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New ways for roadway design – Using driving simulation to restructure the Finkenwerder Ring in the Port of Hamburg aiming at enhanced traffic safety and reliability

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Abstract

The „Finkenwerder Ring“ is an important traffic junction in the Port of Hamburg – however, a lot of accidents per year impair traffic safety and reliability. The current traffic management, the signage, and the high number of lanes might be causal for the many crashes. Therefore, a requirements analysis was conducted to investigate the current traffic situation of the Finkenwerder Ring. Based on these results possible countermeasures were identified and subsequently implemented in a reproduction of the Finkenwerder Ring in a driving simulation. Four variations of the Finkenwerder Ring were realized which differ in signage and roadway geometry and were evaluated in a driving simulator study with N=30 participants. Even a small implementation like a modification of signage is able to have positive effects on drivers' evaluations. However, a quite expensive and complex solution (the separation of traffic streams via an additional traffic light) shows the largest effect. These results show the benefit of driving simulation as a tool for roadway design.

Keywords: road safety, reliability, roadway design, driving simulation.

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1. Introduction

1.1. Background

The Port of Hamburg is one of the most important hubs of international trade within Europe. The road network within the port area is a significant part of many logistical chains as it connects terminals with different companies and highways. Additionally, it is part of the daily commutes of many car drivers. A central requirement for traffic infrastructure is to ensure a continuous accessibility for all port operations. Therefore, it is necessary to reduce negative impacts of road traffic and to provide traffic safety and reliability.

The Finkenwerder Ring is a central traffic junction in the western port area connecting container terminals, the Autobahn, and surrounding areas. Therefore, it has important traffic significance and consists of several intersections and roads with up to six lanes in one direction. The Finkenwerder Ring has four entrances and four exits directed to North, East, South, and West. Prior to the eastern entrance, the traffic streams from Autobahn and city merge. Prior to the western entrance, the traffic streams from northwest and southwest merge (Fig. 1).

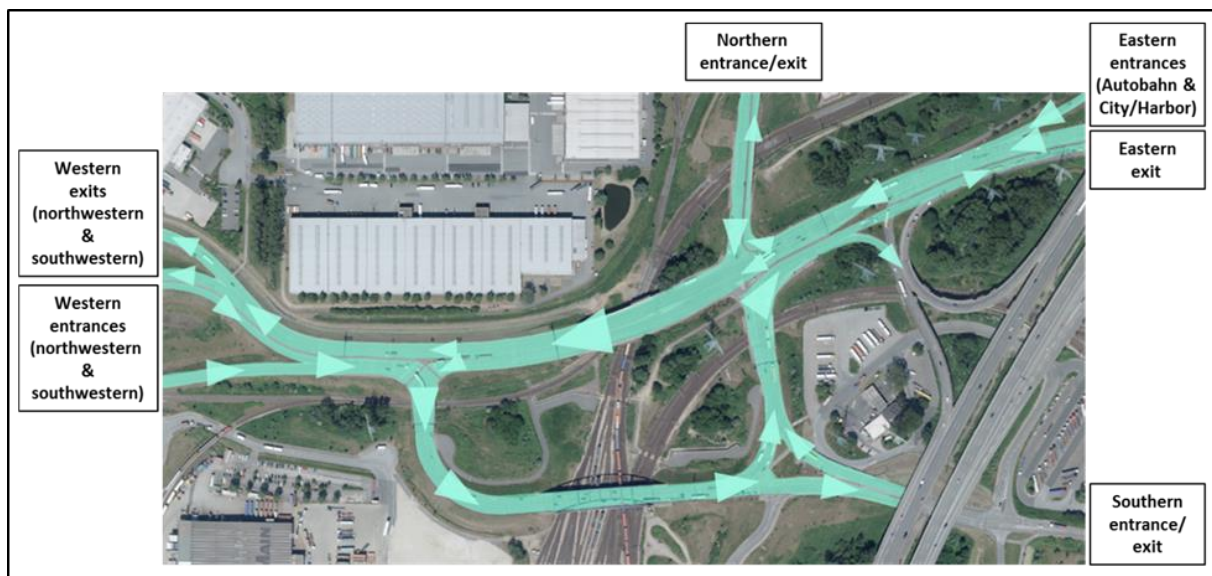


Fig. 1 The Finkenwerder Ring and its entrances and exits. Arrows indicate the driving directions (source of aerial photograph: Landesbetrieb Geoinformation und Vermessung (LGV) Hamburg)

