

PROACTIVE EVALUATION OF TRAFFIC SIGNS USING A TRAFFIC SIGN SIMULATOR

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ABSTRACT

Traffic signs and pavement markings are a crucial aspect of road design since they are essential sources of information for road users to calibrate their driving behavior, evaluate route possibilities and cope with unexpected events. A proactive evaluation of (the quality of) these road design elements will help to improve the safety performance of the roadway. This paper presents the Traffic Sign Simulator, an innovative research tool to study the influence of these elements on road users' routing decisions, lane choice and visual behavior, to investigate road users' comprehension of these signs, and to collect suggestions for improvements.

Using a driving simulator mock-up, participants navigate through a full HD video from route(s) in which the planned traffic signs have been digitally implemented using specialized software for camera-tracking and 3D video-integration. Participants' route and lane choice and their visual behavior (using eye-tracking) are monitored while driving through the scenario(s). Laptop pre- and post-tests are applied to collect additional in-depth information concerning the participants' processing, comprehension and general evaluation of the traffic signs and suggestions for improvement.

The paper illustrates the possibilities of the Traffic Sign Simulator with a case study that examined the effectiveness of temporary work zone signalization (i.e., traffic signs, digital information panels and pavement markings) as it was used during the reconstruction works on the Vilvoorde fly-over near Brussels, one of the busiest interchanges in the Belgian motorway network.

Keywords: Proactive evaluation, ex-ante evaluation, traffic signs and pavement markings, Traffic Sign Simulator, work zones, detour

INTRODUCTION

Road crashes and casualties lead to high physical, psychological, material and economic costs. Measures to improve road safety have mainly focused on reducing the number of serious crashes at existing locations. However, a shift towards a more proactive approach is needed in order to further improve road safety. This proactive approach is the core element of the ‘Sustainable Safety’ principle which aims to prevent (serious) crashes and injuries by applying intrinsic safe road design which takes human’s limited capabilities into account, as opposed to traditional reactive approaches that aim to solve problems after they establish themselves on field, such as black spot treatments (1). The importance of a shift towards more proactive road safety planning is acknowledged by several other policy documents as well (e.g. (2–4)). Also safety researchers and policy makers in other fields such as aviation (e.g. (5)), health care (e.g. (6)), and the petrochemical industry (e.g. (7)) are highly aware of the importance of proactively preventing crashes from happening.

Traffic signs and pavement markings are crucial aspect of road design since they are one of the main information sources for the road user to calibrate driving behavior, to evaluate route possibilities and to cope with unexpected events (8–11). Research shows that the inappropriate positioning of traffic signs leads to higher reaction times and detection errors (12). Therefore, traffic signs and pavement markings are an important safety element in the road environment. A proactive evaluation of (the quality of) these road design elements will help to improve the safety performance of the road design. The Traffic Sign Simulator presented in this paper is a tool that has been developed for this specific purpose.

BACKGROUND

Before describing the effectiveness of traffic signs and providing an overview of already existing research methods to investigate traffic sign effectiveness, we will define what the term ‘traffic sign’ refers to in this paper.

According to the Manual on Uniform Traffic Control Devices (MUTCD) (9), “traffic control devices notify road users of regulations and provide warning and guidance needed for the uniform and efficient operation of all elements of the traffic stream in a manner intended to minimize the occurrences of crashes”. The manual describes guidelines for signs, markings and traffic signals, which are thus included in the concept ‘traffic control device’. Castro and Horberry (8) on the other hand use a wider definition of ‘traffic signs’ that was proposed by the International Commission of Illumination (13) and U.K. Department of Transport (14). They define ‘traffic signs’ as “an integral part of the road environment that can include not only upright signs giving warnings and instructions to traffic, speed limits, directions and other information, but also road markings, traffic light signals, motorway matrix signals, zebra and pedestrian crossings, cones and cylinders used at road works and variable message signs”. In this paper, the term ‘traffic sign’ is used in the wider sense to describe all traffic control devices listed above.

The effectiveness of traffic signs according to Castro and Horberry (8) is dependent upon four processes: (a) sign detection (b) sign readability, (c) sign comprehension and (d) sign-induced action. The road user should be able to successfully pass through these four stages if the traffic sign is correctly designed and positioned. The design standards for signs contain a variety of requirements and are indicated by the picture below (figure 1). This list of requirements is not exhaustive. For instance Gartner et al. (15) add the signal value (i.e. the value of the sign for a road user), the coding system and the information processing capabilities as well as the educational background of the road users to the information processing of traffic signs.

