design measures. Against this background, this study aims to close these gaps in the relevant literature and answer the following research question; what is the impact of continuous road design measures on urban main road driving speed?

This study makes several contributions to existing literature. First, while previous research has mostly examined road design effects in rural or high-speed urban environments, our study focuses on main urban roads with lower speed limits, a topic that has received limited attention and has practical relevance.

Second, this study integrated both objective and subjective measures. Through a VR driving simulator experiment and a follow-up survey, we captured observed driving behavior and drivers' perceptions of safety and complexity, providing a broader perspective on how road design influences both actual and perceived driving speeds.

Third, while many studies propose psychological processes that might explain how road design affects driver behavior (Theeuwes, 2021), empirical evidence on these processes remains scarce. This study explicitly investigated the psychological processes underlying speed selection, contributing to an understanding of why certain road design features influence driver behavior. Our research was guided by the following second research question; what are the psychological processes that explain the impact of road design on chosen speed?

Finally, our findings have practical implications for policymakers and urban planners. As cities increasingly consider lowering speed limits to enhance safety and livability, our results provide empirical evidence on the potential of road design to support these initiatives.

The paper first reviews previous research on the effect of road design as it determines choice of speed, as well as relevant psychological processes. Second, the study reports on a virtual reality (VR) driving simulator study in which participants were asked to drive along a series of roads with varying speed limits and road designs and participated in a follow-up survey. The design of the VR study, procedures and questionnaire are presented in the section 'Methods'. Third, the section 'Results' presents the findings of this research; the paper then concludes with a discussion and outlook.

2. Literature review

2.1. Speed, speed limits, and road design

Speed is a contributing factor to accidents and accident severity. Estimates indicate that in 10% to 15% of accidents, speed was a contributing factor, and 30% of fatal injury crashes are the direct result of excessive speed (van den Berghe, 2021). On urban roads, where 37% of all road deaths occur, over 35% of vehicle speed observations were higher than the legal speed (Adminaité-Fodor & Jost, 2019).

Despite these risks, discussions continue about lowering speed limits to improve road safety. A differentiation can be made between statutory and posted speed limits. The statutory speed limit is the standard speed limit that applies to a specific type of road and is set by local or national governing agencies. The posted speed limit represents the highest legal speed for a particular road and is indicated on a regulatory sign (also see Montella et al., 2024).

In some cases, the posted speed limit is determined by calculating the 85th percentile speed, i.e. the speed that 85% of the drivers choose to drive, ideally under free-flow conditions (e.g. NACTO, 2020). At the same time, there is a growing movement advocating for setting speed limits based not only on existing driving speeds, but rather on speeds that prioritize safety and livability (e.g. FHWA, 2021; Turner et al., 2024).

The most obvious measure to reduce driving speeds is the posting of lower speed limits, but this measure's effectiveness has its limitations. From a driver's perspective, adherence to speed limits, in particular to perceived low speed limits such as 30 km/h, might be difficult for several reasons (Charlton, 2018). First, drivers probably focus on other vehicles rather than speed limit signs and on road features linked to a road's familiarity (Charlton & Starkey, 2013). Second, especially in the case of downward changes of speed limit without visual changes, the road appearance is not a reliable indicator of driving speed (Charlton & Starkey, 2017). Finally, posted speed limits could lose credibility due to a mismatch between road design characteristics and the prevailing speed limit (Yao et al., 2020). These reasons are particularly relevant for main urban roads, as their design, adjacent land use, building typology and landscape features do not always align with a lower speed limit.

From a research perspective, two types of speed can be identified: actual driving speed and credible driving speed. While actual driving speed is an objective behavioral measure, credible speed is a subjective measure that reflects attitudes and behavioral intentions. Previous research has evaluated different subjective speed measures. Goldenbeld and van Schagen (2007) first introduced the phrase 'credible speed': the credibility of a speed limit is influenced by certain combinations of road design and environment features. Road design features and the roadside environment, including visual cues (e.g. road markings) and other design features (e.g. width, surface), provide drivers with cues about appropriate speed (SWOV, 2021). Continuing with this concept, Goldenbeld and van Schagen (2007) evaluate the preferred speed and the preferred safe speed along rural roads. Yao et al. (2019) defines 'credible speed' as speed limits accepted by most drivers without the need for enforcement in a given road layout.

Actual driving speed and credible driving speed are not necessarily aligned, as drivers may choose a driving speed that deviates from the speed they prefer or perceive as safe, particularly if road design sends conflicting signals or does not adequately reflect the intended driving speed.

2.2. Self-explaining roads and psychological processes

The concept of self-explaining roads helps explain the relationship between road design and drivers' behavior (Theeuwes & van der Horst, 2017). Two psychological principles are central to this concept: categorization and expectation. Through experience, drivers learn to categorize roads based on their visual characteristics. Categorization is the foundation for risk assessment and appropriate behavior expectations. By implementing design elements such as lane width, pavement markings and vertical offsets, road spaces can convey information that helps drivers categorize and interpret roads as intended by planning authorities. This, in turn, promotes behavior consistent with those interpretations. For instance, plants adjacent to roads may serve as a visual cue, encouraging drivers to categorize the road as one suited for lower speeds.

Previous literature proposes two underlying psychological mechanisms that explain the effect of road design on driving speed: cognitive load theory and risk perception (Elliott et al., 2003). Cognitive load is defined as the mental effort to perform a task. Cognitive load theory suggests that as a driving situation becomes more complex, cognitive load increases and drivers then reduce their speed. In line with this proposition, an experimental field study found higher cognitive loads in more complex road designs (Harms, 1991). We thus expect that the more complex a road is perceived to be, the slower the chosen speed.

In addition, risk perception is assumed to influence driving speed. As perceived risk increases, drivers reduce vehicle speed to maintain acceptable levels of risk tolerance (Bella, 2013; Calvi et al., 2019; Jamson et al., 2010). Based on this reasoning, the present study assumes that if a road is perceived to be riskier, the chosen speed will be slower.

2.3. Previous research on continuous road design elements and choice of speed

The following sections review literature on how specific road design elements influence drivers' perceptions of complexity, safety and their chosen speeds.

Several methods have been used to study the influence of road design on driving speed. One approach involves experimental studies, where driving behavior is examined in controlled settings using driving simulators (e.g. Taylor et al., 2002; Yao et al., 2020; Montella et al., 2024). A second approach relies on naturalistic studies or speed measurements (Fitzpatrick et al., 2001; Gargoum et al., 2016), where actual driving speeds are recorded in real-world environments using radar, loop detectors, or onboard vehicle sensors. While these methods provide objective data on speed behavior, they do not capture drivers' underlying motivations or perceptions.

Several studies have examined speed preferences and, occasionally, perceived safe speed from drivers' subjective perspectives, (e.g. Goldenbeld & van Schagen, 2007) based partly on experimental designs (Theeuwes et al., 2024). These studies were usually image-based, and asked participants to indicate appropriate, preferred, or safe speed. They offered some insight into drivers' attitudes toward speed limits and road design, but did not measure actual driving behavior.

A limited number of studies also considered psychological or perceptional processes that explain specific road designs' effects on chosen speed. Existing literature mainly discusses how road design features influence risk perceptions or cognitive load, i.e. complexity, without providing empirical evidence (Elliott et al., 2003). The remainder of this section summarizes the main findings from this previous research and derives propositions for this study.

Wide medians Two opposing psychological mechanisms explain the influence of wide medians on chosen speed. On one hand, medians separate vehicles from oncoming traffic, leading to lower levels of perceived risk. On the other hand, wide medians can visually narrow lane width, increasing cognitive load and perceived risk (Elliott et al., 2003). Previous research fails to prove whether medians' effects are determined by greater distance to opposing traffic through the median (lower risk perception), or through (actual or perceived) lane narrowing (more complexity). Nonetheless, we hypothesize that these different effects related to wide medians will influence both perceived complexity and risk.

Focusing on chosen speed, various studies investigated the impact of pavement markings on speed choice, producing mixed evidence on the impact of wide medians - in some papers also referred to as wide center lines - on speed choice. Several driving simulator studies suggested that wide medians with distinct markings could reduce speed on rural roads. Taylor et al. (2002) reported a reduction in speed when a wide median with a hatched pattern was present. Godley et al. (2004) also found that rural roads with a hatched median resulted in lower chosen speeds. In a simulator study that investigated curved rural roads and different types of wide medians, it was found that only rumble-striped yellow double center lines — compared to yellow double center lines with herringbone patterns — led to a significant speed reduction Charlton (2007b). An image-based study indicated that wide medians, in contrast to narrow medians, were associated with lower speed assessments by drivers (Cairney, 1986). It is important to note that these studies focused on rural environments; their findings may not directly translate to the context of main urban roads.

In sum, these studies suggest that wide medians contribute to speed reductions when they are marked in a way that makes them visually salient. Therefore, we hypothesize that wide medians will result in a reduction of chosen speed and that their complexity and perceived risk influence chosen speed.

Center lines Previous literature suggested that center lines can result in lower perceived risk by increasing segregation from opposing traffic (Elliott et al., 2003). In reverse, the absence of a center line increases uncertainty for drivers, leading to higher cognitive load, higher complexity and thus lower safety perceptions (Elliott et al., 2003). We hypothesize that a road without a center line is perceived as more complex and less safe than a road with a center line.

A few studies investigated the impact of the presence or absence of a center line separating opposing traffic. The absence of a center line led to lower speed assessments in an image-based study (Cairney, 1986). A second image-based experimental study found significantly lower speeds for roads without a center line compared to roads with center lines (Theeuwes et al., 2024). An analysis of speed measurements revealed a similar pattern; absence of a center line was associated with lower speeds (Fitzpatrick et al., 2001). In sum, we hypothesize that the absence of a center line will result in a lower chosen speed.