In total, approximately 50.000 vehicles use the Finkenwerder Ring on each working day. The high percentage of trucks in this area (around 27%) is a special characteristic. In the last years, a huge number of crashes was registered by the police (around 200-250 per year). Though the number of accidents with personal injuries is low, the crashes cause damages as well as long-lasting congestions on various adjacent roads. These accidents are scattered across the whole Finkenwerder Ring. According to accident reports of the police, faulty lane change behavior is the main reason for these crashes, making up almost 70%. Furthermore, a truck is involved in more than 70% of the accidents.

The current traffic guidance, the signage, the high number of traffic lanes, and the huge percentage of trucks are factors which complicate driving in this area and might be causal for the high number of crashes – especially for drivers who use the Finkenwerder Ring for the first time.

1.2. Project overview

Due to the high number of accidents, the Wuerzburg Institute for Traffic Sciences (WIVW GmbH) as contractor and the Hamburg Port Authority (HPA) as client collaborated on a research project which aimed to improve the traffic situation by identifying improvement opportunities for traffic guidance and signage. First, a comprehensive requirement analysis was conducted by investigating the current traffic situation of the Finkenwerder Ring. Three studies were carried out to view the situation from different perspectives:

- (1) an **interview study** provided the perspective of frequent users of the Finkenwerder Ring
- (2) a **real driving study** provided the view of first-time users of the Finkenwerder Ring
- (3) a **traffic observation** by helicopter from bird's eye perspective allowed a more holistic view on the Finkenwerder Ring and was used to analyze the whole traffic system concerning traffic flow

All three approaches yield results that are consistent: Sections in which two traffic streams merge are highly problematic. Besides, the high number of lanes and traffic signs are problematic as these factors enhance complexity and make drivers' orientation more difficult (Muehlbacher et al., 2017).

In a further step, countermeasures were developed which should facilitate driving on the Finkenwerder Ring and which should decrease the number of accidents. The countermeasures should represent solutions with different implementation efforts (i.e., quick measures and complex measures). Afterwards, these countermeasures were evaluated in the driving simulation.

2. Driving simulation

2.1. Driving simulation as a research tool

By means of a driving simulation, a participant steers a virtual vehicle in a simulated environment. Driving simulations exist in various levels: In smaller driving simulations the participant controls the vehicle via a joystick in a simulated environment which is presented on a screen. More complex driving simulations feature a motion system which realizes a more realistic presentation of driving dynamics. All driving simulations consist of one or more screens to display the scenery, a mockup to control the vehicle, a sound system to deliver noises, and a dashboard (Carsten & Jamson, 2011).

The popularity of driving simulation is founded on several reasons: The opportunity to create a scenery tailored to the research question is one benefit of driving simulation. Therefore, confounding variables like varying traffic or weather conditions can be controlled or eliminated and the relationship between cause and effect can be identified clearly. Additionally, events which rarely occur in real traffic (like the presence of emergency vehicles or deer on the road) can be analyzed. Furthermore, there are fewer legal or ethical restrictions compared to studies in real traffic. Research has shown that behavior in a driving simulation approximates, but does not exactly replicate driving behavior on a real road. Therefore, relative validity exists instead of absolute validity (Mullen et al., 2011; Törnros, 1998).

On the other hand, driving simulation studies are performed in a laboratory which leads to limitations: Effects like reactivity or demand effects may constrain the external validity of driving simulation studies. Furthermore, simulator sickness can influence the validity as symptoms like headache, sweating, or eye strain might affect a driver's performance negatively (Stoner et al., 2011).

