QUANTIFYING THE EFFECT OF STREET DESIGN ON DRIVING SPEED ON URBAN ROADS

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ABSTRACT

Reducing driving speed is a key factor in improving road safety and combating noise emissions. For this reason, more and more cities across the world reduce speed limits urban in roads to 30 km/h (20 mph). According measures are implemented in major urban areas in Europe (e.g. Paris, Brussels) and the U.S. (e.g. New York City, Seattle). For the implementation of speed reductions main roads are of particular interest.

Main roads in urban areas are different from residential roads in several ways, including, but not limited to the type of trips, vehicular mix and the presence of public transport, and are therefore limited in design options to reduce speeds. The study at hand reports on a virtual reality study conducted in Switzerland using a driving simulator. To assess whether road design influences driving speed, participants were asked to drive through a series of main roads in VR with varying speed limits and street designs. Speed and lateral position were recorded; in a follow-up survey, participants stated their preferred speed along the same segments and were asked about risk aversion. Results indicate that only certain designs result in slightly lower driving speeds, while controlling for self-reported risk aversion and driving style. Given the characteristics of main roads, measures reducing the (perceived) lane width are promising, but require further investigation.

Keywords: urban roads, driving speed, simulator, road design

INTRODUCTION

Reducing driving speed plays a crucial role in promoting road safety as it not only lowers the likelihood of traffic accidents but also decreases their severity (*1*). Moreover, speed reduction is an economical and highly efficient strategy to tackle noise pollution. Improved traffic flow and reduced congestion are other significant advantages of decreasing speed. Ultimately, reducing speed increases driving comfort and enhances the quality of stay for all road users, including, but not limited to pedestrians, cyclists and car drivers.

To this end, many European cities and countries have reduced 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, there is a discussion to reduce speed limits on main roads in urban areas in the Netherlands, Germany, Switzerland and several other countries (*2, 3*). In Helsinki, Finland, maximum driving speeds throughout the city are set at 40 km/h (*4*).

Conventional measures such as speed limits and law enforcement have their merit in ensuring traffic safety. However, they also have their limitations since drivers fail to perceive risks related to increased driving speed and adherence to speed limits is generally low.

A complementary measure to achieve speed reduction is the adaptation of road design. Road design has been found to be critical factor determining the speed at which drivers travel and their adherence to speed limits. An explanation for this observation is found in the concept of self-explanatory roads (SER) (*5, 6*). The SER approach suggests that road designs match their intended function to promote desired driver expectations and safety behavior. Additional explanations for the effect of road design on driving speed are based on cognitive load theory and risk perception (*7*): if a driving situation becomes more complex the cognitive load increases, and the driver reduces the speed. Furthermore, risk tolerance is assumed to influence driving speed. As perceived risk increases the driver reduces the vehicle's speed to maintain their acceptable level of risk tolerance.

Previous research on the impact of road design on speed is still sparse and is mostly limited to investigations on the influence of road design on either rural roads, the transition between urban roads and rural roads and main urban roads with a higher speed limit. Research has shown 'spot' or 'punctual' measures, such as speed-humps (*8*), digital information boards (*9*) or chicanes (*8, 10*) can result in local speed reductions, but do not result in overall lower driving speeds. Continuous design measures, such as markings, have not been investigated to the same extent, for urban roads. These measures are especially relevant, as urban main roads function as places, but also as corridors for public transport, logistics and emergency services. Research that quantifies the impact of road design on main urban roads with lower speed limits is missing.

Against this background, the study at hand aims to close this gap in the research and evaluates the impact of specific road design measures on driving speed on main urban roads, while focusing on continuous road design measures. Also, the present study aims to better understand the underlying psychological processes and to provide evidence based explanations for the impact of road design on speed choice.

The following research questions guide the present investigation: (1) What is the impact of specific road design features on speed choice in urban main roads?; (2) What are the psychological processes that explain the impact of road design on speed choice?

The presented research first reviews previous research on street design, speed choice and psychological processes in order to develop hypotheses in the section. Second, a virtual reality (VR) driving simulator study was conducted in which participants were asked to drive through a series of streets with varying speed limits and street designs. The design of the VR study, procedures and questionnaire are presented in the section 'Methods'. The section 'Results' presents the findings for this research. The paper concludes with a discussion and outlook.

LITERATURE REVIEW

Speed reduction has significant positive consequences. According to the Power Model low speeds decrease both the severity and frequency of crashes (*11, 12*). Lower speeds also contribute to reduced noise levels generated by motorized vehicles, making the environment more pleasant. Additionally, slower speeds can result in reduced emissions, leading to improved air quality and a healthier living environment. Thereby, calming traffic enhance livability of urban environments (*13*). Despite its importance, effective speed management remains challenging.

