Quantifying the effect of street design on driving speed on urban roads

Michael A.B. van Eggermond

Dorothea Schaffner

Nora Studer

Alex Erath

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Michael A.B. van Eggermond
Instute of Civil Engineering
School of Architecture, Civil Engineering and Geomatics
University of Applied Sciences Northwestern Switzerland (FHNW)
michael.vaneggermond@fhnw.ch

Dorothea Schaffner
Institute of Marketing and Consumer Decisions
School of Applied Psychology
University of Applied Sciences Northwestern Switzerland (FHNW)
dorothea.schaffner@fhnw.ch

Nora Studer
Institute of Marketing and Consumer Decisions
School of Applied Psychology
University of Applied Sciences Northwestern Switzerland (FHNW)
nora.studer@fhnw.ch

Alex Erath
Instute of Civil Engineering
School of Architecture, Civil Engineering and Geomatics
University of Applied Sciences Northwestern Switzerland (FHNW)
alexander.erath@fhnw.ch

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Abstract

Reducing driving speed is a key factor in improving road safety and combatting noise emissions. Over the last decades, 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 mph). At the same time, there is a discussion to reduce speed limits on main roads in urban areas in several countries. 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 streets 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

Driving speed, urban roads, 30km/h, driving simulator, virtual reality

1 Introduction

Background 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 (Aarts and van Schagen, 2006). 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 enhances the quality of travel and stay for individuals.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 increased driving speed and adherence to speed limits is generally low.

Self-explanatory roads 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) (Theeuwes and Godthelp, 1995; Theeuwes, 2021). The SER approach suggests that road designs match their intended function to promote desired driver expectations and safety behavior. Two psychological principles are central to the 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.

Cognitive theory Additional explanations for the effect of road design on driving speed are based on cognitive load theory and risk perceptions (Elliott *et al.*, 2003). 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.

Road design 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 or residential roads. So far, research that quantifies the impact of road design in main urban roads is missing. Against this background, the study at hand aims to close this gap in the research and to better understand the impact of specific road design measures on driving speed on arterial urban roads. Thereby, the study focuses on continuous road design measures. Several studies have investigated the impact of pavement markings on speed choice ((for an overview see Elliott *et al.*, 2003). 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 (Charlton, 2007; de Waard et al., 1995; Taylor et al., 2002) in rural roads, other studies report an increase in driving speed (Gargoum et al., 2016)(Fitzpatrick et al., 2001).

Research objective The study at hand investigates whether road design influences driving speed. Participants were asked to drive through a series of streets in Virtual Reality with varying speed limits and street designs. We hypothesize that road design influences speed choice in urban roads, 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.

2 Methods

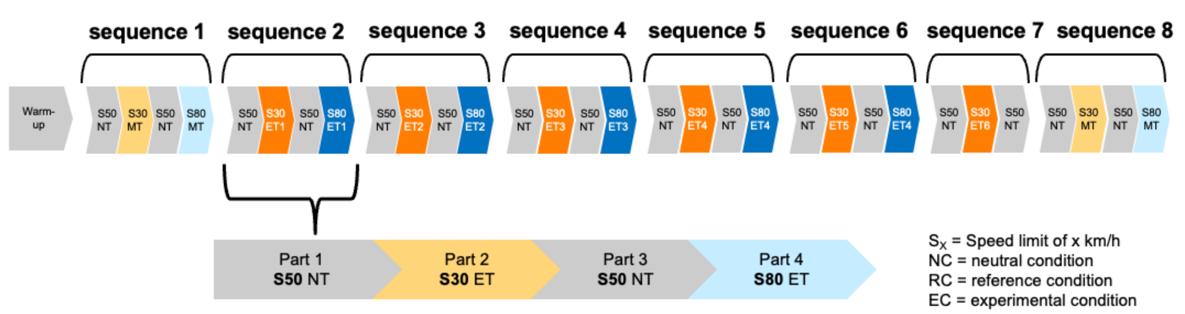
To test the hypotheses a Virtual Reality (VR) driving simulator experiment was conducted. The use of driving simulators has become established both in science and in practice. Numerous studies support the validity of driving simulators as a reliable measurement tool for investigating driving behaviour (Allen *et al.*, 2017; Kaptein *et al.*, 1996). One of the most relevant reasons of using a virtual reality driving simulator for research is the safety factor. The use of simulators allows researchers analyze potentially unsafe scenarios without putting participants in danger (Lee *et al.*, 2003). 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 (Carsten and Jamson, 2011; Kaptein *et al.*, 1996). In addition, there are further benefits for using driving simulators from controlling environmental factors such as traffic, weather and location. 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.

2.1 Evaluated road designs & sequence

The total distance of the road stretch covers a distance 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). 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 minimum 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 minimum 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.