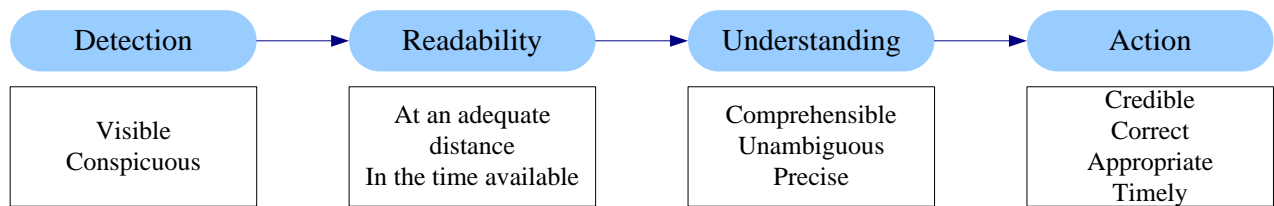


FIGURE 1 Four stages of traffic sign perception and their requirements (8).

Since the development of uniform standards for traffic signs around the thirties, various studies have been carried out to investigate ways to design traffic signs more effectively and better tuned to road users' information processing capabilities. A number of existing research tools or techniques can be distinguished. We briefly discuss them below.

Paper-and-Pencil Method

The most basic technique is the paper-and-pencil method. For the evaluation of planned traffic signs in practice, this method implies that a hard copy or a digital copy of for instance a temporary traffic control plan is shown to a number of people who were not involved in the development of the plan. They are asked to note their considerations and recommendations for improvement. These people can be either professionals or laymen. Ideally, both are questioned, since they can provide interesting feedback from a different point of view.

The most important disadvantage of the technique is that it requires a lot of imagination to mentally picture the real-life layout of the plan. These mental images can differ between respondents, they may contain errors and some information could be lacking, resulting in biased and/or incomplete input. Experts, on the other hand, can only try to predict the performance of drivers, instead of monitoring their actual performance while navigating through the design (16). Therefore, sign detection, readability and understanding can only be evaluated indirectly, and behavioral responses cannot be empirically assessed.

Laptop Tests

In studies using laptop tests, participants are exposed to pictures and/or videos about road environments containing traffic signs, or to general questions about traffic sign position, understandability, readability, etc. Laptop testing is a flexible and low-cost tool to execute a wide range of traffic sign assessments, going from very practical questions about particular situations to more fundamental research questions relating to visibility, conspicuity, understandability and (stated) behavior. For example, Borrowsky et al. (17,18) use a series of pictures of road scenes in laptop tests to link traffic sign location to driver expectancy (17) and driver experience (18). Crundall and Underwood (19) use comparable techniques to analyze the priming function of road signs. An important drawback is the limited dynamics and realism of the situations, which can lead to some biases introduced by the information provided by the researcher to the participant, and to incomplete input from the participant.

Eye Movement Studies

Eye movement studies make use of an eye-tracker to monitor drivers' visual (search) behavior in order to analyze what signs drivers look at, for how long, and in which order. The main advantage of eye tracking is that it is a direct and objective measure for sign detection since eye movements are relatively involuntary and free from bias due to instructions (10). A disadvantage is that eye fixations do not guarantee that the object is internally processed (the common 'look but fail to see' error (20)), and, vice versa, that even without a fixation an object can still be perceived and/or

interpreted. This also appears from the model by Castro and Horberry (8), where it is indicated that detection is only the first step. Eye movement studies are mostly used in combination with other research tools, such as driving simulators or instrumented vehicles.

Field Experiments

In field experiments, the researcher can either make use of the existing road environment to do an on-field data collection, or a real life test layout can be implemented.

Field experiments – public road

On-road testing is highly realistic, but has some important drawbacks as well. Methodologically, the experimenter has only limited control, and ethically, the safety of study participants and other road users might be compromised, especially when being exposed to complex test situations.

The data can be collected in three ways, i.e., on-site observation, in-vehicle observation with trained observers on board, and by means of an instrumented vehicle (i.e., so-called ‘naturalistic driving studies’).

On-site observations about the impact of traffic signs collect generic observable characteristics of the vehicles passing a certain location. For instance, Erke et al. (21) examine the effects of different messages for route guidance on Variable Message Signs (VMS) using route choice, driving speed and braking behavior. Gates et al. (22) study the impact of various sign conspicuity enhancements using traffic operations data, such as vehicle speeds, edge line encroachments and stopping compliance. Important advantages of on-site observations are the non-intrusive nature of the data collection (road users are generally unaware of being monitored) and the large sample size (i.e. all vehicles passing the study location). The main shortcoming is that only parameters describing the revealed behavior can be collected, while factors inducing the behavior cannot be identified.