The most obvious measures for reducing driving speeds is the posting of speed limits, but the effectiveness of this measure has its limitations. From a driver perspective, adherence to speed limits, in particular to perceived low speed limits such as 30 km/h, might be difficult for several reasons (*14*). First, it is likely that drivers focus on other vehicles rather than speeds and other road features due to the familiarity of a road (*15*). Second, especially in the case of downward changes of the speed limit without visual changes, the appearance of a road is not a reliable indicator of driving speed (*16*). Finally, posted speed limits are not credible due to a mismatch between road design characteristics and the prevailing speed limit (*17*). These reasons especially hold for main urban roads, as their design, building features and landscape features do not coincide with a lower speed limit.

The concept of self-explaining roads helps to better understand poor adherence to speed limits. Two psychological principles are central to this concept: categorization and expectancy. Through experience drivers learn to categorize roads based on visual characteristics. The categorization is the foundation for expectations with regards to risks and adequate behavior. By utilizing design elements such as lane width, pavement markings, and vertical offsets the road space can convey information that drivers use to categorize and understand roads as intended by the planning authorities, leading to behavior consistent with the interpretation. For example, road space greenery may be a visual cue that leads drivers to categorize the road as a road in which slower speeds are safe and therefore reduce their speed.

Additional explanations for the effect of road design on driving speed are based on cognitive load theory and risk perception (*7*). Cognitive load is defined as the mental effort to perform a task. The theory suggests if a driving situation becomes more complex the cognitive load increases, and the driver reduces the speed. Further, risk tolerance is assumed to influences driving speed. As perceived risk increases the driver reduces the vehicle's speed to maintain their acceptable level of risk tolerance. Therefore, we hypothesize that an increase in risk perception can lead to a reduction in driving speed and that an increase in complexity leads to reduction in driving speed.

Several studies have investigated the impact of pavement markings on speed choice (*7*). There is mixed evidence on the impact of wide center lines on speed choice. While some research finds that wide center lines (median) reduce the chosen speed in rural roads (*18–20*), other studies report an increase in driving speed (*21, 22*). Medians with a hatch pattern resulted in lower driving speed (*23*), as did medians with a relief on rural roads (*18, 19*). Colored center strip with markings leads to a lower speed on rural roads (*20*). The removal of a center line can result in small reductions in driving speed (*7*). These designs elements partially achieve their effect through different processes: on one hand, a median results in a larger distance to opposing traffic, thus reducing perceived risk. On other hand, if a median is paired with (perceived) lane narrowing and/or a perceived higher driving speed, medians can result in lower driving speeds.

Similar effects could be achieved with side markings. Edge and lane markings on roads outside urban areas bring vehicles to the edge of the road, but do not lead to a reduction in speed (*20, 24*). In combination with a center line marking, speed reductions could be observed (*20*). Again, by reducing the perceived width of the roadway, it is also possible to achieve a reduction in speed by increasing the cognitive load of motorists. On urban roads, the effect of side markings has not been extensively researched.

Painted bike lanes, despite serving a different purpose, can be considered as a special type of side-marking. Widening the bike lanes so that they overlap with the traffic lanes, combined with a horizontal offset, resulted in a reduction in speed (*25*). The introduction of one-way traffic, the widening of the bike lanes, and the installation of a sign resulted in a reduction of speed (*26*). In contrast, a simulator study showed that the bike lanes only led to a speed reduction when a person riding a bike was present; no speed reduction was perceived without cyclists (*27*). Bike lanes can reduce speed because they either lead to an actual narrowing of the lane width, reduce the perceived width of a lane, or share the space between vehicles and cyclists enhancing complexity and risk perceptions.

Studies have shown that the presence of parked cars leads to lower travel speeds. Analysis of speed measurements has shown that parked cars have an impact on the speed traveled (reduction in speed) along major urban roads (*7, 21*) and on the speed selected on urban roads in driving simulators (*10, 27*). Parked vehicles can lead to a (perceived) narrowing of the lane width and thus to a lower speed. Parking can also lead to a higher perceived risk that people may exit parked cars abruptly or that departing cars may veer into the traffic lanes (*7*). Furthermore, the proximity of objects in the peripheral vision can result in a higher perceived driving speed.

Trees or green space have only a small influence on the speed driven, especially for major roads outside towns; within towns, no influence is found in these studies (*7*). Once age and riskiness were included in an analysis found no influence of trees and green space on speed choice (*28*).

METHODS

To evaluate the effect of different road design measures a Virtual Reality (VR) driving simulator experiment was conducted. Numerous studies support the validity of driving simulators as a reliable measurement tool for investigating driving behaviour (*29, 30*). One of the most important reasons of using a VR driving simulator for research is the safety factor. The use of simulators allows researchers analyze potentially unsafe scenarios without putting participants in danger (*31*). From a scientific perspective, the use of a driving simulator enables a controlled experimental manipulation of the relevant influencing factors (e.g. road space design) and the associated systematic investigation of their causal effects on driving behaviour (*30, 32*). Further benefits include the possibility to control environmental factors such as traffic, weather and locations of occurences. Moreover, in recent years a VR driving simulator in comparison to conventional driving simulators have become more cost-effective while allowing for a greater immersion and naturalistic observation of drivers behavior within a three-dimensional simulation.