Figure 2: Experimental treatments

(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) Minimal condition

2.2 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) Driving simulator

(b) View through the head-mounted display

2.3 Procedures

The experiment in the VR driving simulator consists of five steps. The main part of the experiment is driving through a road strecht in the VR driving simulator (step 3).

The total duration of the experiment is 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 in order to increase the external validity.
- 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

2.4 Measures

The followup questionnaire included the following measures: The impact of the road design was subjectively evaluated with questions each experimental condition. Preferred speed and the subjective perceived safe speed were measured (Goldenbeld and van Schagen, 2007). Further measures included perceived risk (Wang *et al.*, 2019) and perceived complexity (Charlton and Starkey, 2017) 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 are asked (Kennedy *et al.*, 1993). Questions about immersion and the feeling of control are used to assess the strength and credibility of immersion in the VR environment (Kronqvist *et al.*, 2016). The driving style is surveyed on the following six dimensions: Speed, Calmness, Social Resistance, Focus, Planning, Deviance

(Chowdhury, 2014; French *et al.*, 1993). In the assessment of driving practice, a subjective assessment of one's own ability to drive safely and attentively is collected. The assessment is based on seven items. Questions on driving practice also elicit objective information on experience and frequency of car use, availability of a car, and involvement in a traffic 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 will be recorded.

3 Results

3.1 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.

3.2 Factor analysis

Two factor analyses were conducted on participants' assessment of driving style and their driving practice. For driving style, the most relevant extracted several factors (out of 6) were:

- Sensation seeking: breaking the speed limit on motorways, breaking the speed limit in urban areas, overtaking on two-lane roads, speeding
- Focus: driving cautiously, ignoring distractions
- Social resistance: do you take advice from other people, do you dislike advice.

For driving practice, the extracted factors (out of 2) were:

- Proficiency: Are you a good driver, do you adjust your speed, do you drive safe, are you confident?
- Obedience: do you comply with traffic rules, a

3.3 Driving speed in VR

Based on literature, we expect two types of effects of road design on driving speed. Certain design elements achieve a short-term effect: only immediately after the 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. Therefore, we decided to segmentize each section in two subsections:

- 50 m - 100 m into a section: after entering a section, drivers adjust their speed. We call this effect a *short-term effect* and calculate the average driving speed of each participant.
- 100 m - 225 m into a section: after entering a section, drivers adjust their speed. We call this effect a *long-term effect*

Model estimation results for the VR driving experiment are shown in Table 1. . Given the fact that we have repeated measurements per participant, we estimated multi-level regression models with the participant as a random effect and the treatment as fixed-effect. To assess whether driving style and/or practice influence driving speed, we estimated models without and with aggregated items describing driving style and practice. For the time being, we decided to include all treatments in the models and to not exclude insignificant effects.

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) and the long-term (1.26 km/h) versus the minimal treatment. The lack of a centre line (T5: No centre 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

Table 1: 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	Short-term effect, incl. driving style and practice	Long-term effect	Long-term effect, incl. driving style and practice
Intercept	33.795 (<0.001)***	33.701 (<0.001)***	33.395 (<0.001)***	33.439 (<0.001)***
Treatment specific effects				
T1: Side-marking	−1.073 (0.117)	−1.073 (0.117)	−0.434 (0.477)	−0.434 (0.477)
T2: Bicycle-lane	−0.133 (0.845)	−0.133 (0.845)	−0.187 (0.759)	−0.187 (0.759)
T3: Wide median	1.046 (0.126)	1.046 (0.126)	0.858 (0.161)	0.858 (0.161)
T4: On-street parking	−0.501 (0.463)	−0.501 (0.463)	−0.241 (0.693)	−0.241 (0.693)
T5: No centre line	−1.304 (0.057)+	−1.304 (0.057)+	0.020 (0.974)	0.020 (0.974)
T6: Greenery	−1.517 (0.027)*	−1.517 (0.027)*	−1.262 (0.039)*	−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	378	378
N (subjects)	54	54	54	54
R2 (conditional)	0.34	0.35	0.32	0.33
R2 (marginal)	0.04	0.09	0.02	0.07
AIC	2113.547	2110.890	2029.970	2024.955

speed 1.0 km/h (p=-0.126)

3.4 Desired & safe driving speed

We follow a similar approach to analyse the results of the survey conducted after the VR experiment.

In this survey, 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 wheter a treatment was complex (1=easy, 5=complex) and whether a treatment was safe (1=safe, 5=unsafe). Different than the driving simulator experiment, the images shown in the survey did not include signalisation (see Figure 2)

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. Model estimations revealed that complexity was best to be included as main effect. Safety is included as interaction with the treatment.