In studies that apply in-vehicle observations, participants drive a normal car while accompanied by one or more trained observers. The participants’ driving behavior is monitored by the observer(s) using a number of observable qualitative or quantitative indicators. An advantage is that more detailed driver behavior data can be collected than in on-site observations. An important drawback is that the presence of the observer(s) can lead to some test biases, for instance showing more socially desirable behavior. Inter- and intracoder reliability issues may also reduce the reliability of the data collection. Furthermore, these observation techniques generally provide little insight in factors leading to the performed behavior. Alternatively (or additionally), participants can be asked to verbally report on certain aspects of traffic signs they pass. Verbal reports have the advantage that they may provide some information about the internal processes of participants that play a role, although participants are likely to omit some information they implicitly use, especially under high mental load (10). In an alternative but related approach by Garvey et al. (23), participants are positioned in the passenger’s seat and are asked to read a traffic sign aloud as soon as the sign is readable.

Finally, we have the instrumented vehicle, i.e., a car equipped with technology that automatically records a number of driving parameters and captures driver behavior on video. This allows a less intrusive data collection because the researcher is not physically present in the vehicle, which can reduce some test biases (24). The collected data from an instrumented vehicle are also much richer and videos can be reviewed multiple times or by multiple researchers to ensure reliability and to increase the number of parameters that can be collected. To the best of our knowledge, no studies have used instrumented vehicles with the specific purpose to assess traffic signs yet, but data collected from running projects such as SHRP2 (25) are expected to be used for this purpose in the future. A major challenge for such projects will be to identify and analyze the

data of interest from the huge data warehouses. Limited control over the experiment can be an important drawback.

Field experiments – test track

It is also possible to implement a real-life test setting on a closed test track (e.g. (26)). An advantage compared to experiments on the public road is that safety can be ensured by the controlled environment. An important disadvantage of the technique is however that the cost of implementing a realistic test track can be very high. There will also be a lack of interaction with other road users, and the driving experience will be more artificial than on the public road.

Driving Simulator Studies

In driving simulator studies, participants sit in a mock-up and navigate through a virtual road environment projected on a screen. Low-level simulators have a fixed mock-up and use one or more computer screens for scenario visualization. High-level simulators on the other hand are more advanced and use a mock-up mounted on a moving base platform and virtual projection on large screens (e.g. 180° to 360°) (27). For evaluating traffic signs, two types of driving simulator studies can be distinguished. Either a virtually simulated road environment is created, or real-life video footage is being used.

Driving simulator – virtual simulation

In these studies, a virtual road environment is created, containing particular scenes of interest with particular traffic signs. The driving simulator logs detailed information about a large number of driving behavior parameters, including speed, acceleration, gear use, lane position, etc., and can be combined with an eye tracker to synchronically log visual behavior. This set up was used by for instance Dutta et al. (28), who explored possibilities to maximize road users' understanding of variable message signs.

Other important advantages are the experimenter being fully in control over the road infrastructure and environment, thereby included the interaction with other (virtual) road users, and the guaranteed safety for road users (29). A major issue is the extent to which behavior in the simulated environment corresponds to participants' actual driving behavior in a real-life environment (27). It must be said however that there is enough research showing that driving simulators generally reach high relative validity (i.e. mutually comparing different scenarios in the driving simulator) (29,30). The realism of a driving simulator scenario can be improved by exactly replicating the scenario from existing road environments (e.g. (30,31)), or from road plans (e.g. (16)). However, even in high-fidelity driving simulators, there are limits to the visual realism that can be offered, which is an important disadvantage compared to on-field studies and applications using video footage. There is also a risk of participant drop-out due to simulator sickness.

Driving simulator – video footage based

Video footage based driving simulations try to create a more realistic driving scene than traditional driving simulator studies that use a virtual road environment. Charlton (32) used such a tool to study conspicuity, memorability, comprehension and priming of a number of different road hazard warning signs. Lai (33,34) used a video footage based driving simulator to analyze the effects of different color schemes and message lines of VMS on driver performance, and to analyze drivers' comprehension of traffic information on graphical route information panels (GRIP).

These driving simulator studies are well-suited to study detection, readability and understanding of signage because the real-life road environment is presented in a more realistic

setting than for instance in a laptop test. Yet, this technique generally does not provide many possibilities to directly study behavioral aspects since there are little possibilities to interact with the video. Put differently, participants are not really controlling their driving through the road scene, and they are therefore not interacting with the road environment. Instead, the driving simulator is mainly used as a more realistic setting to show the video. Another disadvantage is that researchers only have limited control over the experiment because they cannot alter the recorded road environment. Yet, recent improvements in digital image processing allow to integrate virtual objects in a video-taped road environment. Notwithstanding, until so far, research (33,34) using these more advanced techniques has only been focused on minor changes, such as the addition of a particular traffic sign or the replacement of an existing traffic sign by a different one.