Evaluated road designs & sequence

The experiment covers a road stretch of 12,800 metres and can be completed in 14 minutes and 52 seconds if the speed is adhered to exactly. The course consists of eight sequences. Each sequence covers a distance of 1700 metres and can be completed in 1 minute and 56 seconds (if speed is maintained). The experimental set-up is shown in Figure 1.

A sequence contains four sections and has an identical structure with the exception of sequence 7. A sequence starts with a neutral condition at 50 km/h (section 1). A speed 50 km/h was chosen to create a clear differentiation from the road types studied experimentally. In addition, this section serves as a connecting element between the road types and facilitates the speed change. Section 2 is followed by an experimental condition, or the reference condition, for the 30 km/h road type. This is again followed by a neutral condition at 50 km/h (section 3). This section serves to cancel out the effect of the previous experimental condition and forms the transition to the next experimental condition. Section 4 consists of an experimental condition, or the reference condition, for the road type at speed 80 km/h. Sections with a speed limit of 30 km/h and 50 km/h have a length of 300 meters; sections with a speed limit of 80 km/h have a length of 700 meters.

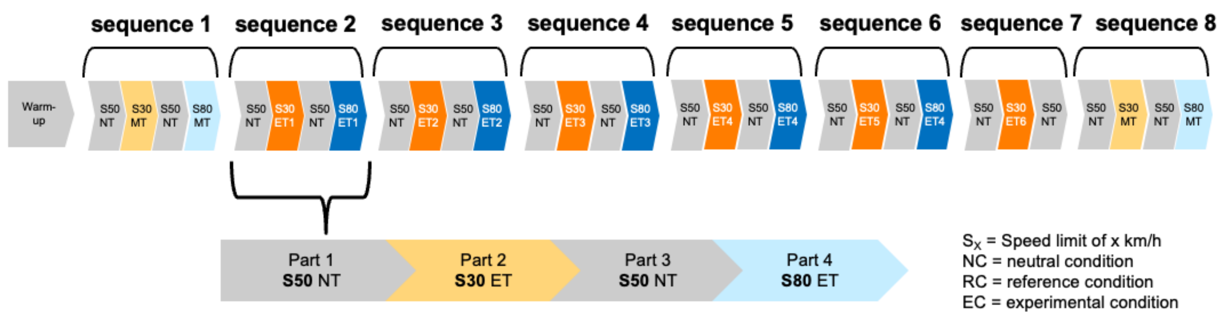


FIGURE 1: Experimental sequence

We included seven road designs in arterial urban roads: ((1) wide pavement edge markings; (2) wide, hatched pavement edge markings; (3) wide center markings / median; (4) core lane / no center line; (5) parking lots; (6) bike lanes; (7) roadside greenery (trees and benches). These six treatments are shown in Figure 2.

Driving simulator

The setup 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 gearstick - 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

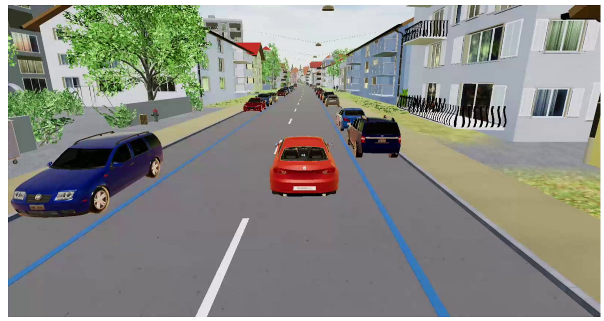
Various software components and assets were used for the software:

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

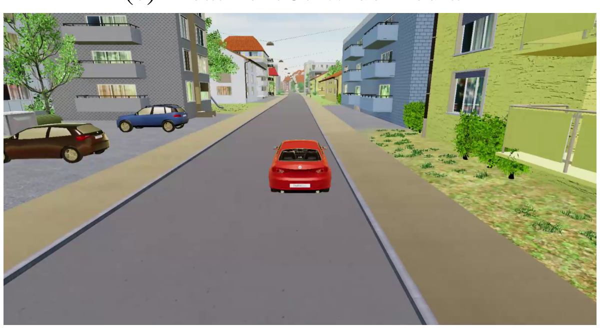
(a) Treatment 1: Side markings

(b) Treatment 2: Bicycle-lane

(c) Treatment 3: Wide median



(d) Treatment 4: On-street parking



(e) Treatment 5: No centre line

(f) Treatment 6: Greenery

(g) Treatment 0: Reference treatment

FIGURE 2: Experimental treatments

Procedures

The experiment in the VR driving simulator consisted of five steps. The main part of the experiment was driving through a road stretch in the VR driving simulator (step 3). The total duration of the