In most cases, the main focus of research using driving simulations is drivers' behavior and perception. For example, a lot of studies deal with driver distraction, driver fatigue, or the evaluation of driver assistance systems. In the last years, driving simulation was also used successfully to investigate traffic infrastructure. Examples are studies concerning the effectiveness of traffic signs (Chrysler & Nelson, 2011), the benefit of rumble strips (Vienne et al., 2014), the effect of roadside planting (Lippold et al., 2006), or the comparison of roadway designs (Bella, 2009; Granda et al., 2011). For these purposes, the benefit of driving simulation is the opportunity to create unique and non-existent roadway geometries and roadway environments.

2.2. Description of the used driving simulator

The study took place in a static driving simulator of the WIVW GmbH. In this simulator, a complete Opel Insignia is used as mockup (Fig. 2). The simulator has a 300° horizontal field of view with five image channels, each one with a resolution of 1400x1050 pixels. In addition, two LCD-displays represent the outside mirrors. A flat screen in the rear of the vehicle shows the scenery behind the vehicle if the driver uses the inside mirror. Two LCD-displays with a resolution of 1024x768 pixels are used as navigation system and speedometer.

Audible output is presented by a 5.1 Dolby Surround System. The update frequency is 120 Hz. The simulator runs with the driving simulation software SILAB. During the experimental trials, the experimenter observes all driver views on separate display screens and communicates with the participants via intercom.

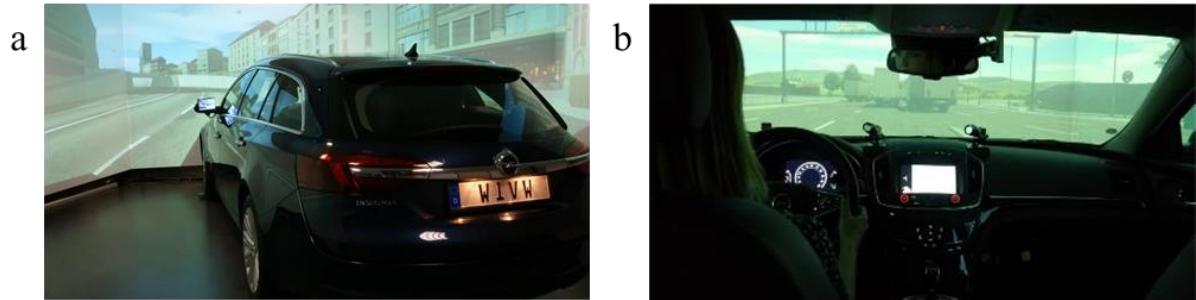


Fig. 2 (a) driving simulator mockup; (b) inside of the mockup

2.3. Realization of the Finkenwerder Ring in the driving simulation

The current status of the Finkenwerder Ring was implemented comprehensively in the driving simulation (Fig. 3). For this purpose, the following factors were considered: road geometry, buildings and constructions, road markings, road signage, traffic light circles, navigation system (voice announcements and visual layout). Traffic density and composition (i.e., distribution of trucks and cars) were defined according to the observed data of the traffic observation by helicopter. A preliminary study compared driving in the real and in the simulated Finkenwerder Ring and verified the validity of the driving simulation.

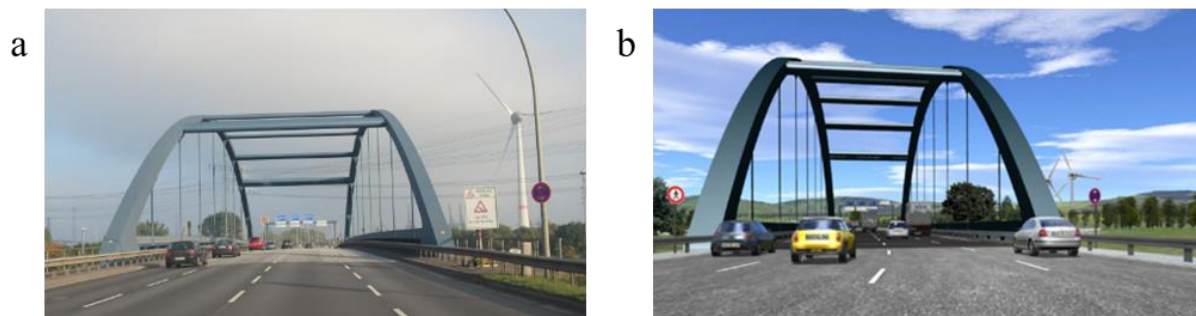


Fig. 3 (a) road segment in reality; (b) road segment in driving simulation

3. Variations of the Finkenwerder Ring

Based on the results of the preceding requirements analysis (Muehlbacher et al., 2017), three additional variations of the Finkenwerder Ring were realized:

- (1) Variation 1 (new signage): This variation consists of the current roadway geometry with a modified design of the signage. While the current signage uses one sign for each location (Fig. 4 (a)), in the modified signage several locations are clustered on one sign. (Fig. 4 (b)).

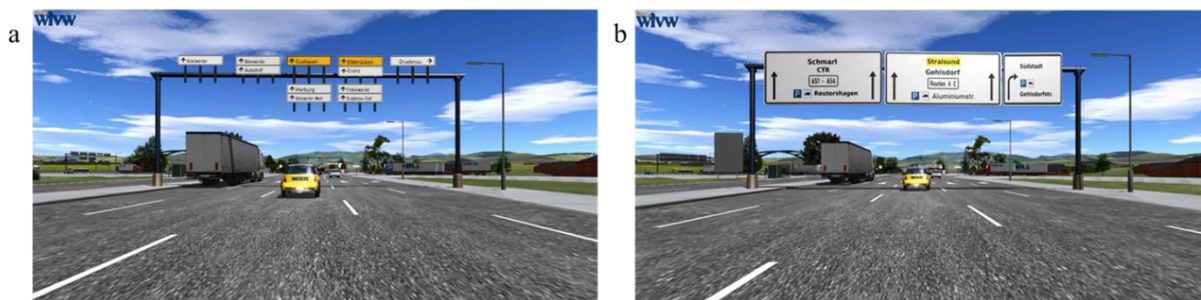


Fig. 4 (a) current status of signage; (b) clustered signage

- (2) Variation 2 (quick measures): Besides the new signage of variation 1, this variation comprises measures which can be implemented quickly. Examples are additional road markings and lane closings.
- (3) Variation 3 (complex measures): Besides the new signage of variation 1 and the quick measures of variation 2, this variation comprises measures which need high effort to be implemented. Examples are structural separations of lanes and additional traffic lights.

Table 1 gives an overview of the different variations compared to the current status.

Table 1. Overview of the current status of the Finkenwerder Ring and the variations

	signage		roadway geometry		
	current	modified	current	quick measures	complex measures
current status	x		x		
variation 1		x	x		
variation 2		x		x	
variation 3		x			x

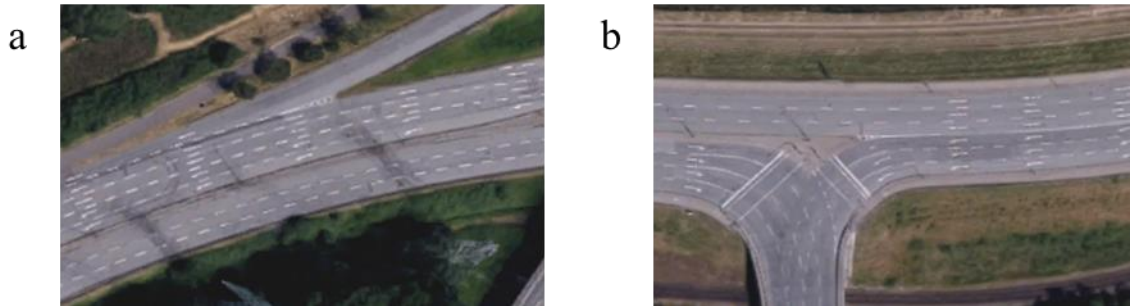


Fig. 5 (a) section 1 with the Autobahn exit coming from the upper part of the picture; (b) section 2 with six lanes coming from the right part of the picture

In the following, variations 2 and 3 are presented by using the example of two locations of the Finkenwerder Ring.