Side markings Side markings, also called edge markings, can visually narrow a road, leading to the impression of reduced maneuvering space and increased perceived speed. This can increase the perception of risk and complexity, as outlined in previous studies (Elliott et al., 2003; Taylor et al., 2002). Therefore, we hypothesize that roads with side markings will be perceived as both more complex and less safe.

A simulator study found that side markings, in combination with center line marking, could lead to speed reductions (Taylor et al., 2002). A meta-analysis by Davidse and van Driel (2002) found that edge markings on rural roads tended to shift the lateral position towards the road's edge, but did not, by themselves, lead to a reduction in speed. However, the same study indicated that removing the center line, in conjunction with edge markings, resulted in speed reductions, whereas the presence of both center and edge lines was associated with increased speeds (Davidse & van Driel, 2002; Taylor et al., 2002). An image-based experimental study by Theeuwes et al. (2024) found significantly higher chosen speeds on roads with edge markings compared to those with center lines. Hence, the extent to which side markings alone influence speed remains unclear. This study thus investigates whether side markings result in lower chosen speeds.

Bicycle lanes Although the primary function of bicycle lanes is to provide dedicated space to cyclists, they share a characteristic with side markings; they can induce a sense of visual narrowing. This perceptual narrowing can contribute to the impression of less available space. Moreover, bicycle lanes serve as a cue for the presence of cyclists, potentially increasing drivers' perceived risk and cognitive load (Elliott et al., 2003). On the other hand, bicycle lanes can also create the appearance of wider roads and result in a segregation of vehicles and cyclists, which could lead to higher perceived safety. Therefore, we hypothesize that these different effects of bicycle lanes will influence perceived complexity and safety. We will explore whether the effects point to a perception of increased complexity and reduced safety, or whether the potential for perceived widening and segregation moderates this effect.

An analysis of speed measurements found reductions in actual speed when bicycle lanes were present (Gargoum et al., 2016). In line with these findings, a simulator study also showed slower speeds when bicycle lanes were present (Taylor et al., 2002). Another simulator study showed that bicycle lanes only led to a speed reduction when a cyclist was present; no speed reduction was found without cyclists (Chinn & Elliott, 2002). An image-based experimental study found significantly lower speeds for roads with bicycle lanes in urban areas compared to roads without bicycle lanes (Theeuwes et al., 2024).

Based on these findings, the present study expects that roads with bicycle lanes have lower chosen speeds than roads without bicycle lanes.

On-street parking On-street parking can affect speed choice in multiple ways. First, parked cars create a visual narrowing of the roadway. They also create a physical buffer, limiting the actual space available for maneuvering. Both of these factors contribute to a reduction in the effective width of the travel lane, increasing cognitive load and adding to the perceived driving complexity (Elliott et al., 2003). Furthermore, parked cars can increase the perceived risk of driving due to potential hazards such as drivers leaving vehicles or cars pulling out of parking spaces (Elliott et al., 2003). In addition, parked cars influence peripheral vision. Objects in the environment may appear to approach faster, creating the illusion of higher speed. Therefore, this study finds that roads with on-street parking are perceived as more complex and less safe.

Analysis of speed measurements revealed that parked cars had an impact on travel speed, leading to a reduction in speed along major urban roads (Gargoum et al., 2016; Elliott et al., 2003). Some simulator studies also concluded that lower speeds were chosen on urban roads when parked cars were present (Chinn & Elliott, 2002; Molino, 2009). However, another simulator study found no effect from parked cars (Taylor et al., 2002).

To clarify the mixed evidence on the influence of parked cars on chosen speed, the present study investigates whether the presence of on-street parking leads to lower speeds.

Greenery The presence of trees along roadways has been linked to increased cognitive load, contributing to a greater sense of complexity for drivers (Elliott et al., 2003). Trees also reduce forward visibility, making hazards more difficult to detect, resulting in higher perceived risks (Elliott et al., 2003). In addition - similar to the presence of parked cars - trees influence peripheral vision. For these reasons, we expect roads with trees to be perceived as both more complex and less safe.

There is mixed evidence on the influence of roadside greenery such as trees or green space on chosen speed. Speed measurements, conducted on rural roads, indicated lower speeds when trees and greenery were present (Qin et al., 2020). Similarly, an experimental field study found a reduction in speed when roadside greenery was present (de Waard et al., 1995). A literature review reported that trees and green space had little influence on speed, especially for major roads outside towns; within towns, no influence was found (Chinn & Elliott, 2002). No influence of trees and green space on chosen speed was found in another image-based study, once age and risk-taking behavior were factored into the analysis (Goldenbeld & van Schagen, 2007). Other simulator studies also found no effect of trees on driving speed (Abele & Møller, 2011; Bella, 2013). To resolve these inconclusive findings, the present study investigates whether the presence of trees results in lower chosen speeds.

2.4. Driver-related factors

Driver-related factors are known to influence driving speed and include socio-demographic characteristics, such as age and gender, but also personality traits and risky driving behavior. An extensive review by Jonah (1997) evaluated the relationship between sensation-seeking and different measures of risky driving, such as driving while impaired, speeding and tailgating. The review focused on studies employing Zuckerman's Sensation-Seeking Scale (SSS) (Zuckerman, 1994). The SSS consists of 40 items. Factor analyses indicate that it is possible to extract four factors from the scale: thrill and adventure seeking, experience seeking, boredom susceptibility and disinhibition. The items included in the SSS do not focus on driving behavior, but several studies point to a correlation of sensation-seeking with speeding (for an overview see Jonah, 1997). Several other self-report instruments have been developed to study driving styles (see Sagberg et al., 2015), including the driving style questionnaire (DSQ, French et al., 1993) and the driving behavior questionnaire (DBQ, Reason et al., 1990). Driving style concerns the way individuals choose to drive; it includes the chosen speed, the threshold for overtaking and the preference for a certain headway (Elander et al., 1993). The DSQ comprises six factors: propensity to speed, calmness, social resistance, focus, planning and deviance. The speed scale, specifically, has been used in several studies to investigate individuals' propensity to speed (Jamson, 2006; Hill et al., 2023). In a naturalistic experiment, where drivers were equipped with dashboard cameras, it was found that drivers who scored high on the DSQ speed scale were significantly more often involved in speed-related heavy-braking events (Hill et al., 2023). In a simulator experiment, it was found that drivers scoring high on the DSQ speed scale, were less likely to accept an intelligent speed adaption (ISA) system. In summary, we expect that lower scores in the speed dimension of the driving style lead to lower chosen speeds.

2.5. Summary and aim of study

In summary, the literature suggests a complex relationship between road design, perceived complexity and safety and chosen speed. While previous research explored these relationships, particularly in rural settings, the specific effects of individual design elements on main urban roads remain unclear. This study addresses this gap by investigating how specific road design elements, such as medians, center lines, side markings, bicycle lanes, on-street parking and greenery influence drivers' perceptions of complexity and safety. It also examines how perceived complexity and safety relate to chosen speed on urban main roads and whether these design elements lead to different speed choices compared to a neutral road design on main urban roads with a speed limit of 30 km/h. The study also explores whether driver-related factors, specifically driving style, moderate the relationship between road design elements and chosen speed. To answer these research questions, a combination of methods, including a simulator and an image-based survey, will be used. The following section will detail the methods and procedures employed in this study.

3. Methods

To evaluate the effect of different road design measures, a virtual reality (VR) driving simulator experiment was conducted. This experiment was accompanied by a survey to assess subjective evaluations of road design with respect to complexity and safety, as well as to determine the influence of additional driver-related factors.

(a) Driving simulator (b) View through the head-mounted display

Fig. 1. Apparatus: VR driving simulator.

3.1. VR driving simulator

The use of driving simulators has become standard, in both science and practice. One of the most important reasons to use a VR driving simulator for research is the safety factor. Use of simulators allows researchers to analyze potentially unsafe scenarios without putting participants in danger (Lee et al., 2003). From a scientific perspective, use of a driving simulator enables a controlled experimental manipulation of the relevant influencing factors (e.g. road space design) and associated systematic investigation of their causal effects on driving behavior (Carsten & Jamson, 2011; Kaptein et al., 1996). Further benefits include the ability to control environmental factors, such as traffic, weather and occurrence locations. Moreover, in recent years, VR driving simulators have become more cost-effective compared to conventional driving simulators, while allowing for greater immersion and naturalistic observation of driver behavior within a three-dimensional simulation.

The present study uses a fixed-base VR driving simulator (also see Fig. 1). The set-up of the VR driving simulator consists of several hardware and software components. The hardware includes the following input and output devices and instruments:

- Hardware for the HCI with force feedback steering wheel and pedals, without gear stick - Thrustmaster T300 RS
- Hardware for VR output with integrated sensor technology for measurements: HTC Vive Pro Wireless HMD and Lighthouse Stations
- Hardware for VR simulation: Desktop PC with high-end graphics card
- Display of the VR simulation via a control screen
- Car seat

Various components and assets were used for the software:

- Game Engine (Unreal Engine v4.25.4)
- Several Unreal plug-ins (traffic and pedestrian simulation, car control)
- Procedurally generated assets with ArcGIS City Engine (road sections, buildings)
- Manually generated assets with Blender (point elements, terrain)
- Audio elements, as well as third-party 3D models (cars, avatars, etc.)

Two interlinked key issues with driving simulators are fidelity and validity. Fidelity refers to the extent a simulator replicates real-world driving conditions (Wynne et al., 2019). Kaptein et al. (1996) categorized simulators based on their fidelity, considering physical design elements, such as vehicular controls and distinguished between low-fidelity, medium-fidelity and high-fidelity simulators.

According to this categorization, the apparatus used in the present study qualified as medium-fidelity, featuring advanced imaging techniques, a realistic cab and functional vehicular controls (Kaptein et al., 1996).