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

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: Instruction VR driving simulator and driving through a training section: After the introduction, participants were made familiar with the VR driving simulator. First, they were asked to drive through a practice track.
- Step 3: Driving through a road stretch in the VR driving simulator: following the practice track, participants drove through the test track with the seven experimental and the control conditions. The test track lead along a continuous route through several small towns. The road type alternated between urban main roads with a speed limit of 30 km/h as well as 50 km/h (arterial main roads) as well as rural roads with a speed limit of 80 km/h. The appearance of the towns and villages in the VR simulation is based on the Swiss countryside. The test track was designed as realistic as possible, creating the impression of an ordinary car journey.
- Step 4: Questionnaire on route sections (preferred and safe speed, risk and complexity of the route section), driving experience in VR, current well-being, driving style, driving experience, experience with VR, socio-demographics: after the completion of the test track participants completed a questionnaire measuring perceived risk, complexity, and subjective speed choice as well-as several control measures.
- Step 5: Debriefing

Measures

The impact of the road design was subjectively evaluated with questions on each experimental condition. Preferred speed and the subjective perceived safe speed were measured (*28*). Further measures included perceived risk (*33*) and perceived complexity (*16*) of the respective road sections. Symptoms of simulator sickness were assessed with a questionnaire on the participants' current well-being. A total of 16 symptoms were included (*34*). Questions about immersion and the feeling of control were used to assess the strength and credibility of immersion in the VR environment (*35*). The driving style was surveyed on the following six dimensions: Speed, Calmness, Social Resistance, Focus, Planning, Deviance (*36, 37*). In the assessment of driving practice, a subjective assessment of one's own ability to drive safely and attentively was collected. The assessment is based on seven items (*38*). Questions on driving practice also elicit objective information on experience and frequency of car use, availability of a car, and involvement in a traffic

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 driving 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	

accident (regardless of responsibility). In order to collect already existing experiences with VR, the frequency of using VR glasses, a VR driving simulator and driving car races with a gaming console were recorded.

RESULTS

Sample

The sample for the VR driving simulator experiment included a total of 61 people. Seven people had to be excluded from the data analysis because no data were recorded due to technical errors (n = 4) or because they discontinued the experiment due to motion sickness (n = 3). Thus, the final sample consists of 54 participants that have completed the test-drive. Sample sociodemographic characteristics are reported in Table 1. We note an even distribution between male and female participants. The majority of the participants was between 21 and 35 years old (48%), followed by participants aged between 36 and 50 years old (35%). The majority of the sample always had a car available or on arrangement within the household (87%). Over 80% of the participants indicated that they used the car on a weekly basis or more frequently. The majority of participants did not have experience with Virtual Reality (91%) and did not play driving games on a game console (70%).

Factor analysis

Driving style was assessed using the driving style scale (*37*). This previous research indicated that six factors should be extracted from this scale. However, 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 loading is thought to be due (1) the omnipresence of navigation aids as when 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 omitting these items, four factors were identified: sensation seeking, social resistance, calmness & preparedness and focus. Factor loadings are included in the Appendix in Figure 6. These factors are inline with French et al. (37), except for the factors 'planning' and deviance'.The reliability of the items reflecting sensation seeking was $\alpha = .78$, the reliability of the items reflecting social resistance was $\alpha = .7$, the reliability of the items reflecting calmness & preparedness was $\alpha = 0.47$ and the reliability of the items reflecting focus was $\alpha = 0.42$. Subsequently mean scores were computed for these items. The distribution of the item 'sensation seeking' ranged from 1.5 to 4.75 with an average of 2.84. The distribution of the item 'social resistance ' ranged from 1 to 5with an average of 3.4.

Driving performance was assessed using a modified version of the self-rated driving scale Victoir et al. (*38*). Items of the scale were modified to reflect general driving performance rather than reflecting on past driving performance. Based on a visual examination of a scree plot, we found that two factors could be extracted from this scale for our sample: driving proficiency and rule obedience. Factor loadings are included in the Appendix in Figure 5. The reliability of the items reflecting driving proficiency was $\alpha = .73$ and the rule obedience was indicated to be unreliable at $\alpha = .33$. Subsequently mean scores 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.

Descriptive analysis

Based on literature, we expect two types of effects of road design on driving speed. Certain intervention and design elements achieve a short-term effect: only immediately after an intervention and/or a change in design, a speed adjustment is achieved. Other design elements aim to achieve an effect that can be measured along a longer distance.