TRAFFIC SIGN SIMULATOR – DESIGN AND CASE STUDY

Since all methods have their advantages and drawbacks, it is recommended to combine several research methods when experimentally investigating traffic sign effectiveness (10). The Traffic Sign Simulator described in this paper is an innovative research tool that combines a number of techniques to analyze road users' detection, readability, understanding and behavior in an integrated way.

The core of the research tool is that participants can really operate a simulator mock-up and thus have active control over their driving when being exposed to a real-life full HD video recorded road environment in which a variety of 3D virtual traffic signs (ranging from signs, pavement markings and variable message signs to signs used in work zones and advertisement panels) have been digitally integrated using specialised software for camera-tracking and 3D video-integration. Participants' accelerations and decelerations (e.g., gas and brake pedal), as well as their route and lane choices (e.g., indicator and steering wheel) and their visual behavior (using an eye-tracker) are monitored while navigating through the different scenarios.

In addition to this video-based driving test, laptop pre- and post-tests are used to collect additional information concerning the participants' understanding and general evaluation of the traffic signs, and their suggestions for improvement. As such, this approach ensures that the strengths of different research techniques are fully utilized and combined.

Scenario Production

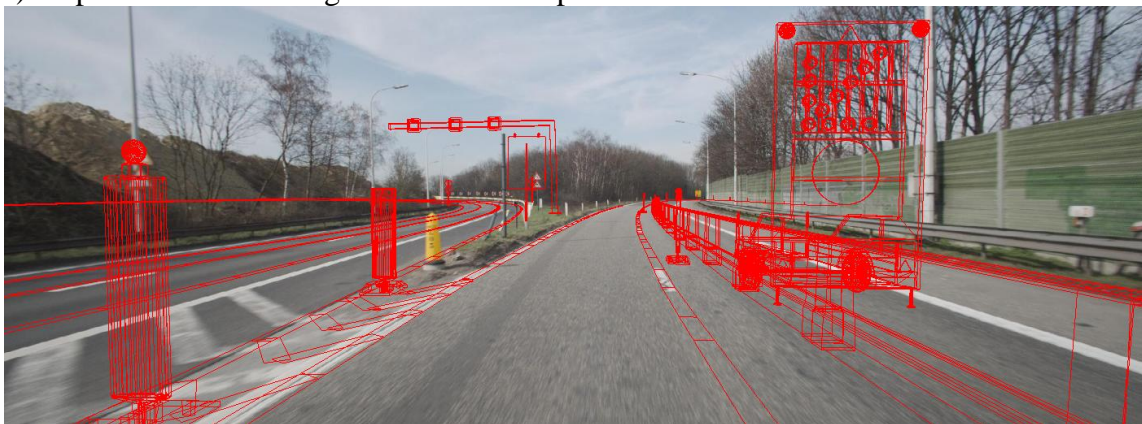
First, the route(s) of interest are filmed using a high-resolution RED-cam camera with a wide-angle lens that allows to collect video footage in full-HD resolution (4096 x 2304 pixels in 16:9 aspect ratio). The camera is mounted on the hood of a minivan, so that the footage is filmed from the viewpoint of a normal car driver. The minivan should drive as much as possible at a constant driving speed. In case the driving speed during recording is lower than the customary driving speed on the route, the number of 'frames per distance' can be improved; the camera films at a constant rate of 25 frames per second, but the distance that is traveled between two frames that are taken by the camera is reduced by recording at a lower speed, which improves the quality of the final scenario film. For safety reasons, it can be recommended to guide the camera van with police cars, for instance when recording at lower speeds on a motorway.



a) Step 1: optimizing image quality



b) Step 2: camera-tracking of 3D reference points



c) Step 3: video-integration of 3D object models



d) Step 4: Rendering and masking: generating 25 photorealistic frames/second.

FIGURE 2 Four-step process to insert signage of interest in video.

Next, the traffic signs of interest are digitally integrated in the video footage by means of an innovative technique using specialized software for camera-tracking and video-integration. In the Vilvoorde case, it means that all planned traffic signs for the project are digitally inserted into the video. This is a semi-automatic process that is done in four steps (see figure 2):

- In the first step, the original HD footage is optimized by adjusting brightness, color contrast and balance.
- In the second step, existing reference points in the image are identified using specialized 3D software. This step is called camera-tracking.
- In the third step, 3D object models of traffic signs are positioned in the virtual 3D-environment.
- The final step includes rendering and masking of the object models. Rendering means that a realistic digital image from the 3D object model is generated to be displayed in the video. Masking means that the simulated objects are hidden behind real-world objects in the video when the real-world objects are in reality more proximate. This process is not straightforward and is much more complicated than the reverse, i.e. covering a real-world object behind a simulated object. Integrating simulated digital objects realistically in a real world video requires both techniques. Using these techniques, 25 photorealistic frames per second are created.