Numerous studies support the validity of driving simulators as a useful measurement tool to investigate driving behavior (Allen et al., 2017; Kaptein et al., 1996; Wynne et al., 2019). The validity of simulators can be evaluated in various ways (Kaptein et al., 1996; Wynne et al., 2019). Actual or absolute validity examines whether behavior within the simulator aligns with real-world behavior, such as matching driving speeds. Relative validity assesses whether trends or relative magnitudes of effects observed in the simulator correspond to those in real-world scenarios, such as speed reduction.

While actual or absolute validity is difficult to achieve unless a high-fidelity driving simulator is used (Wynne et al., 2019), medium-fidelity driving simulators - such as the one used in this study - are reported to achieve relative validity (Pawar et al., 2022). Thus, conclusions drawn from this study are based solely on relative speed. In particular, relative validity is a sufficient and tested measure when the research goal is to analyze changes in driving behavior (chosen speed) under specific conditions (road design), as in the present study (Pawar et al., 2022).

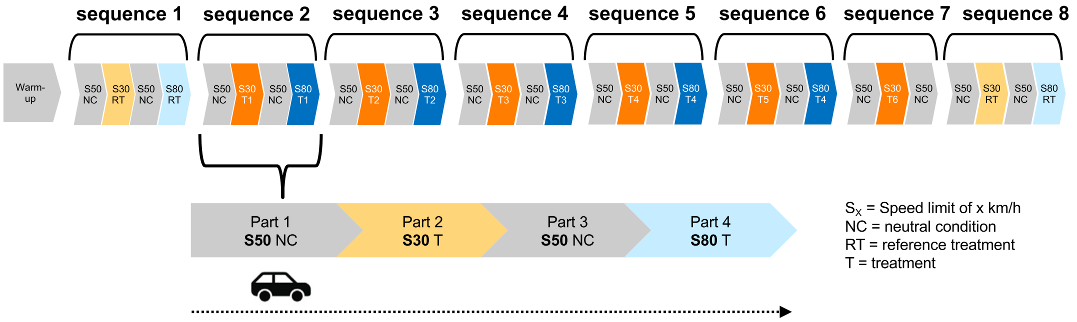

Fig. 2. Overview of Experiment.

3.2. Evaluated road designs & sequence

The experiment covers a 12,800-meter road segment and can be completed in 14 minutes, 52 seconds if the speed is adhered to. The course consists of eight sequences; each sequence covers a distance of 1700 meters and can be completed in 1 minute, 56 seconds (if the posted speed limit speed is adhered to). The experimental setup is shown in Fig. 2.

A sequence contains four parts and all have an identical structure, with the exception of sequence 7. A sequence starts with a neutral condition at 50 km/h (part 1); a speed limit of 50 km/h was chosen to create a clear differentiation from the road types studied experimentally. In addition, this part serves as a connecting element between road types and facilitates speed changes. Part 2 consists of an experimental treatment - or the neutral condition - for the 30 km/h road type. This is again followed by a neutral condition at 50 km/h (part 3), which serves to cancel out the effect of the previous experimental treatment and forms the transition to the next experimental treatment. Part 4 consists of an experimental treatment - or the neutral condition - for the road type, with an 80 km/h speed. Sections with a speed limit of 30 km/h and 50 km/h are 300 meters long (urban roads); sections with a speed limit of 80 km/h are 700 meters long (rural roads). This study focuses only on the impact of road design measures on urban roads.

The first sequence, with the neutral condition, was repeated in the last sequence (sequence 8).

The treatments were presented in a fixed order. The neutral intervals may help reduce carryover effects, but presenting treatments in this predetermined order introduces the risk of order effects influencing driving behavior.

We included six road design measures (experimental treatments) on main urban roads and a neutral condition: (1) side markings; (2) bicycle lanes; (3) wide median; (4) on-street parking; (5) absence of center line; (6) greenery, (0) neutral condition. These treatments are shown in Fig. 3. Table 8 in Appendix A shows the exact dimensions of these treatments. In all cases, sidewalk width was 3 meters; additionally, there was an added building setback of 3 meters.

3.3. Survey procedures and measures

Following the VR experiment, all participants completed a survey consisting of three parts. First, the impact of the road design was subjectively evaluated with questions about each experimental treatment. Preferred speed and perceived safe speed were measured with two open-ended questions (Goldenbeld & van Schagen, 2007). Further measures included perceived safety (Wang et al., 2019) and perceived complexity (Charlton & Starkey, 2017) of the respective road sections. Perceived safety and complexity were assessed using bipolar scales ranging from 1 (safe) to 5 (unsafe) and 1 (simple) to 5 (complex), respectively. These four questions were supplemented with a still image of the respective road section taken from the VR simulation. Unlike the driving simulator experiment, the images shown in the survey did not include speed signs. The images used in the survey are presented in Fig. 3.

Second, driver-related factors were measured. Driving style was assessed in the following six dimensions: speed, calmness, social resistance, focus, planning and deviance (Chowdhury, 2014; French et al., 1993). These dimensions were measured on a 5-point scale ranging from 1 (never / very rarely) to 5 (very often / always). Driving performance was assessed using a modified version of the self-rated driving scale (Victoir et al., 2005). Items were adapted to reflect general driving performance rather than focusing on past driving behavior. This subjective assessment of one's ability to drive safely and attentively was measured using six items, which (Victoir et al., 2005) were measured using a 5-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree).

Third, the survey contained several control measures. Symptoms of simulator sickness were assessed with a series of items on the participants' current well-being. A total of 16 symptoms were included (Kennedy et al., 1993). Questions about immersion and feeling of control were used to measure the strength and credibility of VR environment immersion (Kronqvist et al., 2016). These questions were answered on a 4-point scale ranging from 1 (not at all) to 4 (strongly). To obtain information about driving practice, questions included experience and frequency of car use, car availability and involvement in traffic accidents (regardless of responsibility). To assess previous experiences with VR, the frequency of using VR glasses, a VR driving simulator and racing games on gaming consoles were recorded. Finally, socio-demographic data (gender and age) was collected.

(a) Treatment 1: Side-markings

(b) Treatment 2: Bicycle-lanes

(c) Treatment 3: Wide median

(d) Treatment 4: On-street parking

(e) Treatment 5: No center line

(f) Treatment 6: Greenery

(g) Treatment 0: Neutral condition

Fig. 3. Experimental treatments.

3.4. Procedures

The experiment in the VR driving simulator consisted of five steps. The main part of the experiment consisted of driving along a stretch of road in the VR driving simulator (Step 3). The total duration of the experiment was approximately 45 minutes and consisted of the following steps:

- Step 1: Information on the purpose and procedure of the experiment (Informed consent)
- Step 2: VR driving simulator instruction and driving through a training section: participants were familiarized with the VR driving simulator by driving along a practice track.
- Step 3: Driving in the VR driving simulator: following the practice track, participants drove along the test track with seven experimental and one neutral conditions. The test track followed a road through several small towns. The road type alternated between main urban roads with a speed limit of 30 km/h and 50 km/h (arterial main roads) and rural roads with a speed limit of 80 km/h. The towns' appearance in the VR simulation was based on Swiss scenery. The test track was designed to be as realistic as possible, creating the impression of an ordinary car journey.

Table 1
Sample statistics.

Variable	Value	n	%
Gender	Male	28	52
	Female	26	48
Age	21–35 years	26	48
	36–50 years	19	35
	51–65 years	9	17
Car availability	Always available	31	57
	Available upon arrangement	16	30
	Via car-sharing	3	6
	Not available	4	7
Car usage	Daily	17	31
	Multiple days per week	16	30
	Weekly	10	19
	Monthly	7	13
	Less than 1 time per month	4	7
Experience with VR	Weekly	3	6
	Monthly	1	2
	Less than monthly	9	17
	None	49	91
Experience with racing games	Weekly	1	2
	Monthly	3	6
	Less than monthly	12	22
	None	38	70
Simulator sickness	25% percentile	15	
	50% percentile	33.7	
	75% percentile	48.6	

- Step 4: After finishing the test track, participants completed a survey about the road sections (preferred and safe speed, safety and complexity of the road section), driving experience in VR, current well-being, driving style, driving experience and experience with VR and socio-demographics.
- Step 5: Debriefing

3.5. Recruitment and sample

The sample was recruited over the panel of a market research company, mailing lists and social media ads. Inclusion criteria were the possession of a driver’s license for at least three years, as well as low susceptibility to motion sickness according to the Motion Sickness Susceptibility Questionnaire (MSSQ-Short) (Golding, 2006).

The total sample of the VR driving simulator experiment included 61 people (Table 1). Seven people had to be excluded from the data analysis, either because of technical errors (n = 4) or because they discontinued the experiment due to motion sickness (n = 3). Thus, the final sample consisted of 54 participants. Socio-demographic characteristics are reported in Table 1. We note an even distribution between male and female participants; most were between 21 and 35 years old (48%), followed by participants aged between 36 and 50 (35%). The majority of the drivers sampled always had a car available, or could arrange this within the household (87%). Over 80% of the participants indicated that they used the car on a weekly basis or more. Most did not have experience with VR (91%) and did not play racing games on a gaming console (70%).

The SSQ divides motion sickness symptoms into three factors: nausea, oculomotor (relating to issues with vision) and disorientation. The total score can be calculated by adding the unweighted factor scores, and multiplying by 3.74 (see Kennedy et al., 1993). The percentiles of this total score are shown in Table 1.

3.6. Data analysis

3.6.1. Multi-level regression

To evaluate the effect of road design on driving speed, safe speed and preferred speed multi-level regression models were estimated using the lmerTest library (Kuznetsova et al., 2017) in R (R Core Team, 2024).

Driving speed was analyzed by first averaging the driving speed for each participant per sequence along specified distance sections within a treatment. A multi-level regression model was applied, where the participant was treated as a random effect and the road design treatment was treated as a fixed effect. The model takes into account the average speed within a treatment in 25-meters bins (i.e. averages over ranges of 25 meters).

To assess the impact of possible ordering effects, we tested the data in two separate models: one comparing the treatments to the first neutral condition and the other comparing the treatments to the second neutral condition.