Section 1 (Fig. 5 (a)) represents a merging situation: an exit from the Autobahn encounters a four-lane road. The lane coming from the Autobahn becomes the fifth lane and forks right after 200m at an intersection, while the other lanes are directed straight ahead. A lot of accidents occur at this situation as vehicles are changing lanes from the right to the left, while other vehicles change from the four-lane road to the right as they want to turn right at the following intersection. Additionally, many vehicles approaching from the Autobahn exit are driving too fast.

Therefore, a measure could be to separate the two traffic streams via a traffic light. In consequence, either the vehicles from the Autobahn exit or from the four-lane road can approach the intersection. This measure was realized in variation 3. In contrast, variation 2 shows no intervention (Table 2 on the left).

Section 2 (Fig. 5 (b)) is located on the northern passage. In the current status, a one-way street with six lanes approaches an intersection. At the intersection, three lanes are directed straight and three lanes turn left. This situation leads to a lot of lane changes which are causal for accidents. Furthermore, some drivers are overstrained with driving on these six lanes.

A quick intervention is to close the left lane – this measure was implemented in variation 2. As consequence, there are five lanes left instead of six which could facilitate driving in this section. According to the traffic observation the efficiency of the junction will probably not be negatively influenced because the lane is used by a very small number of vehicles. An additional separation of the lanes via guide barriers is a more complex measure with higher effort. This intervention was realized in variation 3 (Table 2 on the right).

The variations of the Finkenwerder Ring were realized in the driving simulation. Comparable to the creation of the current status of the Finkenwerder Ring factors like signage, building, traffic density, or traffic composition were considered.

Table 2. Screenshots demonstrating the different measures concerning road geometry for the current status and the three variations on the two exemplary situations

	section 1: merging	section 2: northern passage
current status (current signage) variation 1 (modified signage)		
variation 2		
variation 3		

4. Study procedure

4.1. Study plan and participants' task

The study aimed at comparing the current status of the Finkenwerder Ring with the three variations. Therefore, a repeated measures design was chosen in which the participants got to know all variations.

The participants had to complete four test blocks. Each block represented one variation of the Finkenwerder Ring and consisted of six routes each in the simulated environment. The participants' task was to travel to a destination which was given by the experimenter prior to the run. The routes had specific difficulties and challenges.

An example for a route is shown in Fig. 6. The participants start at the Autobahn and merge on a four-lane road. Then, they have to pass the northern passage and turn left to drive on the southern part of the Finkenwerder Ring. At the next intersection, the participants have to leave the Finkenwerder Ring at the southern exit to reach the given destination.

The participants completed the four blocks with different variations in counterbalanced order. So, possible confounding influences as learning effects or fatigue were controlled. Furthermore, the six routes within a block were also performed in counterbalanced order.



Fig. 6 Route from the Autobahn to the southern exit of the Finkenwerder Ring

4.2. Dependent variables

A large number of dependent variables were collected. These can be grouped into subjective measures, performance measures, and driving behavior.

The subjective measures comprise of a short inquiry directly after each run, a block inquiry after each block, and a final inquiry at the end of the session. All inquiries addressed various aspects like task difficulty, workload, or evaluation of surrounding traffic.

The performance measures included if the participants absolved the route successfully, i.e. if they reached the predetermined destination or if they took a wrong turn. Furthermore, the experimenter coded the following driving errors during the run:

- safety-critical lane changes: a lane-change which causes a near accident.
- unnecessary braking: e.g., braking in front of signage to orientate themselves.
- solid line crossing: at some parts of the Finkenwerder Ring the lanes are separated by solid lines to avert lane changes at this point. A crossing of these lanes is rated as a driving error.

Furthermore, the simulation software SILAB recorded all parameters of vehicle handling (e.g., usage of gas and brake pedal, steering wheel angle) and of the vehicle model (e.g., velocity, longitudinal acceleration).