Driving Mockup and Eye-Tracker

During the driving simulator experiment, the participant is seated in a fixed-base mock-up in front of a large seamless curved screen on which the HD-video (25 photorealistic frames per second) is projected (see figure 3). Participants can speed up and slow down the video by means of the accelerator and the brake pedal. Because both the constant speed of the minivan during the filming of the route and the proportion of participants' acceleration/deceleration compared to this driving speed are known, an indication of participants' driving speed can be derived afterwards. Participants can indicate their route choices and lane changes by means of the indicator and by using the steering wheel. Based on this data, the number of lane changes and the route choices are evaluated.

Eye movements are recorded by faceLAB 5.0 (Seeing Machines, Canberra, Australia), a video-based, dash-mounted eye tracking system. The FaceLAB system can track eye movements via the relationship between the pupil and the reflection of the infrared light on the cornea. The system runs at a sampling rate of 60Hz and an accuracy of approximately 0.5° of visual angle ($\sim 1^\circ$ at the periphery). With the current configuration, the system can accommodate head rotations of $\pm 45^\circ$ and gaze rotations of $\pm 22^\circ$ around horizontal-axis, allowing participants to have large freedom of movement. Additionally, the faceLAB system can make estimates outside the viewing angle (e.g., glances to a side mirror), based on head movement and tracking of facial features. An overlay of the video and the logged eye tracking is used afterwards to derive parameters which are related to the detection of the traffic signs, such as the number of glances at a certain traffic sign per participant or the number of participants with or without detection moment for a certain traffic sign (see figure 4b and 4c further down this paper for an illustration). Eye Works software is used to carry out these analyses.

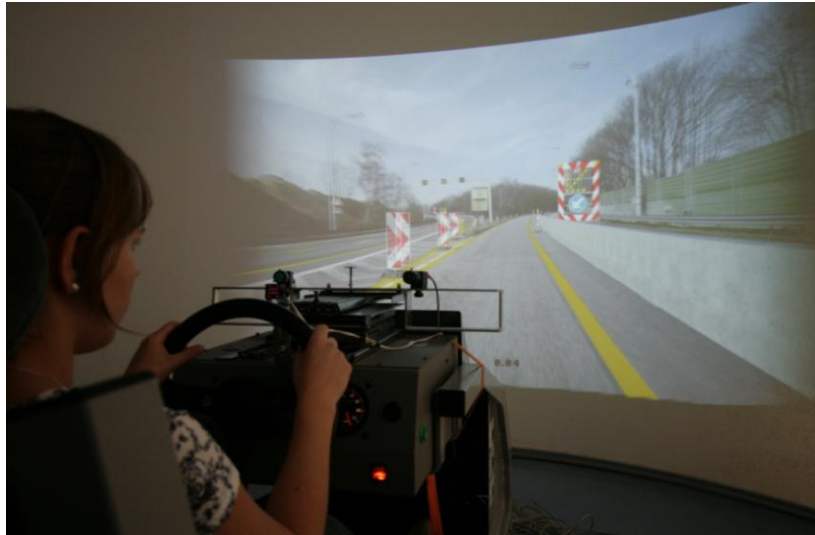


FIGURE 3 Traffic Sign Simulator mock-up with eye-tracking system.

Laptop Pre- and Post-Tests

Laptop pre- and post-tests further complement the simulated driving sessions. The main purpose of these tests is to improve the insight in participants' understanding and processing of particular traffic signs or situations. Participants' understanding can to some extent be derived from their decisions in the simulated drives, but more detailed insight is usually helpful.

In the pre-test, participants can be asked to draw specific traffic signs that have been shown to them to investigate how easily the signs can be recalled. Participants' comprehension of traffic signs can be tested by asking them to explain the meaning of the signs in their own words.

In the post-test, participants evaluate the traffic signs of interest on aspects such as sign complexity, difficulty, lay-out, etc. Suggestions about positioning, frequency etc. can also be collected. Finally, the researcher can go through the scenario movie(s) again together with the participants to ask for detailed feedback and suggestions for improvement.

An Illustrative Test Case

The case study we will use to illustrate the application of the Traffic Sign Simulator relates to the reconstruction works on the Vilvoorde fly-over, one of the busiest interchanges in the Belgian motorway network (140,000 vehicles per day) (35). More precisely, we have evaluated the temporary traffic sign plan for the reconstruction works before it was implemented. Proactively evaluating the quality of temporary traffic sign plans is highly relevant because motorway work zones are dangerous locations due to the temporarily changed road environment and rules and the presence of workers at the construction site (36). In such situations, the quality and accuracy of information offered to the road users is of crucial importance, not only to ensure road safety, but also to improve traffic flow and to minimize economic loss caused by congestion. The work zone in Vilvoorde is a challenging case since it involves a complex traffic detour that only applies in a limited time frame, as can be seen in figure 4. The usual exit towards the fly-over (which is indicated in red) is closed each day from 2 PM to 9 PM during the reconstruction works, during which period road users need to follow a detour (indicated in green). The rest of the day, the usual exit towards the fly-over is open, and road users can take the normal route.