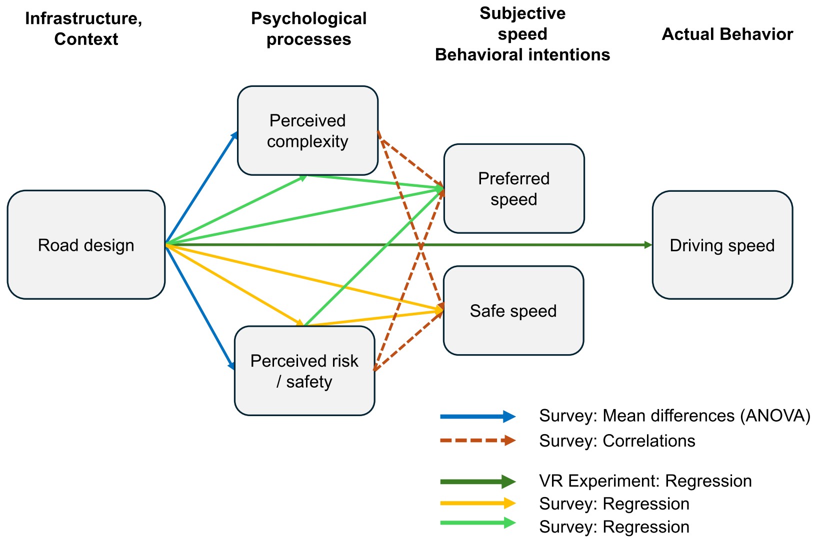

Fig. 4. Graphical outline of expected relationships between road design, complexity, safety and chosen speed. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

For safe and preferred speed, data from the survey responses was used directly as the dependent variables in the models. Participants provided their perception of the safe and preferred speed for each treatment. Like the driving speed model, the participant was treated as a random effect to account for personal variability in speed perception; road design treatment was treated as a fixed effect.

3.6.2. Factor analysis of driver-related factors

Driving style was assessed using the driving style scale (French et al., 1993). Previous research indicated that the scale consisted of six factors. However, an initial factor analysis revealed that several items did not provide meaningful loadings. These were: 'Do you ever drive through a traffic light after it has turned red?', 'How often do you set out on an unfamiliar journey without first looking at a map?' and 'Do you ignore passengers urging you to change your speed?'. The fact that these items did not provide meaningful loadings is thought to be due to (1) the omnipresence of navigation aids compared to when the scale was developed and (2) the general adherence to traffic rules in Switzerland due to high fines and social norms. After excluding these items, four factors were identified: speeding, social resistance, calmness & preparedness and focus. Factor loadings are included in Appendix A in Table 10. These factors are in line with French et al. (1993), except for the factors 'planning' and 'deviance'. The reliability of the items reflecting speeding was $\alpha = .78$, the reliability of the items reflecting social resistance was $\alpha = .7$, the reliability of the items reflecting calmness & preparedness was $\alpha = .47$ and the reliability of the items reflecting focus was $\alpha = .42$. Subsequently, mean scores were computed for the respective items. Distribution of the items 'speeding' ranged from 1.5 to 4.75 with an average of 2.84. Distribution of the items 'social resistance' ranged from 1 to 5 with an average of 3.4.

Driving performance (Victoir et al., 2005) was analyzed based on a visual examination of the scree plot, where we found that two factors could be extracted from this scale for our sample: 'driving proficiency' and 'rule obedience'. Factor loadings are included in Appendix A in Table 9. The reliability of the items reflecting driving proficiency was $\alpha = .73$, whereas the items concerning 'rule obedience' showed low reliability at $\alpha = .33$. Subsequently, mean scores were computed for these items. The distribution of the item 'driving proficiency' ranged from 3.25 to 5 with an average of 4.3. The distribution of the item 'rule obedience' ranged from 2.33 to 4.33 with an average of 3.3.

4. Results

In this section, the analysis of the VR experiment, as well as the survey results are presented. A graphic outline of the results analysis is presented in Fig. 4.

Starting with the relationship between road design and perceived complexity and safety, an analysis of the differences of means is presented in section 4.2. Correlations between perceived complexity, safety and preferred and safe speed are presented in section 4.3. This section also includes regression models investigating the relationship between road design, perceived safety, perceived complexity and chosen speed. Subsequently, the relationship between road design and driving speed is presented in section 4.4. Prior to continuing with the statistical analyses, a descriptive analysis of the results will be presented.

4.1. Descriptive analysis

Table 2 presents the survey results. The columns perceived safe speed and preferred speed contain the mean, median and 85th percentile of the stated values. Furthermore, the mean values of complexity (1 = easy, 5 = complex) and safety (1 = safe, 5 = unsafe)

Table 2
Safe speed, desired speed, safety, and complexity based on follow-up survey (n = 54). Safety varies from 1 (safe) to 5 (unsafe) and complexity varies from 1 (easy) to 5 (complex).

Treatment	Safe Speed (km/h)			Preferred Speed (km/h)			Safe	Complex
	v_{mean}	v_{50}	v_{85}	v_{mean}	v_{50}	v_{85}		
T0: Neutral condition	41.4	50	50	45.3	50	50	2.2	1.9
T1: Side-marking	43.3	50	50	45.1	50	50	2.0	1.8
T2: Bicycle-lane	48.4	50	50	50.2	50	55	2.0	1.9
T3: Wide median	39.9	40	50	41.2	43	50	2.3	2.3
T4: On-street parking	33.3	30	50	34.1	30	45	3.8	3.4
T5: No center line	40.7	50	50	43.1	50	50	2.5	2.2
T6: Greenery	43.4	50	50	46.6	50	50	2.1	1.9

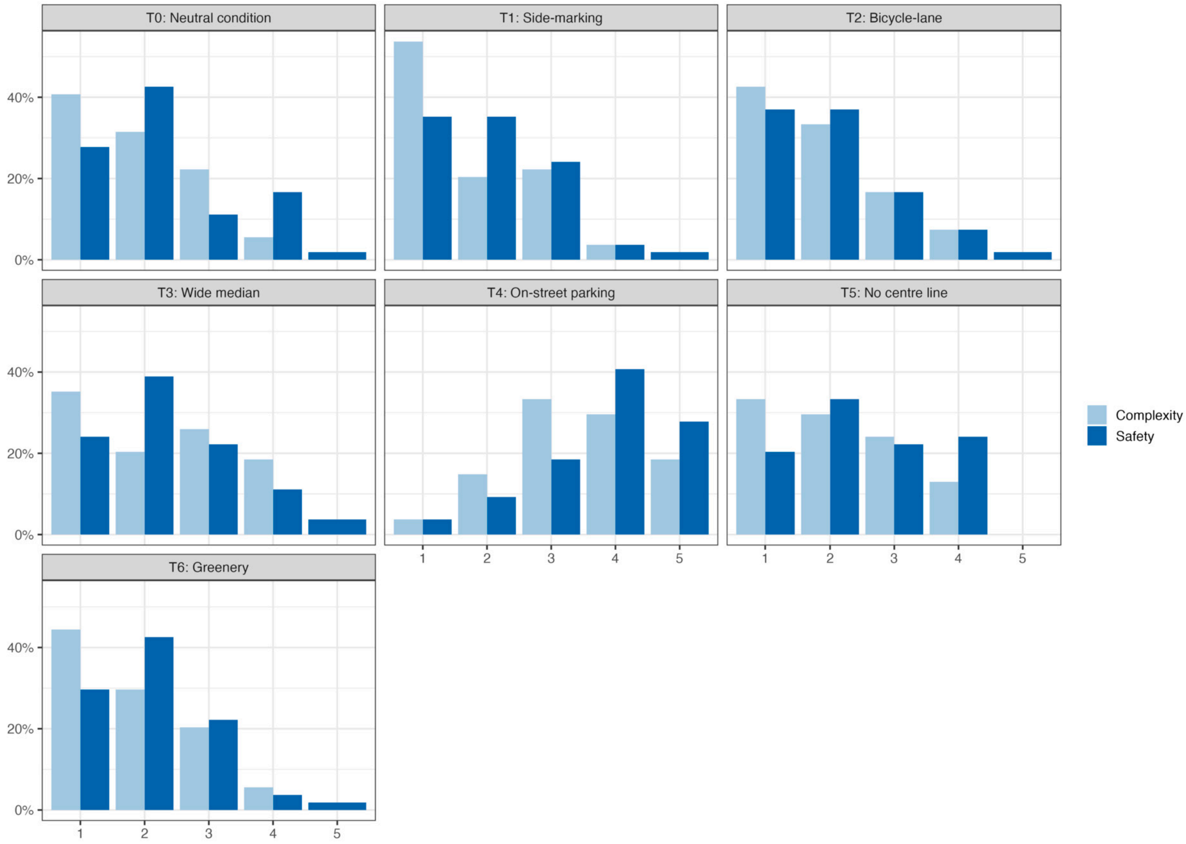

Fig. 5. Complexity and safety of different treatments.

are shown. The distribution of perceived complexity and safety of the different treatments is shown in Fig. 5. The mean safe speed (v_{mean}) varied across treatments, ranging from 33.3 km/h (T4: On-street parking) to 48.4 km/h (T2: Bicycle-lane). Similarly, the mean preferred speed ranged from 34.1 km/h (T4) to 50.2 km/h (T2).

Regarding safety ratings, participants perceived T4 (On-street parking) as the least safe ($M = 3.8$) and the most complex ($M = 3.4$). In contrast, T3 (Wide median) was perceived as the safest ($M = 2.3$), as well as the least complex.