4.3. Sample

$N = 30$ participants (14 women and 16 men) between 25 and 65 years of age ($M = 44.9$; $SD = 11.0$) took part in this study. The participants were recruited via the test driver panel of the WIVW. Prior to the study, all participants were trained with the driving simulator (based on Hoffmann and Buld, 2006) in order to introduce them to the simulator and to reduce the probability of simulator sickness. The participants were paid for taking part in the study.

5. Results

On one hand, the study yields results concerning single routes (e.g., data from the short inquiry directly after each run or driving behavior). On the other, some results are more general (e.g., data from the block inquiry or the final inquiry). The next chapter provides several results exemplarily for the route shown in Fig. 6. Afterwards, some more general results are given.

A Cochran's-Q-Test was used to test differences between the four variations for dichotomous dependent variables; in contrast, a repeated measures ANOVA was used for interval-scaled variables.

5.1. Route-specific results

With the current status, $n = 4$ drivers do not reach the destination as they make wrong turns during the route. With variation 1 and variation 2 this number is not lower ($n = 6$ and $n = 4$). Most participants reach the destination with variation 3 as here only $n = 2$ drivers take a wrong turn. However, the differences between the variations do not reach statistical significance (Cochran's-Q-Test, $\chi^2(3) = 2.82$; $p = .42$).

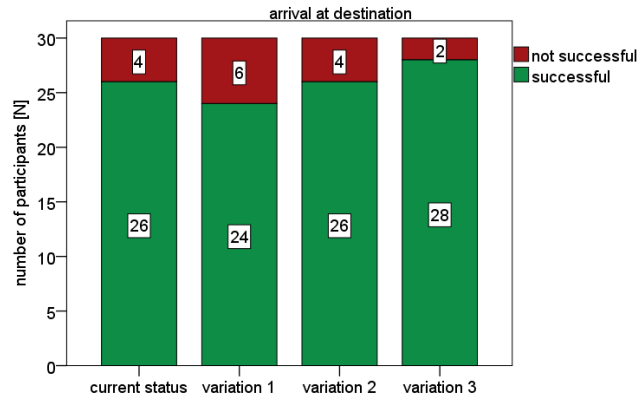


Fig. 7 Number of participants who reached or did not reach the predetermined destination

The participants evaluate variation 3 as most positive: Compared to the other variations, drivers rate it as less difficult to reach the destination (Repeated measures ANOVA, $F(3, 48) = 3.50$; $p = .02$; see Fig. 8 (a)); furthermore, they rate driving as less impaired by surrounding traffic (Repeated measures ANOVA, $F(3, 48) = 7.84$; $p < .01$; see Fig. 8 (b)) than in the other variations.

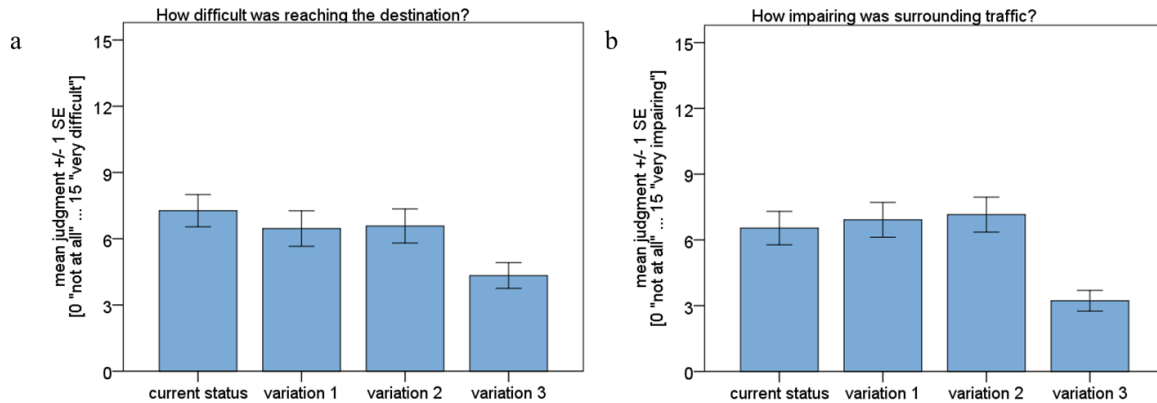


Fig. 8 Subjective judgments concerning (a) task difficulty and (b) impairment by surrounding traffic