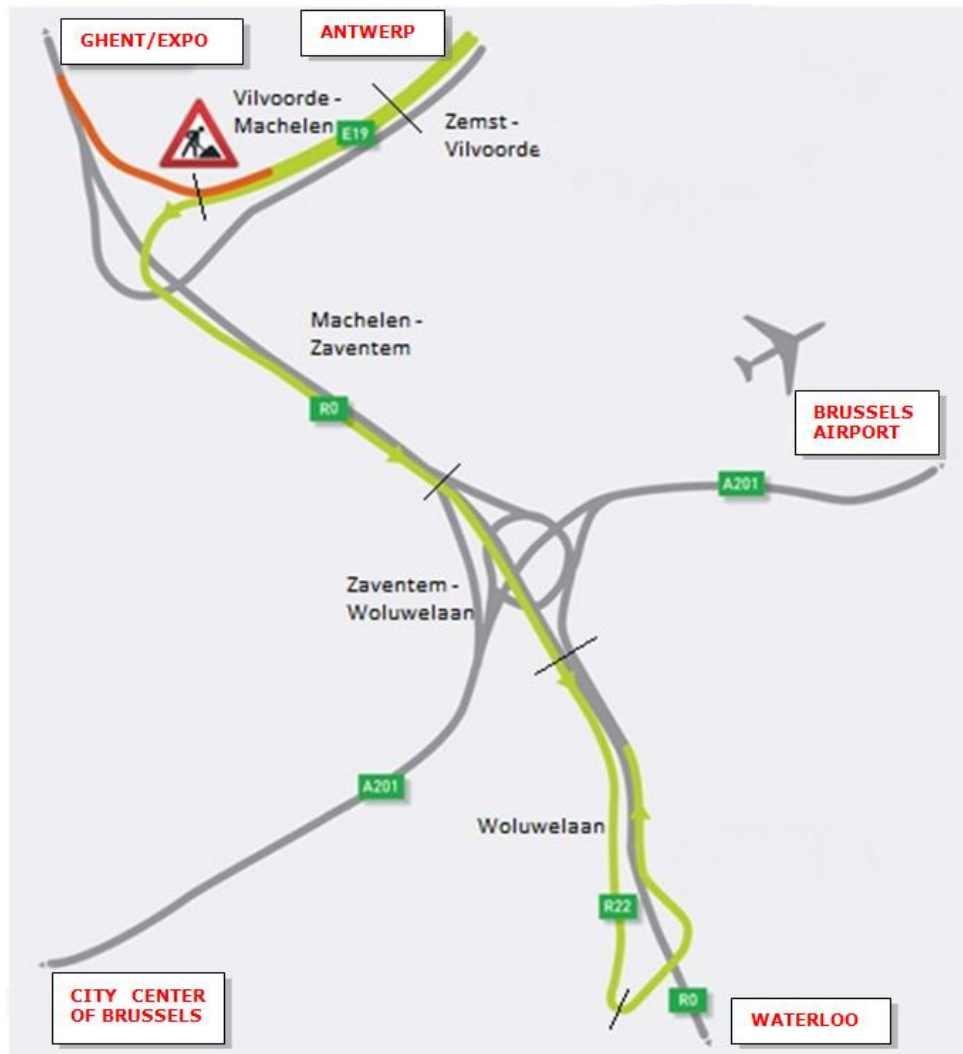
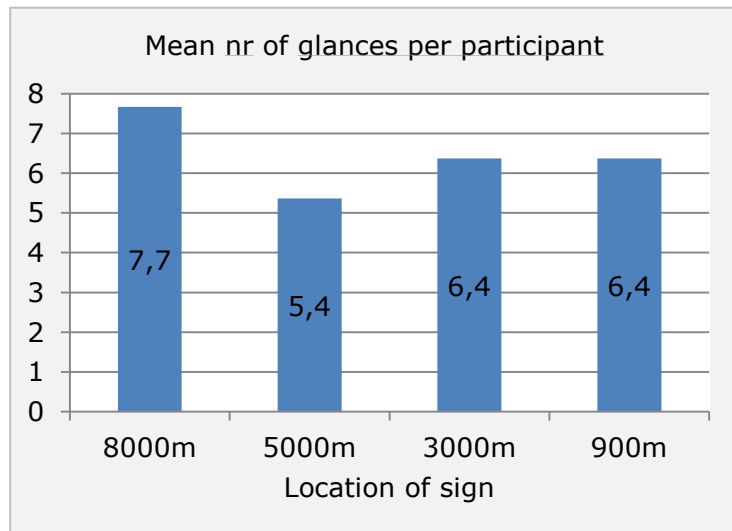
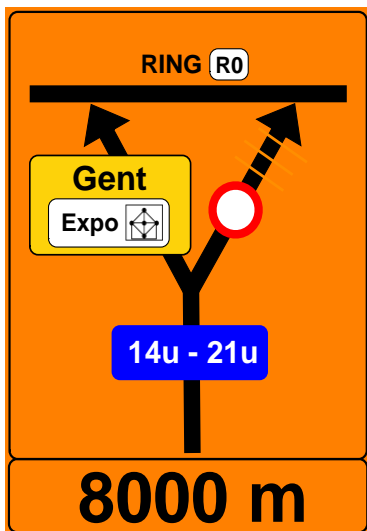