A descriptive analysis of the driving speed per section revealed that drivers adjusted their speed in the initial 50 meters of the section, and thereafter drove with a constant speed or increased their speed again. Figure 4 depicts the driving speed prior to the reference condition (speed limit 50 km/h), within the reference condition (speed limit 30 km/h) and after the reference condition (speed limit 50 km/h).

Based on this visual analysis for each condition, we decided to segmentize each section in two subsections. Section 1 is defined from 50 m to 100 m into a section: after entering a section, drivers adjust their speed. We call this effect a *short-term effect*. Section 2 starts at 100 m and ends at 225 m into a section: after entering a section, drivers adjust their speed. We call this effect a *long-term effect*.

Subsequently, to allow for a visual comparison between treatments, mean speeds over all participants are calculated for every 2 meters of each treatment. The resulting speed profiles of each treatment are shown in Figure 5. Mean speeds the first section of the treatments 'Side-marking',

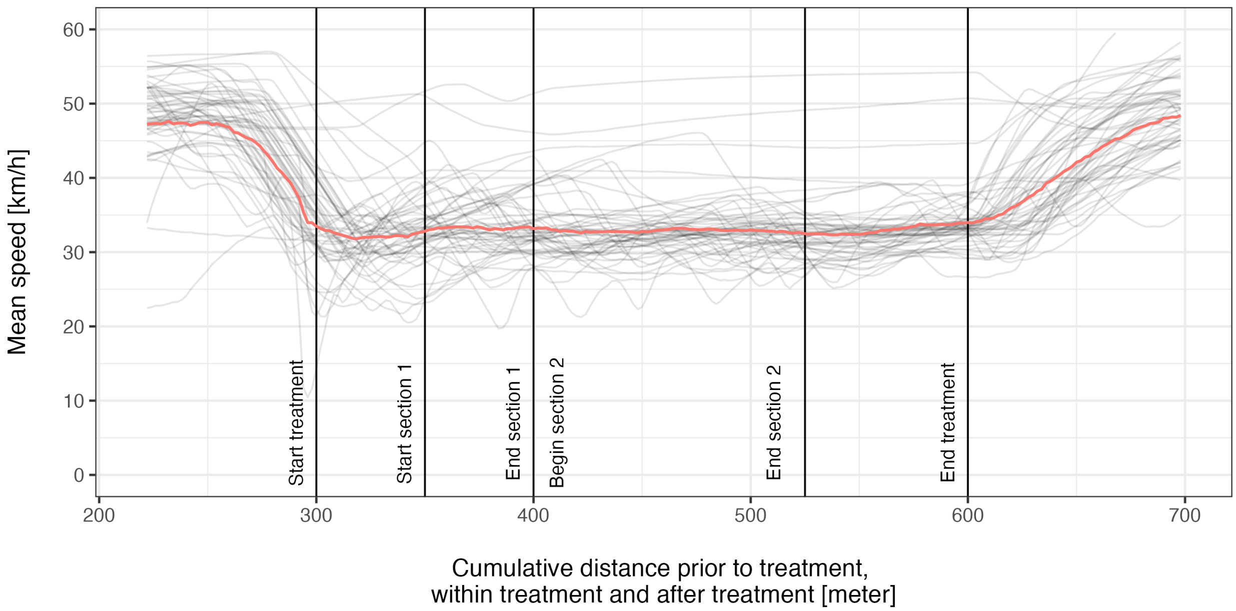


FIGURE 4: Mean driving speed in treatment T0: Reference condition. Thick line depicts the mean driving speed; thin lines represent individual trajectories

'No center line', 'On-street parking' and 'Greenery' are lower than in the reference treatment (T0). Subsequently, driving speed increases again, except in the treatment with greenery.