As most accidents occur when vehicles change lanes, the number of lane changes was assessed. On average, the number of lane changes varies between 2.5 and 3 per participant and is not affected by the variation (Repeated measures ANOVA, $F(3, 48) = 1.81$; $p = .16$; see Fig. 9 (a)). However, the variation has an influence on the location of lane changes: Compared to the current status and variation 1, the drivers perform more lane changes prior to the Finkenwerder Ring (i.e., between Autobahn exit and first intersection) and perform less lane changes within the Finkenwerder Ring with variation 2 and variation 3 (Repeated measures ANOVA, $F(3, 78) = 11.33$; $p < .01$; see Fig. 9 (b)).

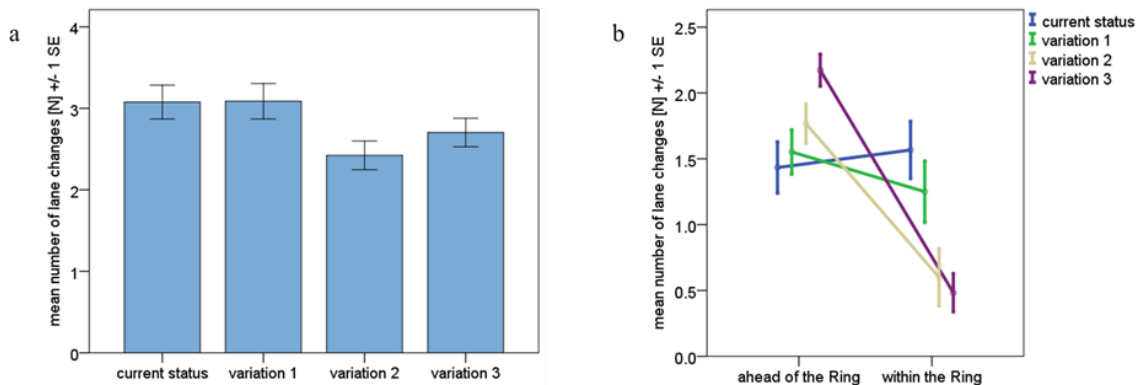


Fig. 9 (a) mean number of lane changes on the whole run; (b) mean number of lane changes for the two sections

However, the number of lane changes is no indicator for traffic safety when the lane changes are performed in a safe way. Therefore, only the number of safety-critical lane changes was assessed. Besides, unnecessary braking and solid line crossings were recorded as further driving errors. The least driving errors occur with variation 3, while most driving errors are conducted with current status and variation 2 (Repeated measures ANOVA, $F(3, 87) = 3.13$; $p = .03$; see Fig. 10 (a)).

To evaluate the variations' effect on driving behavior, drivers' velocity was analyzed. As example the maximum velocity on the southern part of the Finkenwerder Ring is shown in Fig. 10 (b). The maximum value was used as it is crucial for traffic offences. With variation 2 and variation 3, drivers are faster on this part compared to the current status and variation 1 (Repeated measures ANOVA, $F(3, 51) = 4.38$; $p < .01$). Furthermore, they are faster than the speed limit of 60 km/h.