FIGURE 4 Vilvoorde fly-over detour.

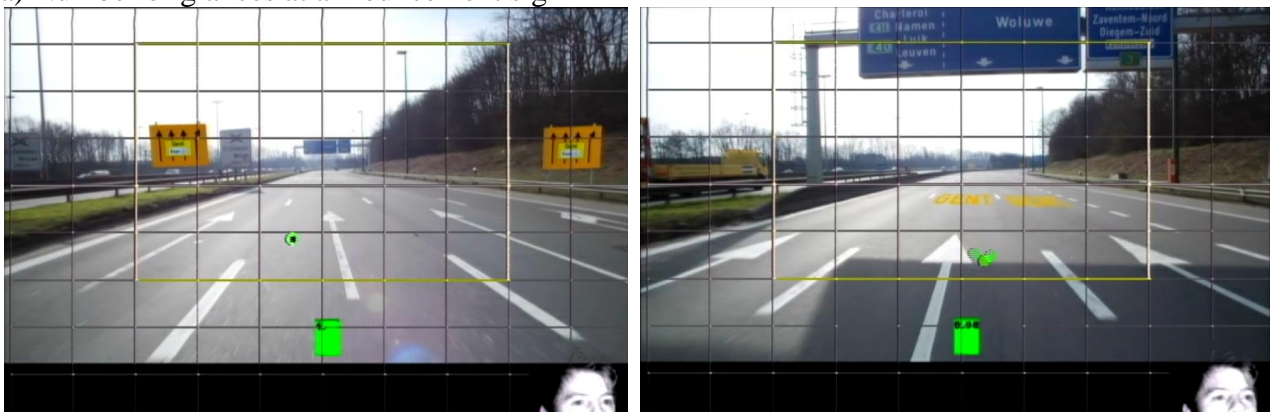
Twenty-three participants drove through two video recorded scenarios, i.e., the detour route (assuming it was 4 PM) and the normal route (assuming it was 10 AM), and completed a laptop pre- and posttest. Based on the outcome of the experiment a number of practical conclusions and recommendations could be formulated. Some of the most important conclusions and recommendations were as follows:

- Repeated exposure to the main announcement sign is required (both over distance and by positioning the sign systematically at both road sides). This can be derived from the participants' high number of glances to the repeated panels in the scenarios (on average 5-6 glances per person per sign for the repeated signs, see figure 4a), as well as from participants' feedback, and the relatively high amount of incorrect route choices (7 out of 21) in the scenario between 9 PM and 2 PM, taking the detour route while the regular connection is open as well.
- Discrepancy between temporary traffic signs (orange sign panels) or markings and regular traffic signs (blue sign panels) or digital information panels is to be avoided, even though traffic regulations clearly indicate that the regular traffic signs are to be ignored when temporary traffic signs are present (see figure 4b).
- Temporary pavement markings with destination names ('GENT') require only few and short glances, and they are considered very useful by participants (see figure 4b).