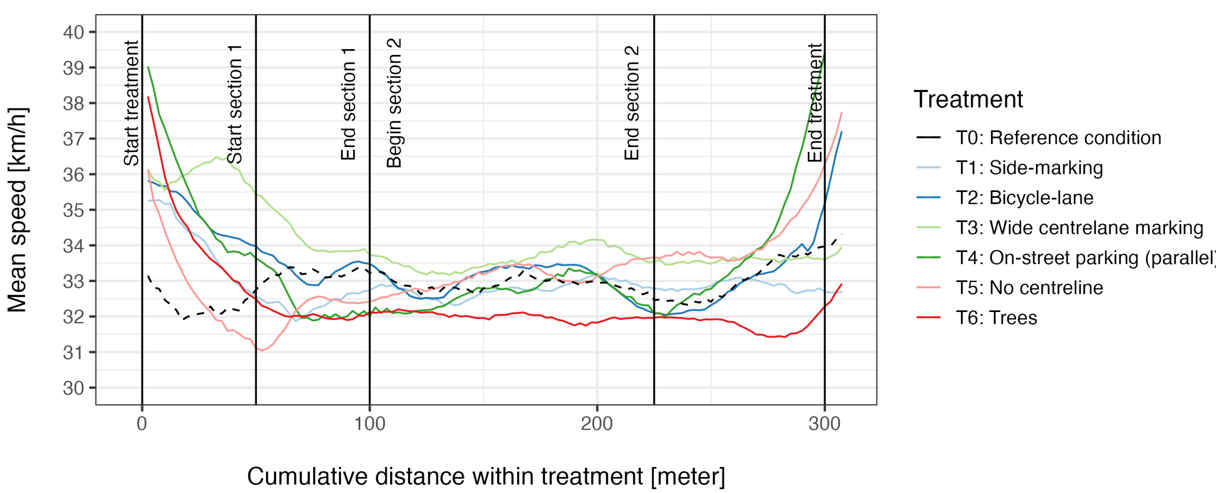


FIGURE 5: Mean driving speed in all treatments

Detailed statistics are presented in Table 2. In the table, the mean driving speed of section 1 (short-term effect) and section 2 (long-term effect) are shown. Also, the median speed (v_{50}) and the 85% percentile is shown (v_{85}). Percentiles are calculated based on the mean speed per participant per section and can be compared to percentiles as available from speed measurements. All speeds are in km/h. Minor speed differences between treatments can be observed, but in all cases speed exceeds the posted speed limit of 30 km/h.

Table 2 additionally includes the results from the follow-up questionnaire. In this survey,

TABLE 2: Average driving speed (v_{mean}, km/h), 50% percentile (v_{50}, km/h), 85% percentile (v_{85} , km/h) derived from simulator and follow-up questionnaire (n=54). Mean safety and complexity are computed from follow-up questionnaire (n=54) with safety varying from 1 (safe) to 5 (unsafe) and complexity varying from 1 (easy) to 5 (complex)

Treatment	Short-term effect			Long-term effect			Safe speed			Desired speed			Safety	Com-plex
	v_{mean}	v_{50}	v_{85}	v_{mean}	v_{50}	v_{85}	v_{mean}	v_{50}	v_{85}	v_{mean}	v_{50}	v_{85}		
T0: Reference	33.8	33	37.1	33.4	32.4	35.5	41.4	50	50	45.3	50	50	2.2	1.9
T1: Side-marking	32.7	32.8	36.2	33	32.5	35.4	43.3	50	50	45.1	50	50	2.0	1.8
T2: Bicycle-lane	33.7	33.5	36.5	33.2	33.2	35.1	48.4	50	50	50.2	50	55	2.0	1.9
T3: Wide median	34.8	33.7	38.8	34.3	32.9	37.4	39.9	40	50	41.2	43	50	2.3	2.3
T4: On-street parking	33.3	32.2	37	33.2	32.9	35.5	33.3	30	50	34.1	30	45	3.8	3.4
T5: No center line	32.5	32.1	35.9	33.4	33.3	36	40.7	50	50	43.1	50	50	2.5	2.2
T6: Greenery	32.3	32.5	35.5	32.1	31.9	34	43.4	50	50	46.6	50	50	2.1	1.9

we asked participants to state their desired speed along each treatment, as well as to state the speed that they considered to be safe. Furthermore, participants were asked whether a treatment was complex (1=easy, 5=complex) and safe (1=safe, 5=unsafe). Different than the driving simulator experiment, the images shown in the survey did not include signalisation (see Figure 2).

Driving speed in VR

We estimated multi-level regression models with the participant as a random effect and the treatment as fixed-effect, given the fact that we have repeated measurements per participant. Model estimation results for the VR driving experiment are shown in Table 3. To assess whether driving style and/or practice influence driving speed, we estimated models without and with aggregated items describing driving style and practice. Across all models, based on the intercept, we note that participants drove between 33.7 km/h (short-term effect) and 33.3 km/h (long-term effect). Only treatment 'T6: Greenery' results in a significant lower driving speed on the short-term (-1.52 km/h, p=0.027) and the long-term (1.26 km/h, p=0.039) versus the reference treatment.

Considering the small sample size, we choose to report other results as well. The lack of a center line (T5: No center line) results in a short-term effect of -1.3 km/h (p=0.057). Introducing a side-marking results in reduction of -1.1 km/h (p=0.117). A wide median results in a higher driving speed 1.0 km/h (p=0.126). The driving speed along these sections was not significantly lower when compared to the reference treatment.

Individuals who tend to driver faster ('sensation seeking'), drive 1.5 km/h faster in the first section and 1.2 km/h (p=0.087) faster in the second section. On other hand, individuals who state to adher to traffic rules, drive 1.3 km/h faster in the first and second section.