Driving speeds in the virtual reality simulator are shown in Table 3. We made a distinction between the short-term effect of driving speed in VR - immediately after an intervention and/or a change in design and effects that can be measured over a longer distance. A descriptive analysis of driving speed per section revealed that drivers adjusted their speed in the initial 50 meters of the section and afterward drove with a constant speed or increased their speed again. Fig. 6 shows the driving speed prior to the neutral condition (speed limit 50 km/h), within the neutral condition (speed limit 30 km/h) and after the neutral condition (speed limit 50 km/h). To allow for a visual comparison of treatments, all participants' mean speeds were calculated for every 2 meters of each treatment. Speed profiles for each treatment are shown in Fig. 7. Based on this visual analysis, we decided to segment each section into two

Table 3
Short-term and long-term effects on driving speed derived from simulator (n = 54).

Treatment	Short-term Effect (km/h)			Long-term Effect (km/h)		
	v_{mean}	v_{50}	v_{85}	v_{mean}	v_{50}	v_{85}
T0: Neutral condition (First occurrence)	33.8	33	37.1	33.4	32.4	35.5
T0: Neutral condition (Second occurrence)	33.4	32.6	36.8	33.2	32.9	35.5
T1: Side-marking	32.7	32.8	36.2	33.0	32.5	35.4
T2: Bicycle-lane	33.7	33.5	36.5	33.2	33.2	35.1
T3: Wide median	34.8	33.7	38.8	34.3	32.9	37.4
T4: On-street parking	33.3	32.2	37.0	33.2	32.9	35.5
T5: No center line	32.5	32.1	35.9	33.4	33.3	36.0
T6: Greenery	32.3	32.5	35.5	32.1	31.9	34.0

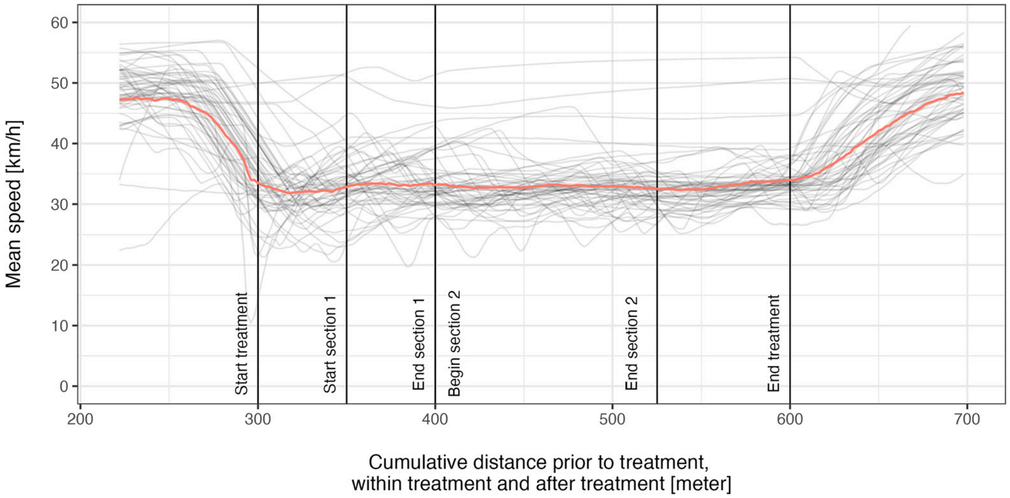

Fig. 6. Mean driving speed in treatment T0: Neutral condition. Thick line depicts the mean driving speed; thin lines represent individual trajectories.

Table 4
Correlation between safe speed, preferred speed, safety and complexity.

Treatment	Safe speed		Preferred speed	
	Safety	Complexity	Safety	Complexity
T0: Neutral condition	-0.29 (-2.35) *	-0.04 (-0.33)	-0.33 (-2.79) ***	-0.22 (0.07) +
T1: Side-marking	-0.24 (-1.93) +	-0.11 (-0.89)	-0.14 (-1.18)	-0.23 (0.06) +
T2: Bicycle-lane	-0.47 (-3.85) ***	-0.31 (-2.59) ***	-0.42 (-3.45) ***	-0.39 (0.00) ***
T3: Wide median	-0.20 (-1.69) +	-0.08 (-0.70)	-0.12 (-1.02)	-0.14 (0.25)
T4: On-street parking	-0.28 (-2.31) *	-0.29 (-2.47) *	-0.34 (-2.85) ***	-0.23 (0.05) +
T5: No center line	-0.49 (-4.06) ***	-0.26 (-2.17) *	-0.46 (-3.98) ***	-0.36 (0.00) ***
T6: Greenery	-0.44 (-3.59) ***	-0.33 (-2.64) ***	-0.25 (-2.03) *	-0.40 (0.00) ***

Significance levels: $^{+}$ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

subsections. The first subsection, from 50 m to 100 m, reflects the initial adjustment in speed after entering a section, which we refer to as the short-term effect. The second subsection, from 100 m to 225 m, captures the driving speed after drivers adjusted to the treatment, which we refer to as the long-term effect.

In Table 3, mean driving speeds of section 1 (short-term effect) and section 2 (long-term effect) are shown. Median speed (v_{50}) and the 85th percentile are also shown (v_{85}). Percentiles were calculated based on the mean speed per participant per section and can be compared to percentiles as available from speed measurements. All speeds were indicated in km/h. Minor speed differences between treatments were observed, but recorded speeds exceeded the posted speed limit of 30 km/h in all cases. Mean speeds in section 1 of the treatments 'T1: Side markings', 'T4: On-street parking', 'T5: No center line', and 'T6: Greenery' were lower than in the neutral condition (T0). Subsequently, driving speed increased, except for the treatment with greenery, where driving speed remains low.

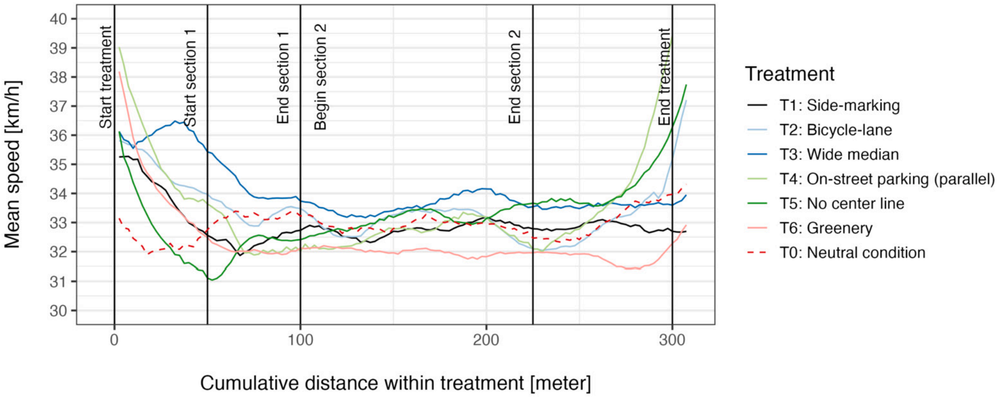

Fig. 7. Mean driving speed in all treatments.

4.2. *Mean differences: perceived safety and complexity*

To test whether different road designs differed from the neutral condition with respect to perceived safety and complexity, we applied the aligned rank transform (ART) to address non-normality and heteroscedasticity before performing a repeated measure ANOVA. Participants were included as a random effect; treatments were treated as a fixed effect. The ART ANOVA revealed a significant main effect of treatments on perceived safety ($F(6, 318) = 27.33, p < 0.0001$). Post-hoc analysis indicated that the treatment “T4: On-street parking” was rated less safe ($M = 3.8$) compared to the neutral condition ($M = 2.2, F = 128.63, df = 14.1, p < 0.0001$). Other differences were not significant versus the neutral condition.

A similar approach was followed for the perceived complexity. In this case, the ART ANOVA revealed a significant main treatment effect on the response variable ($F(6, 318) = 27.525, p < 0.0001$). Post-hoc analysis indicated that the treatment “T4: On-street parking” was perceived to be significantly more complex ($M = 3.4$) compared to the neutral condition ($M = 1.9, F = 126.91, df = 13.3, p < 0.0001$).

4.3. *Preferred & safe driving speed*

The relationship between safety, complexity, preferred speeds and safe speeds was analyzed in two steps. First, we inspected the correlations between perceived safety, perceived complexity, safe speed and preferred speed. Second, we estimated multi-level regression models with chosen speed as a dependent variable and with the treatment, perceived safety and complexity as independent variables.

Kendall’s tau correlations are shown in Table 4. Both perceived safety and perceived complexity were negatively correlated with stated safe speeds and preferred safety. However, correlations with perceived safety were stronger and more statistically significant compared to those with perceived complexity.

The correlation between stated safe speed and perceived safety revealed a consistent negative relationship across treatments, indicating that as perceived safety worsens (higher scores), the stated safe speed decreases. Strongest correlations are observed in T2: Bicycle-lane ($\tau = -0.47, p < .001$), T5: No center line ($\tau = -0.49, p < .001$), and T6: Greenery ($\tau = -0.44, p < .001$). Moderate relationships are present for T4: On-street parking ($\tau = -0.28, p = .021$) and T0: Neutral condition ($\tau = -0.29, p = .019$).

Similarly, correlation between stated preferred speed and perceived safety reveals a relative consistent negative relationship across treatments. Strongest correlations are observed in T5: No center line ($\tau = -0.46, p < .001$), T2: Bicycle-lane ($\tau = -0.34, p < .001$), and T6: Greenery ($\tau = -0.44, p < .001$). Moderate relationships are present for T4: On-street parking ($\tau = -0.34, p = .021$) and T0: Neutral condition ($\tau = -0.25, p = .019$). However, no significant correlations were found for T1: Side-marking and T3: Wide median.

Overall, the correlation between stated safe speed and perceived complexity also revealed negative relationships across treatments, indicating that with augmented perceived complexity, the stated safe speed decreases. However, these correlations were less consistent. Strongest correlations were observed in T6: Greenery ($\tau = -0.33, p < .001$), T2: Bicycle-lane ($\tau = -0.31, p < .001$). Moderate relationships were present for T4: On-street parking ($\tau = -0.29, p = .021$). Again, no significant correlations were found for T1: Side-marking and T3: Wide median.