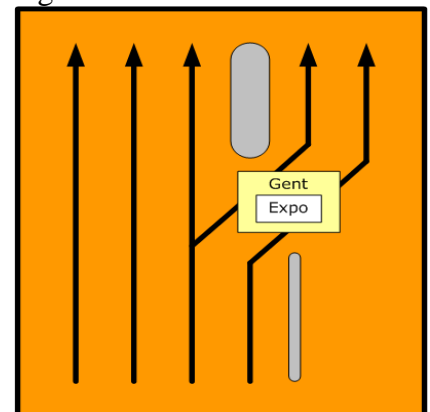
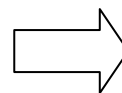
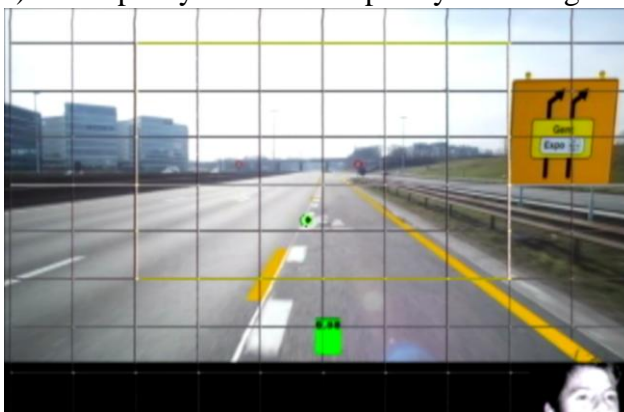
- Context-dependent design of the traffic signs (e.g. by adding location-specific additional road elements such as median position and other lanes) improves understanding of the traffic sign (see figure 4c).
- Most participants chose the middle lane in the scenario where the detour applies (2 PM till 9 PM); only two participants chose the right-most lane. Both choices are correct, but it indicates that a number of participants may be in doubt about the status of the right-most lane. This implies that the right lane capacity will not be optimally used, especially at the start of the road works.



a) Number of glances at announcement sign



b) Discrepancy between temporary traffic signs and regular traffic signs



c) Context-dependent traffic sign design

FIGURE 5 Illustration of case study results.

DISCUSSION

Benefits of the Traffic Sign Simulator

As indicated before, the proactive evaluation and optimization of traffic signs in a realistic environment can lead to major benefits to society. Effective traffic signs can improve road safety by reducing driving errors and by avoiding unexpected behavior that is caused by confusion or by late decision making. It can also lead to improvements in traffic flow and reduced congestion for road users.

Up until now, research using video-based driving simulations have not been able to apply major adjustments to the videos, limiting the possibilities for studying traffic signs in a real-life setting. The Traffic Sign Simulator is unique in combining a video-based driving simulator with sophisticated 3D-engineering and visualization techniques to study complex traffic signs in a highly realistic setting. The combination of high realism and more advanced control over actual driving in a safe environment is the major strength of the research tool. In its combination with specialized eye tracking techniques and laptop pre- and post-tests, the Traffic Sign Simulator allows to study all components of traffic sign effectiveness in detail.

Furthermore, differences between different socio-demographic groups can be explored, and feedback from different groups can be included, which will help to 'design for all'. Design for all is a strategy indicating that design standards need to recognize the variability in performance between different road users, and that therefore the least fitted users of the system should form the basis for design requirements (37,38).

Challenges

The inclusion of participants' actual driving speed could be an important improvement to the tool. At this point, the accelerator and braking pedal are used to determine the pace of the video, but driving speed could be included more explicitly.

The inclusion of interactions with other road users would be another possibility to reduce the gap between the driving scenario and the real-life situation. In the Vilvoorde study, the video was free of other vehicles since approaching traffic was blocked by escorting police cars for safety reasons because of the slow driving speed of the camera van.

Improving the flexibility of the camera track is another possibility for improvement in further research. At this point, the camera track is fixed, and some behavior of the participant will not be visually supported (e.g. incorrect route choices). By having a more flexible camera track, lane changes can be visualized more realistically.

In summary, it can therefore be stated that the tool in its current form is suitable to evaluate driving tasks at the tactical level (such as lane choice and route decisions based on information provided by traffic signs), but less suitable to evaluate operational driving tasks (such as lane position, interaction with other drivers and driving speed).

One final limitation is the fact that application of the traffic sign simulator remains partly dependent on the existing road environment. The use of sophisticated software for camera tracking and video-integration allows for significant highly realistic changes to the existing road environment. However, new sites or reconstructions with large changes to the alignment of the existing roadways are difficult to assess using the traffic sign simulator.

Research Opportunities

The combination of different research methods in the Traffic Sign Simulator allows to do research on many traffic sign related topics that are of scientific and/or public interest. Besides the proactive evaluation of the traffic sign plan for the reconstruction works on the Vilvoorde fly-over,

the Traffic Sign Simulator has already been used in a wide range of applications, such as the testing of parking routes in cities, route guidance systems to industrial zones and detour routes from the motorway network to the secondary road network in case of an incident on the motorway. Other examples of research opportunities could involve sight distance (e.g. (39)), the effect of different messages displayed on VMS (e.g. (33)), the implementation of VMS in the context of dynamic traffic management (e.g. traffic lane signalization, variable speed limits and the opening or closure of a rush-hour lane), dynamic route choice behavior (e.g. (40)) or the impact of advertisement panels on driving behavior and visual attention (e.g. (19,41)).

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