Desired & safe driving speed

We follow a similar approach to analyse the results of the survey conducted after the VR experiment and estimated multi-level regression models with the participant as a random effect and the treatment as fixed-effect. To evaluate whether complexity and/or safety influence driving speed, we estimated models with treatment effects only, and models that include stated perception of complexity and safety. The safety rating was included as interaction with the treatment. Also, the

TABLE 3: Driving speed in Virtual Reality: 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

	Short-term effect	Long-term effect
Intercept	33.701 (<0.001)***	33.439 (<0.001)***
Treatment specific effects		
T1: Side-marking	−1.073 (0.117)x	−0.434 (0.477)
T2: Bicycle-lane	−0.133 (0.845)	−0.187 (0.759)
T3: Wide median	1.046 (0.126)x	0.858 (0.161)
T4: On-street parking	−0.501 (0.463)	−0.241 (0.693)
T5: No center line	−1.304 (0.057)+	0.020 (0.974)
T6: Greenery	−1.517 (0.027)*	−1.262 (0.039)*
Driving style & practice		
Sensation seeking	1.571 (0.024)*	1.150 (0.087)+
Rule obedient	−1.290 (0.082)+	−1.281 (0.057)+
N	378	378
N (subjects)	54	54
R2 (conditional)	0.35	0.33
R2 (marginal)	0.09	0.07
AIC	2110.890	2024.955

p-value between brackets, $^{***}p < 0.01$, $^{*}p < 0.05$, $^{+}p < 0.1$, $^{x}p < 0.15$

highest safety rating was coded as 0. The lowest safety rating was coded as 4. Including interaction effects with safety rating for the different treatments results in an increased model fit, based on evaluation of the marginal R^2. In the final model specification we omitted several insignificant main and interaction effects, which will be discussed in the ensuing, and specified each interaction individually. Model results are presented in Table 4.

TABLE 4: Desired and safe speed: model estimation results.

	Safe speed	Desired speed
Intercept	41.679 (1.012)***	40.774 (2.073)***
Treatment specific effects		
T1: Side-marking	4.324 (1.690)*	
T2: Bicycle-lane	10.584 (1.645)***	7.273 (1.608)***
T3: Wide median		−3.963 (1.226)**
T4: On-street parking		−11.148 (1.226)***
T5: No center line	6.379 (1.942)**	4.651 (1.907)*
T6: Greenery	7.406 (1.755)***	4.386 (1.719)*
Safety perception (safe -> unsafe)		
T1: Side-marking	−2.645 (1.114)*	
T2: Bicycle lane	−3.912 (1.052)***	−2.292 (1.040)*
T3: Wide median	−1.504 (0.717)*	
T4: Parking	−2.995 (0.424)***	
T5: No center line	−4.879 (0.984)***	−4.471 (0.974)***
T5: Greenery	−5.414 (1.153)***	−2.857 (1.141)*
Attitudes		
Sensation seeking		1.556 (0.671)*
N	378	378
N (subjects)	54	54
R2 (conditional)	0.48	0.40
R2 (marginal)	0.29	0.32
AIC	2639.372	2614.718

Std. Error between brackets, $^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$

Starting with the model describing 'Safe speed', we find that participants, on average, state a safe speed of 41.7 km/h (intercept). Significant main effects include the presence of a side-marking (4.3 km/h), the presence of a bicycle lane (10.6 km/h), the lack of a center line (6.4 km/h) and the presence of greenery (7.4 km/h). All main effects are positive, indicating that participants who rated these treatments as safe, would consider a speed higher than 41.7 km/h to be safe, as compared to the omitted treatments (reference treatment, treatment with a wide median and treatment with on-street parking). In all cases, we find that individuals who consider a treatment as unsafe, would consider a lower speed safer. Only for the treatments 'wide median' and 'on-street parking' no significant treatment specific parameter could be estimated, but only a parameter for the safety rating of this treatment (-3 km/h per point). Parameter estimates for attitudes were not significant.

Continuing with the model 'Desired speed', we find that participants, on average, state their desired speed to be 40.7 km/h (intercept). When a bike lane is present, participants desire to drive faster by 7.2 km/h. On other hand, when a wide median is present, participants prefer a lower speed (-3.9 km/h). On-street parking results in the lowest preferred speed: participant state, on average, that they desire to drive 11 km/h slower.

Significant interaction effects could be estimated for the treatments with a bicycle lane (-2.3 km/h), the lack of a center line (-4.5 km/h) and the presence of greenery (-2.9 km/h). Participants who considered these treatments unsafe desired a lower driving speed.

Participants who prefer to speed ('sensation-seeking'), drive 1.6 km/h faster on average.

DISCUSSION & OUTLOOK

The paper at hand investigated driving speed on urban main roads. To this end, different road design 'continious' elements that are applied along a stretch of road (e.g. markings, parking) were evaluated, as opposed to 'spot' measures (e.g. speed humps, information displays) that are commonly applied to lower driving speeds locally. We were especially interested in the fact whether these designs elements would result in different driving speeds with a posted speed limit of 30 km/h (20 mph), as opposed to a speed limit of 50 km/h, as currently in place. To this end, a virtual reality (VR) driving simulator experiment was conducted, with varying design elements on urban and rural roads. Additionally, participants were asked to rate the safety and complexity of each treatment and state their desired speed along each treatment, as well as to state the speed that they considered to be safe, based on still images of each treatment excluding the posted speed limit.