Model results are presented in Table 2. Starting with the model 'Desired speed', we find that participants, on average, state their desired speed to be 44 km/h (intercept). When a bike lane is present, participants desire to drive faster by 4.9 km/h. On other hand, when a wide median is present, participants prefer a lower speed (-4 km/h). On-street parking results in the lowest preferred speed: participant state, on average, that they desire 11 km/h slower. Participants who prefer to speed, driver 2.8 km/h faster on average. Continuing with the model 'Safe speed', we find that individuals consider a lower speed to be safer. As indicated by the intercept, participants consider 41 km/h to be a safe speed. Other than that, we find similar effects for the treatments as for the model 'Desired speed'.

If we include effects for complexity and safety, we find slightly different effects for models explained the desired driving speed and the safe driving speed. Overall the desired speed is lower along treatments that are perceived as complex (1.6 km/h). Moreover, the moderating effect of on-street parking can be explained by the fact that on-street is perceived as unsafe. Also, we find that participants who consider a lacking centre line (T5: No centre line) to be unsafe, desire to drive slower than participants in general. A similar effect can be found for greenery. Continuing with 'safe speed' we find that participants prefer to drive faster if a side-marking is present, but that this effect is moderated by the safety perception. A similar effect can be observed for the lack of a centre line and the presence of greenery.

Including interaction effects for the different treatments results in an increased model fit. Marginal R^2 (R^2 for the fixed effects) results in improvement of 0.26 to 0.35 (desired speed) and 0.17 to 0.3 (safe speed).

Table 2: Desired and safe speed: model estimation results

	Desired speed	Desired speed, incl. complexity & safety	Safe speed	Safe speed, incl. complexity & safety
Intercept	44.329 (<0.001)***	48.383 (<0.001)***	41.278 (<0.001)***	42.252 (<0.001)***
Treatment specific effects				
T1: Side-marking	−0.148 (0.919)	1.619 (0.545)	1.907 (0.207)	6.747 (0.015)*
T2: Bicycle-lane	4.907 (<0.001)***	8.225 (0.001)**	6.926 (<0.001)***	14.309 (<0.001)***
T3: Wide median	−4.037 (0.006)**	−3.028 (0.261)	−1.500 (0.320)	2.172 (0.432)
T4: On-street parking	−11.222 (<0.001)***	−0.982 (0.803)	−8.093 (<0.001)***	3.302 (0.417)
T5: No centre line	−2.130 (0.147)	7.784 (0.006)**	−0.685 (0.650)	11.092 (<0.001)***
T6: Greenery	1.296 (0.376)	5.798 (0.037)*	1.944 (0.198)	12.594 (<0.001)***
Driving style and practice				
Sensation seeking	2.845 (0.019)*		0.444 (0.791)	
Complexity and safety				
Complexity		−1.612 (0.003)**		−0.429 (0.468)
T1: Side-marking (safe -> unsafe)		−1.013 (0.367)		−2.444 (0.036)*
T2: Bicycle lane (safe -> unsafe)		−1.688 (0.114)		−3.699 (<0.001)***
T3: Wide centrelane marking (safe -> unsafe)		−0.191 (0.852)		−1.521 (0.151)
T4: Parking (safe -> unsafe)		−2.053 (0.046)*		−2.830 (0.008)**
T5: No centre line (safe -> unsafe)		−3.810 (<0.001)***		−4.670 (<0.001)***
T6: Greenery (safe -> unsafe)		−2.234 (0.055)+		−5.192 (<0.001)***
N	378	378	378	378
N (subjects)	54	54	54	54
R2 (conditional)	0.36	0.43	0.41	0.48
R2 (marginal)	0.26	0.35	0.17	0.30
AIC	2642.690	2597.499	2695.538	2636.640

4 Discussion & conclusions

The paper at hand investigated driving speed on urban roads. To this end, we conducted a driving simulator experiment and subsequently conducted a survey on desired and safe speeds. Based on the driving simulator experiment we find small differences between treatments. Most notably, we find that introducing greenery & benches results in lower driving speeds. Other design elements not necessarily result in a reduction of driving speed. The survey including images of the same treatments, without posted speed limits, does yield clear differences between treatments for the indicators 'desired speed' and 'safe speed'. Nevertheless, individuals, on average, state that they prefer to drive 44 km/h per hour, well above the desired 30 km/h in urban centres. Only the introduction of on-street parking results in a reduction of speed towards 30 km/h.

Most of these 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.

Individuals who prefer to speed ('sensation-seeking individuals'), overall, prefer to drive faster (between 1.5 and 3 km/h). Interventions targeting these individuals can result in a similar reduction of speed. Such interventions can include sticks (e.g. speed cameras, fines) but could also positively reward behaviour (e.g. displays). It should be pointed out, that 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.

We recommend to investigate further combinations of treatments. Most promising are treatments that influence the peripheral vision (e.g. trees, parking) as well as reduce the (perceived) lane width.

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