Finally, the correlation between stated preferred speed and perceived complexity revealed some negative relationships across treatments, indicating that with augmented perceived complexity, the stated preferred speed decreased. Strongest correlations were observed in T6: Greenery ($\tau = -0.40, p < .001$), T2: Bicycle-lane ($\tau = -0.39, p < .001$), and T5: No center line ($\tau = -0.36, p < .001$). Only marginal or no significant correlations were found for T1: Side-marking, T3: Wide median and T4: On-street parking.

Second, we estimated multi-level regression models with the participant as a random effect and the treatment as a fixed effect. To evaluate whether complexity and/or safety influence driving speed, we estimated models with treatment effects only, and models that include perceived complexity and perceived safety. The highest safety rating was coded as 0 and the lowest coded as 4.

Table 5
Safe speed: model estimation results.

	Safe speed	Safe speed incl. safety
Intercept	41.759 (0.823)***	50.640 (1.172)***
Treatment specific effects		
T0: Neutral condition	-	-
T1: Side-marking	-	-
T2: Bicycle-lane	6.593 (1.176)***	5.996 (1.095)***
T3: Wide median	-	-
T4: On-street parking	−8.426 (1.176)***	
T5: No center line	-	-
T6: Greenery	-	-
Safety & complexity		
Complexity (easy to complex)	-	-
Safety (safe to unsafe)		−4.142 (0.374)***
Model indicators & Goodness-of-fit		
N	378	378
N (subjects)	54	54
R2 (conditional)	0.39	0.48
R2 (marginal)	0.16	0.30
AIC	2706.343	2650.318

Significance levels: $^{+}$ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Safe speed Two models were estimated with perceived safe speed as a dependent variable; model results are presented in Table 5. The first model (‘Safe speed’) contained treatment-only effects. We found that participants, on average, stated a safe speed of 41.8 km/h (intercept). Significant treatment-specific effects included the presence of a bicycle lane (6.6 km/h) and the presence of on-street parking (-8.4 km/h). These results indicated that participants, on average, considered a higher speed to be safe if cyclists were separated from motorized traffic, while the presence of on-street parking resulted in a lower speed to be safe, compared to the other treatments. The second model additionally included perceived safety as an independent variable. When perceived safety was included, the intercept of the model increased to 50.6 km/h. The only treatment-specific effect that remained significant was the presence of a bicycle lane. Neither perceived complexity nor driving style were significant in the model. The negative parameter for safety suggests that when a treatment is rated less safe, a lower speed was considered safe; for every unit change in the rating of safety, the safe speed decreased by 4.1 km/h. The fact that the parameter for bicycle lanes remained significant indicates that factors other than safety played a role when assessing safe speed. The marginal r-squared considered fixed effects variance; improvement of the marginal r-squared from 0.16 to 0.30, indicating that perceived safety in the model explains the variance better than treatment-only effects.

Preferred speed Three models were estimated with preferred speed as an dependent variable; model results are presented in Table 6. The first model (‘Preferred speed’) contained treatment-only effects. We found that participants, on average, stated their preferred speed to be 45.7 km/h (intercept). When a bicycle lane was present, participants preferred to drive faster by 5.1 km/h. On the other hand, when a wide median was shown, participants preferred a lower speed (-3.8 km/h). On-street parking results in the lowest preferred speed; participants stated, on average, that they wished to drive 11 km/h slower compared to the treatments for which no parameter was estimated. When driving style was included as an independent variable, average driving speed (intercept) was reduced to 44.1 km/h; treatment-specific effects otherwise remained the same. Participants who reported speeding frequently preferred to drive 2.8 km/h faster on average. The final model included perceived safety and perceived complexity as independent variables. The negative parameter for perceived complexity suggested that, as a treatment is rated as more complex, a lower speed was preferred; for every unit change in the rating of complexity, safe speed decreased by 1.2 km/h. The negative parameter for perceived safety suggests that when a treatment was rated less safe, a lower speed was preferred; for every unit change in the rating of safety, safe speed decreased by 1.9 km/h. The additional variable ‘Safety T5: no center lane marking’, with an estimate of 1.4 km/h, suggests heterogeneity in the perceived safety of a road without center line. Participants rated this treatment as unsafe and reported a lower preferred speed. Interestingly, other than in the models evaluating safe speed, all treatment effects remained significant. This indicates that, beyond safety and complexity, other road design elements influenced preferred driving speed. Including perceived complexity and perceived safety resulted in an insignificant estimate for sensation-seeking. The improvement of the marginal r-squared from 0.24 to 0.36 indicates that perceived safety and perceived complexity explain the variance better than treatment-only effects.

Table 6
Preferred speed: model estimation results.

	Preferred speed	Preferred speed incl. sensation-seeking	Preferred speed incl. safety and complexity
Intercept	45.032 (0.683)***	44.084 (0.775)***	52.187 (1.151)***
Treatment specific effects			
T0: Neutral condition	-	-	-
T1: Side markings	-	-	-
T2: Bicycle lane	5.153 (1.162)***	5.153 (1.162)***	4.195 (1.106)***
T3: Wide median	−3.792 (1.162)**	−3.792 (1.162)**	−3.666 (1.124)**
T4: On-street parking	−10.977 (1.162)***	−10.977 (1.162)***	−6.535 (1.388)***
T5: No center line	-	-	-
T6: Greenery	-	-	-
Driving style			
Sensation seeking		2.845 (1.206)*	
Safety & Complexity			
Complexity (easy to complex)			−1.176 (0.548)*
Safety (safe to unsafe)			−1.988 (0.536)***
Safety T5: No center lane marking (safe to unsafe)			−1.380 (0.622)*
Model indicators & Goodness-of-fit			
N	378	378	378
N (subjects)	54	54	54
R2 (conditional)	0.35	0.36	0.44
R2 (marginal)	0.24	0.25	0.36
AIC	2654.973	2649.384	2600.089

Significance levels: $^{+}$ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

4.4. Driving speed in VR

A similar approach was followed to investigate treatment influence on driving speed. Multi-level regression models were estimated with the participant as a random effect and the treatment as a fixed effect. Model estimation results for the VR driving experiment are shown in Table 7; the results consider the first and second occurrences of 'T0: Neutral condition' as the respective reference conditions. To assess whether driving style and/or driving practice influence driving speed, we estimated models with and without the respective aggregated items. The presented models include variables for driving style and/or driving practice.

Based on the intercept, we observe that participants drove at an average speed of 33.7 km/h (short-term effect) and 33.5 km/h (long-term effect) across all models. For validity reasons, we will focus on the interpretation of relative changes in speed versus the neutral condition.

Among the tested conditions, 'T3: Wide center lane marking' led to a significantly higher driving speed. When evaluated against the first neutral condition, the increase was 1.16 km/h ($p < 0.01$) in the short term and 0.85 km/h ($p < 0.01$) in the long term. When evaluated against the second neutral condition, this effect was slightly more pronounced, with an increase of 1.56 km/h ($p < 0.001$) in the short term and 1.10 km/h ($p < 0.001$) in the long term. Similarly, 'T6: Greenery' consistently led to lower driving speeds. In comparison to the first neutral condition, reductions of -1.49 km/h ($p < 0.001$) in the short term and -1.22 km/h ($p < 0.001$) in the long term were observed. These reductions remained statistically significant when evaluated against the last neutral condition, though they were slightly smaller in magnitude (-1.08 km/h, $p < 0.01$ short term; -0.97 km/h, $p < 0.001$ long term).

Given the small sample size, we also report other notable results. The introduction of side markings (T1: Side-marking) initially led to a short-term reduction of -0.96 km/h ($p = 0.022$) when evaluated against the first neutral condition, but this effect was no longer significant when evaluated against the second neutral condition (-0.56 km/h, $p = 0.164$). Similarly, the absence of a center line (T5: No center line) showed a short-term reduction of -1.37 km/h ($p = 0.001$) in comparison to the first neutral condition, which was slightly reduced to -0.96 km/h ($p = 0.017$) when evaluated against the second neutral condition.

Regarding individual driving characteristics, sensation-seeking remained a significant predictor of increased driving speed. When evaluated against the first neutral condition, participants scoring higher on this scale drove 1.53 km/h faster ($p = 0.045$) in the short term. This effect slightly increased to 1.70 km/h ($p = 0.019$) when evaluated against the second neutral condition. Conversely, individuals who reported being rule obedient continued to show a tendency to drive more slowly in the long-term section, with a slightly stronger effect when evaluated against the second neutral condition (-1.14 km/h, $p = 0.096$ vs. -1.17 km/h, $p = 0.055$).

Table 7
Driving speed in VR: Model estimation results. Short-term effect is defined as the effect that occurs between 50 and 100 meters in the experimental condition. Long-term effect is defined as the effect that occurs between 100 and 225 meters in the experimental condition. As a reference condition, the first resp. second occurrence of 'T0: Neutral condition' is chosen.