The survey revealed clear differences in safe and desired driving speeds between treatments. Individuals, on average, state that they prefer to drive 44 km/h per hour, lower than the current speed limit on urban roads of 50 km/h, but within the range of driving speeds in urban areas (*39*). Between treatments with different road designs differences can be observed in individuals' desired speeds and speeds that are considered safe. Safe and desired speeds along roads with a painted bicycle lane are highest at 50 km/h. Drivers clearly categorize this road as a main urban road, and consider a speed of 50 km/h to be appropriate: the image of this type of road explains itself as 50 km/h. Roads with a bicycle lane are also considered to be most safe and the least complex: the separation of traffic lowers the perceived risk of sharing the road with cyclists and the allocation of space reduces complexity.

For other road designs, expect for roads with on-street parking, a clear dichotomous distribution can be observed, despite the survey question being formulated open-ended. Whereas some participants consider a safe speed to be 30 km/h, other participants consider a speed of 50 km/h to be safe, resulting in mean speeds varying between 40 km/h and 44 km/h. The introduction of on-street parking results in a reduction of safe and desired speed towards 30 km/h. On one hand, a road with on-street parking resembles residential roads, with a speed limit likely to be 30km/h. Also, these roads are considered to be least safe, likely stemming from cars potentially leaving their parking lot, as well as the risk of swiveling doors, or pedestrians unexpectedly crossing the road. Previous research has shown that the presence of parking results in lower driving speeds (*27*).

Given these results, urban main roads are not categorized as roads with a lower speed limit and, at the moment, do not explain themselves as roads with 30 km/h. However, over the course of time, it could be that drivers update their mental images of these roads and categorize urban main roads as roads with a speed limit of 30 km/h.

Desired speeds are between 1 km/h to 4 km/h higher than speeds considered to be safe. Earlier research has found larger absolute differences between speeds considered to be safe and preferred for rural roads (between 4 km/h and 8 km/h) (*28*). When relative instead of absolute speed differences would be considered, these would be in a similar order of magnitude of 5% to

10%.

Speeds in the VR driving simulator were generally lower than elicited safe and desired speeds and in line with a posted speed limit within a treatment of 30 km/h. Between treatments only small differences in driving speeds could be observed. In line with previous results, the presence of the bicycle lane did not result in lower driving speeds (*27*). Speed measurements do point to the potential of bicycle lanes to reduce driving speeds (*25*). In the latter case, bike lanes were widened and paired with a reduction of lane width for vehicular traffic. Several road design elements resulted in a short-term effect that could be measured between 50 and 100 meters after a change in road design, but did not result in a lasting effect, measured as the speed between 100 and 225 meters after a change in road design. A wide median resulted in a higher driving speed in the first section. The introduction of a side-marking and 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. Only the presence of greenery resulted in significantly lower driving speeds in the first and second section. These results could also point to a faster adaptation to the new driving speed: designs that reduce perceived lane width result in lower driving speeds. Surprisingly we did not find an effect of on-street parking in the simulator.

Individuals who prefer to drive faster ('sensation-seeking individuals'), overall, desire higher driving speeds and drive faster in the driving simulator (between 1.5 km/h and 3 km/h), as also found in earlier studies (*28*). Interventions targeting these individuals can result in a similar reduction of speed. Such interventions can include sticks (e.g. speed cameras) but could also positively reward behaviour (e.g. displays). However, previous research has found that these punctual measures only have a short-term effect, and work well for certain areas (e.g. school areas), but do not result in effects that can be measured over a longer distance. Promotional campaigns or higher fines could result in more lasting speed reductions.

Most of the observed effects can be attributed due to the fact that certain treatments are considered to be complex or unsafe. Thus, designs that introduce risk and complexity can, controversially, result in lower driving speeds. Such elements 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.

A limitation of the simulator study is that human factors were limited in the simulation, that only included oncoming vehicular traffic and bicycles on the opposite side of the road when a bike 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.

We recommend to investigate further combinations of treatments and to include certain human factors. Most promising are treatments that influence the peripheral vision (e.g. trees, parking) as well as reduce the (perceived) lane width. Also, the inclusion of other participants, such as bicycles, opposing traffic and crossing pedestrians, is recommended. This study has focused on driving speed. Additionally, 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 to be extended to all road users and different user groups, including, but not limited to pedestrians and cyclists, given the dual function of urban roads as place and corridor.

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TABLE 5: 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

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APPENDIX

TABLE 6: 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