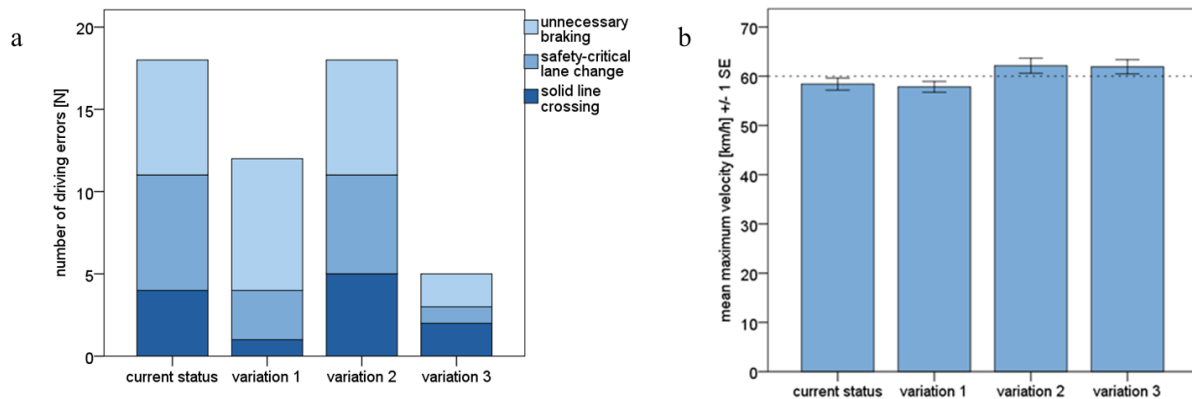


Fig. 10 (a) number of driving errors; (b) maximum velocities on the southern part of the Finkenwerder Ring

5.2. General results

After the whole session, the experimenter asked the participants which signage design (current or modified) is clearer and more appropriate for driving in the Finkenwerder Ring. 66% of the drivers prefer the modified version and 34% favor the current signage design.

Furthermore, after each block with six routes the drivers had to rate workload in the previous block. According to the participants, driving in variation 2 and 3 is rated as least strenuous (Repeated measures ANOVA, $F(3, 87) = 3.66$; $p = .02$) while the other blocks do not differ regarding workload (Fig. 11).

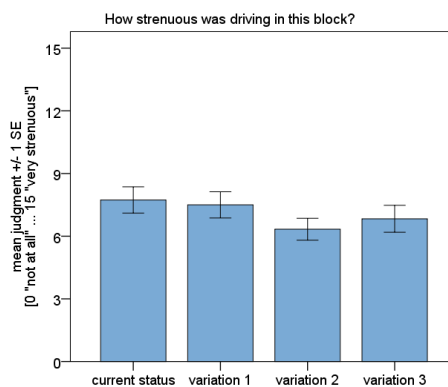


Fig. 11 Subjective judgments concerning workload

6. Discussion

The presented study aims at comparing different infrastructural measures which should enhance road safety and reliability of the Finkenwerder Ring in the Port of Hamburg. For this purpose, the current status of the Finkenwerder Ring was implemented in a driving simulation. Furthermore, three variations of the Finkenwerder

Ring ranging from a redesign of signage to complex measures were developed and also realized in the driving simulation. These variations were compared in a participant study.

The results show that small implementations are able to have positive effects on drivers' evaluations (e.g., a modification of the signage). However, the strongest effect was demonstrated for complex measures: In the Finkenwerder Ring, a merging situation is one of the accident blackspots. Only a quite expensive and complex solution – the separation of traffic streams via an additional traffic light – could show clear and positive effects.

However, the results also point out that participants are driving faster with decreasing perceived complexity and difficulty. These results are consistent with the risk homeostasis theory (Wilde, 1982) which indicates that drivers compensate higher perceived driving safety (e.g., via seat belts or air bags) by taking more risk. When realizing infrastructural countermeasures which facilitate driving and enhance safety this effect has to be considered.

This study shows the benefit of using driving simulation as a tool for roadway design. The opportunity to create unique and non-existent roadway environments and to evaluate these implementations in a participant study are advantages which are not present in other research methods. Of course, an evaluation on real roads is theoretically possible - however, these studies are much more expensive and such experiments might be dangerous for the participants.

Therefore, a driving simulator study is able to evaluate the comprehensibility and safety of non-existing roadway designs from drivers' perspective. However, it is difficult to make statements concerning the whole traffic system with a driving simulator study. Therefore, the measures which are recommended by a driving simulator study should be implemented in a traffic engineering study which uses, e.g., a traffic simulation to demonstrate the effects of infrastructural measures on traffic efficiency. Such a combination of research tools would be a highly beneficial method for planning new roadway design in order to increase the reliability of traffic infrastructure by reducing accidents proactively.

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