	Model 1 Reference condition: first neutral condition		Model 2 Reference condition: second neutral condition	
	Short-term effect	Long-term effect	Short-term effect	Long-term effect
Intercept	33.703 (0.001)***	33.508 (0.001)***	33.226 (0.001)***	33.286 (0.001)***
Treatment specific effects				
T0: Neutral condition	-	-	-	-
T1: Side-marking	−0.961 (0.022)*	−0.425 (0.123)	−0.557 (0.164)	−0.177 (0.500)
T2: Bicycle-lane	−0.055 (0.896)	−0.207 (0.453)	0.350 (0.382)	0.041 (0.876)
T3: Wide median	1.157 (0.006)**	0.849 (0.002)**	1.562 (0.001)***	1.097 (0.001)***
T4: On-street parking	−0.373 (0.374)	−0.260 (0.345)	0.032 (0.937)	−0.012 (0.963)
T5: No center line	−1.365 (0.001)**	−0.009 (0.974)	−0.960 (0.017)*	0.239 (0.363)
T6: Greenery	−1.486 (0.001)***	−1.217 (0.001)***	−1.081 (0.007)**	−0.969 (0.001)***
Driving style & practice				
Sensation seeking	1.529 (0.045)*	1.078 (0.114)	1.696 (0.019)*	1.037 (0.090)+
Rule obedient	−1.054 (0.166)	−1.135 (0.096)+	−1.004 (0.164)	−1.172 (0.055)+
Model indicators & Goodness-of-fit				
N	1134	2268	1134	2268
N (subjects)	54	54	54	54
R2 (conditional)	0.35	0.33	0.35	0.31
R2 (marginal)	0.07	0.05	0.08	0.06
AIC	6364.943	12308.144	6260.554	12081.259

Significance levels: $^{+}$ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Overall, while small differences could be observed in the model estimates using the first and second neutral conditions, the general pattern of results remained stable, with some changes in significance levels - most notably with treatment 'T1: Side marking'.

5. Discussion

The present study investigated the impact of continuous road design measures on driving speed on main urban roads. Unlike point-specific interventions, such as speed bumps or information displays, continuous measures, such as road markings or parking configurations, were applied along a stretch of road and may have influenced driving behavior over a longer distance. While previous research primarily focused on rural roads and village approaches, with limited studies addressing urban contexts (e.g. Charlton & Starkey, 2017), our study specifically examined how these measures affected preferred speed, safe speed and driving speed differences versus a neutral condition.

In particular, we explored whether these measures resulted in divergent driving speeds when implemented under a 30 km/h (20 mph) speed limit compared to the existing 50 km/h (30 mph) limit. As an increasing number of cities seek to lower speed limits to enhance road safety and livability, our findings offer insights into such measures' effectiveness.

To investigate these effects, a virtual reality (VR) driving simulator experiment was conducted. Additionally, a follow-up survey gathered subjective evaluations, where respondents rated the perceived safety and complexity of each treatment and indicated both their preferred speed and the speed they considered safe, based on still images without reference to the posted speed limit.

Preferred speeds were between 1 km/h and 4 km/h higher than speeds considered safe. Earlier research found larger absolute differences between speeds considered safe and preferred for rural roads (between 4 km/h and 8 km/h) (Goldenbeld & van Schagen, 2007). When considering relative speed differences instead of absolute speed differences, these would be in a similar range of 5% and 10%. The survey revealed clear differences in safe and preferred driving speeds between treatments. Individuals, on average, stated that they preferred to drive 44 km/h per hour, lower than the current speed limit on urban roads of 50 km/h.

Speeds measured in the VR driving simulator tended to be lower than the elicited safe and preferred speeds, aligning closely with the posted speed limit of 30 km/h within the treatment. Only small differences in driving speeds could be observed between treatments. However, due to concerns with absolute validity, results from the simulator study should be interpreted as relative speed differences between treatments.

5.1. *Psychological processes*

Based on previous literature, it was expected that the more complex a road is perceived, the slower the chosen speed (Harms, 1991; Elliott et al., 2003). Also, it was proposed, that as perceived risk increases, drivers choose a lower speed to maintain their acceptable level of risk tolerance (Bella, 2013; Calvi et al., 2019; Jamson et al., 2010). Survey results revealed that participants chose a lower preferred and safe speed when they rated a treatment as less safe or more complex. When comparing road designs, it was apparent that perceived safety and complexity moderated the impact of effective road design measures, particularly on preferred speed. This is in line with previous research that proposed an influence of cognitive load (complexity) (Harms, 1991; Elliott et al., 2003) and perceived risk (Bella, 2013; Calvi et al., 2019; Jamson et al., 2010).

Contrary to our expectations, our study did not provide evidence for significant differences in the perceptions of complexity or safety that can be attributed to the experimental manipulation of different road designs. However, our study only adjusted a single road design feature per treatment (see also limitations). The only feature to reveal a significant change was the addition of on-street parking, which resulted in significantly higher complexity and risk perceptions (see also paragraph “on-street parking” further below).

In sum, we conclude that perceptions of complexity and safety are relevant to explain the influence of road designs on chosen speed. However, changing only a single road design feature was not sufficient to influence actual behavior.

In addition, the continued significance of certain road design measures (such as bicycle lanes and on-street parking), even after considering perceptions of safety and complexity, demonstrate that there are additional relevant processes explaining the relationship between road design and driving speed.

5.2. *Discussion of findings along road designs*

The impact of road design on safe, preferred and driving speed in the simulator varied across different tested road design measures. The underlying psychological processes might provide some explanations for these distinct differences. In the next section, road design findings are discussed, combining survey results with results from the VR-simulator study.

Side-markings In sum, the present study provided no evidence that roads with side-markings are perceived as more complex or less safe. Also, the study found marginal or no relationship between perceived safety or complexity with safe and preferred speed. In that way, the results contradicted our assumptions, as well as previous literature, predicting perceived complexity and risks to influence speed choice (Elliott et al., 2003; Taylor et al., 2002). Finally, there was no significant difference between safe and preferred speed for roads with side markings compared to a neutral control condition. These survey results are in line with the results of a meta-analytic approach by Davidse and van Driel (2002) that found no influence on speed.

Data from the VR study revealed that the introduction of a side-markings resulted in a lower short-term driving speed, similar to Taylor et al. (2002) but not in lower driving speeds over a prolonged period as compared to the neutral condition. Theeuwes et al. (2024) found an increase in chosen speed in an image-based study.

Bicycle lanes The present study provided no evidence that roads with bicycle lanes were perceived as more complex or less safe compared to the other investigated treatments. Nevertheless, survey results showed that if roads with bicycle lanes are perceived as more complex or less safe, individuals indicate lower safe and lower preferred speeds. These results are in line with our expectations regarding basic psychological mechanisms that explain the relationship between perceptions of complexity and safety at the chosen speed (Elliott et al., 2003). Contrary to our expectations, stated safe and preferred speeds along roads with a bicycle lane were highest at 50 km/h, significantly higher compared to stated speeds along the neutral condition (road without bicycle lanes). Drivers appeared to categorize this road as a main urban road, considering a speed of 50 km/h to be appropriate; the image of this type of road explains itself as a road with a speed limit of 50 km/h. Driving speed, measured in the simulator, did not differ from the neutral condition.

There are two possible explanations to reconcile these conflicting or missing results. First, traffic segregation might have diminished the perceived risk associated with sharing the road with cyclists, while the allocation of dedicated space may have reduced complexity. Moreover, the bicycle lanes, as they were designed in our study, led to a visual widening of the road. Additionally, the virtual environment used for this study included cyclists only on the opposite side of the road, while the pictures shown for the survey did not include any cyclists. Since cyclists’ presence was presumably the cue for inducing higher risk perceptions, these variations might explain why we did not find similar results in the VR simulator study. These findings are in line with Chinn and Elliott (2002), who found a reduction of driving speed only when cyclists were present. We therefore conclude that dynamic factors related to the presence of other road users, such as cyclists, presumably co-determined the effectiveness of road design measures.

Wide median Results indicated that neither complexity nor safety perceptions of roads with wide medians differed in comparison to the neutral control condition nor did these perceptions influence indicated preferred or safe speed. These results reflected the opposing predictions of previous literature (Elliott et al., 2003) presumably leveling out the different influences of narrowing and segregation. Our findings showed that driving speed was higher compared to the reference treatment, unlike previous simulator studies measuring the effects of medians on rural and trunk roads (Taylor et al., 2002; Charlton, 2007a; Godley et al., 2004). In these cases, a wide median combined with side marking or a hatch pattern resulted in lower driving speeds. As such, the sole introduction of a wide median might not be sufficient, especially if the lane is not shared with other traffic participants like cyclists.

On-street parking In line with expectations, roads with on-street parking were perceived to be more complex and less safe in comparison to the neutral control condition. As assumed, these perceptions correlated - at a moderate level - with safe and preferred speed for roads with on-street parking. These findings were in line with the influence of psychological processes recognized by previous literature (Elliott et al., 2003). The introduction of on-street parking resulted in a reduction of the stated safe and preferred speed towards 30 km/h. On one hand, a road with on-street parking resembles a residential road, where the speed limit is likely to be 30 km/h. Also, these roads were considered to be least safe, likely stemming from cars potentially leaving their parking lot, as well as the risk of opening doors, or pedestrians unexpectedly crossing the road. This finding is in line with previous research showing that the presence of parked cars results in lower driving speeds (Gargoum et al., 2016; Charlton et al., 2010; Molino, 2009). In our case, the pictures additionally might have triggered an expectation that other road users are present. Driving speed, measured in the simulator, provided no evidence for lower speeds on roads with on-street parking. One explanation for this discrepancy is that the simulation did not show cars entering or leaving a parking lot. Hence, the danger of cars driving off or car doors opening might not have been expected during the driving task, but might have been contemplated when providing the answers for the survey.

Center line The lack of a center line was not perceived to be more complex or less safe when compared to the neutral condition with a center line. However, perceptions of safety and complexity of roads without center lines were consistently associated with lower safe and preferred speeds. This later finding is in line with our expectations and the assumptions of previous literature (Elliott et al., 2003). The survey results indicated no significant difference between perceived safe and preferred speeds compared to the neutral condition Nevertheless, the lack of a center line resulted in a lower driving speed in the first section, but not in lower driving speeds in the second section. These results could point to a faster adaptation to the new driving speed, similar to the processes involved in reducing speed on roads with side-markings. The lack of cyclists, or other car drivers, could have moderated the effect found in the first section. In sum, our study's results only partially confirmed our expectations and findings from previous research (Fitzpatrick et al., 2001; Theeuwes et al., 2024; Cairney, 1986).

Greenery The presence of greenery did not result in perceptions of higher complexity or lower safety as compared to the neutral condition. Within the treatment, the perception of complexity and safety correlated negatively with indicated safe or preferred speedy. These findings met our assumptions based on previous considerations Elliott et al. (2003). Safe and preferred speeds did not differ significantly from the neutral condition. However, driving speeds in VR showed that the introduction of greenery was linked to significantly lower speeds in the short and long term as measured in our study. Thus, our results only partially confirmed our expectations. At the same time, they reflected the mixed evidence found in previous investigations. Our survey results were in line with those previous investigations that failed to find a link between greenery and chosen speed (Goldenbeld & van Schagen, 2007; Abele & Møller, 2011; Bella, 2013), The differences found in the VR driving simulator study were consistent with research which provided evidence for lower speeds on roads with greenery (Qin et al., 2020; de Waard et al., 1995; Chinn & Elliott, 2002). In sum, the present study did not succeed in resolving the inconclusive previous research results. Since there were no obvious systematic differences with these studies based on the methodological approaches, we can only speculate that the mixed result can be explained based on psychological processes that have not been examined in the present study. One obvious explanation is related to the processes of peripheral vision: that is, that trees along the roadside may appear to approach faster, creating the illusion of higher speeds, which in turn may influence higher risk perception. This effect can be simulated in VR, but not in an image-based study.

5.3. Influence of driving style

Individuals who prefer to drive faster ('sensation-seeking individuals', as measured by the DSQ speed scale), exhibited a tendency to drive faster within the driving simulator, surpassing the speeds of the control group by an average of 1.5 km/h to 3 km/h, which confirms earlier studies (Goldenbeld & van Schagen, 2007; Ju et al., 2022). This effect was not found in the survey, when perceived safety and complexity were included in the analysis. Interventions targeting these individuals can result in a speed reduction similar to the evaluated road design measures. Such interventions may encompass deterrents, such as speed cameras, as well as incentives, such as positive reinforcement mechanisms (e.g., displays), to encourage desired behavior. However, prior research has found that these punctual measures have only short-term effects and work well for certain areas (e.g. school areas), but do not result in effects that can be measured over longer distances (e.g. Ullman & Rose, 2005).

5.4. Self-explaining roads

The concept of self-explaining roads is rooted in the psychological principles of categorization and expectation (Theeuwes & van der Horst, 2017). Categorization serves as the basis for risk and appropriate behavior expectations. The results of the VR study revealed minimal differences between road designs when a speed limit of 30 km/h is posted. However, in real-world driving, it seems plausible that posted speed limits play a secondary role, while other design factors exert a greater influence. Differences in individual perceptions of safety and complexity within each treatment suggest that risk perception contributes to expectations about both risks and speed choice. Findings align with previous literature (e.g Goldenbeld & van Schagen, 2007), which suggests that the tendency to speed and take risks — often linked to sensation-seeking behavior — reinforces these results. Individual differences play a significant role in preferred speeds, perceived safe speeds, and driving speeds. Nevertheless, the road designs, overall, evoke expectations of sufficient safety and low complexity, leading to their categorization as roads where driving at 50 km/h is perceived as safe.

The effectiveness of categorization and expectation-based principles depends on learning processes and the consistent implementation of road designs in practice (Theeuwes, 2021; Gitelman et al., 2016). In this context, and to support this learning process, a consistent match between the road design and posted speed limits along main urban roads seems necessary to facilitate this learning process.

5.5. Limitations and further research

One limitation of this study is that it found only small or no effects of street design on driving speed in the driving simulator when the posted speed limit was 30 km/h. To adhere to the principles of an internally valid experimental design (i.e. to ensure that observed changes in the dependent variable (speed choice) can be confidently attributed to the manipulation of the independent variable (a specific measure), we chose to vary only one street design measure per treatment. This principle of experimental research might have been in conflict with the principles of the concept of self-explaining roads (Theeuwes & van der Horst, 2017): one single measure might not be sufficient to convey the cognitive load and induce sufficient risk perceptions necessary to influence actual speed choice (Harms, 1991).

A second limitation is the fixed sequence of treatments in the driving simulator, with neutral conditions placed between them. While these neutral intervals may help reduce carryover effects, presenting treatments in a predetermined order introduces the risk of order effects influencing driving behavior. Participants may adapt their speed due to potential learning effects or fatigue over the course of the simulation. Randomizing or counterbalancing the treatment order would have improved internal validity by minimizing these biases.

A third limitation of the present study with reference to the concept of self-explaining roads is that the effectiveness of the respective principles relies on learning processes and a consistent implementation of road designs in practice (Theeuwes, 2021; Gitelman et al., 2016). A laboratory experiment with a cross-sectional design - as was applied in the present study - again for reasons of internal validity - cannot provide the data necessary to investigate the long-term effects of road design measures. A longitudinal field study that compares chosen driving speeds for a longer period of time, either on differently designed roads or before and after a redesign of the same road stretch could shed light on these processes.

A further limitation of the simulator study is that human factors were limited in the simulation, which only included oncoming vehicular traffic and bicycles on the opposite side of the road when a bicycle lane was present. Other human factors could vary from cars exiting side roads, cyclists and pedestrians crossing the road. They were excluded to maintain comparability between the driving speeds of participants within each section, and to attribute speed differences due to road design and not other factors.

Most of the observed effects can be attributed to the fact that certain treatments suggested that the street section was considered complex or unsafe. Thus, designs that introduce risk and complexity can, controversially, result in lower driving speeds. Such measures can stem from street design, but also from unexpected occurrences, such as pedestrians crossing the street, or sharing the lane with cyclists. Whether such designs also result in safer roads is subject to further research.

Overall, we recommend investigating combinations of various road treatments and including certain human factors. Most promising are treatments that influence the peripheral vision (e.g. trees, parking), as well as reduce the (perceived) lane width. The inclusion of other road users as part of the experiment, such as bicycles, opposing traffic and crossing pedestrians, is also recommended. This study has focused on driving speed, but other performance indicators could be measured, such as alertness (reaction times), stress (e.g. with physiological measurement) and perceived comfort. Finally, we recommend similar studies be done on all road users and different user groups, including, but not limited to, pedestrians and cyclists, given the dual function of urban roads as a place but also as a corridor.

6. Conclusion

The research at hand provides empirical evidence for safe speeds, preferred speeds and driving speeds, relative to a neutral condition, along main urban roads by means of a driving simulator experiment and a follow-up survey. Results from the driving simulator reveal that road design measures have only limited effects. Drivers with a tendency to speed, as measured by the driving style questionnaire, drive faster. The safe and preferred speeds, as indicated in a subsequent survey, are higher and align with the current prevailing speed limit of 50 km/h. Psychological processes explain the observed results to some extent: safe speeds are largely explained by the perception of the safety of a given treatment; preferred speeds can be explained by the perceived safety and complexity of certain road design measures. Clearly, single and small changes in the street design are not sufficient to influence drivers' behaviors. Considering the importance of lower speeds for road safety and the well-being of road users, the results of this study call for further investigations as well as the implementation of approaches that combine human-factors, policy and infrastructure measures.

CRediT authorship contribution statement

Michael A.B. van Eggermond: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Dorothea Schaffner:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Nora Studer:** Writing – review & editing, Investigation, Formal analysis. **Alexander Erath:** Writing – original draft, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

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Appendix A

Table 8
Dimensions of design elements; all measurements are in meters and apply to one side of the road.

Treatment	Center line	Wide median	Lane width	Bicycle lane	Side marking	Greenery	Parking lots
0: Neutral condition	0.15	0	3	0	0	0	0
1: Side-markings	0.15	0	2.5	0	0.5	0	0
2: Bicycle lane	0.15	0	3	2	0	0	0
3: Wide median*	0	2.6	3	0	0	0	0
4: On-street parking	0.15	0	3	0	0	0	2
5: No center line	0	0	3	0	0	0	0
6: Greenery	0.15	0	3	0	0	1	0

Note: The width of the wide median applies to both sides of the road. The width to the center of the road would be 1.3 meters.

Table 9
Factor analysis of driving practice.

Item	Proficiency	Rule obedience	Communality
I drive in a self-assured way	**0.774**	-0.11	0.61
I drive very well	**0.759**	**-0.385**	0.72
I drive safely	**0.588**	0.287	0.43
I pay sufficient attention to the surroundings.	**0.479**	0.057	0.23
I comply with the traffic rules	0.088	**0.619**	0.39
I adapt my driving style to the circumstances	-0.05	**0.333**	0.11

Note: extraction method principal factor solution, rotation method: varimax.

Table 10
Factor analysis of driving style.

Item	Sensation seeking	Social resistance	Calmness & preparedness	Focus	Communality
Do you drive fast?	**0.892**	-0.027	-0.152	0.112	0.83
Do you break the motorway speed limit?	**0.659**	-0.064	0.108	-0.036	0.45
Do you exceed the speed limit in built up areas?	**0.643**	-0.139	0.059	-0.209	0.48
Do you overtake on a dual carriageway if you have the opportunity to do so?	**0.54**	-0.014	0.04	0.167	0.32
Are you happy to receive advice from people about your driving?	-0.158	**1.015**	0.26	0.093	1.13
Do you ignore passengers urging you to change your speed?	0.076	**-0.605**	0.297	0.112	0.47
Do you become flustered when faced with sudden dangers while driving?	-0.036	-0.082	**0.654**	-0.165	0.46
Do you plan long journeys in advance including places to stop and rest?	-0.104	0.029	**0.443**	0.272	0.28
Is your driving affected by pressure from other motorists?	0.21	-0.002	**0.427**	-0.032	0.23
Do you drive cautiously?	**-0.517**	0.035	-0.032	**0.715**	0.78
Do you find it easy to ignore distractions while driving?	0.107	-0.17	0.062	**0.416**	0.22
Do you remain calm when things happen very quickly and there is little time to think?	0.099	0.209	-0.124	**0.352**	0.19

Note: extraction method principal factor solution, rotation method: varimax.

Data availability

Data will be made available on request.

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