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Proactive Evaluation of Traffic Signs Using a Traffic Sign Simulator

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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'

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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, pavement markings, Traffic Sign Simulator, work zones, detour.*

1. 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 a core element of the 'Sustainable Safety' principle which aims to prevent (serious) crashes and injuries through application of intrinsically safe road design, taking humans' limited information processing capabilities into account. Such an approach differs from traditional reactive approaches that aim to solve problems after they establish themselves in the field, such as black spot treatments (Wegman et al., 2008). The importance of a shift towards more proactive road safety planning is acknowledged by several important policy documents (e.g. AASHTO, 2010; European Parliament & Council of the European Union, 2008; RiPCORD-iSEREST, n.d.). Also safety researchers and policy makers in other fields such as aviation (e.g. Kontogiannis & Malakis, 2009), health care (e.g. Kessels-Habraken et al., 2010), and the petrochemical industry (e.g. Burns, 2006) are highly aware of the importance of proactively preventing crashes from happening.

Traffic signs and pavement markings are a 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 (Castro & Horberry, 2004; Federal Highway Administration, 2012; Martens, 2000; Zhang & Ge, 2012). Research shows that the inappropriate positioning of traffic signs leads to increased reaction times and detection errors (Theeuwes & Godthelp, 1995). A proactive evaluation of (the quality of) these road design elements will help road designers and decision makers to improve the safety performance of road infrastructure.

The Traffic Sign Simulator presented in this paper is an innovative research tool that combines a number of techniques to proactively evaluate the quality of traffic signs and pavement markings by means of analysis of road users' detection, readability, understanding and behavior in an integrated way. The aim of this paper is to describe how the tool works, to compare it with a number of other existing techniques for the evaluation of traffic signs and pavement markings, and to illustrate the results that can be expected from the tool based on a test case.

2. 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) (Federal Highway Administration, 2012), "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 (2004, p. 2) on the other hand use a more encompassing definition of 'traffic signs', namely the one that was proposed by the International Commission of Illumination (1988) and the U.K. Department of Transport (1991). 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 broader sense with inclusion of all traffic control devices listed above.

According to Castro and Horberry (2004), the effectiveness of traffic signs depends 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 that are indicated in the picture below (figure 1). This list of requirements is not exhaustive. For instance, Gartner et al. (1992) 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.

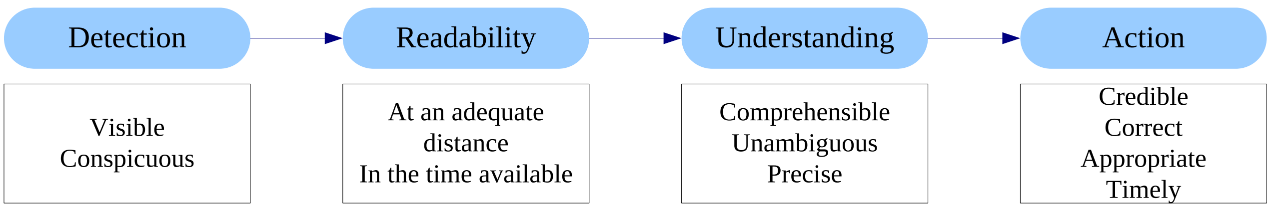


Figure 1. Four stages of traffic sign processing and their requirements (Castro & Horberry, 2004).

Since the proposition 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.

2.1 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, may contain errors or could be missing relevant information, 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 (Santiago-Chaparro et al., 2013). Therefore, sign detection, readability and understanding can only be evaluated indirectly, and behavioral responses cannot be empirically assessed.

2.2 Laptop tests
In studies using laptop tests, participants are exposed to pictures and/or videos representing road environments containing traffic signs, with rather general questions about traffic sign position, understandability, readability, etc. Laptop testing is a flexible and low-cost strategy allowing 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. (2008a,b) use a series of pictures of road scenes in laptop tests to link traffic sign location to driver expectancy (2008a) and driver experience (2008b). Crundall and Underwood (2001) use comparable techniques to analyze the priming function of road signs. Important drawbacks are 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.

2.3 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 (Martens, 2000). A disadvantage is that eye fixations do not guarantee that the object is internally processed (the common 'look but fail to see' error (Crundall et al., 2012)), and, vice versa, that even without a fixation an object can be perceived and/or interpreted. This also appears from the model by Castro and Horberry (2004), 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.

2.4 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 format 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. From an ethical perspective, 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 observable generic characteristics of the vehicles passing a certain location. For instance, Erke et al. (2007) 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. (2004) 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 within a certain time period). The main shortcoming is that only parameters describing the revealed behavior can be collected, while underlying causative 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 participant's 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 causative 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 of providing more information relating to participants' internal processes that play a role, although participants are likely to omit some information they implicitly use, especially under high mental load (Martens, 2000). In an alternative but related approach by Garvey et al. (2004), participants are positioned in the passenger's seat and are asked to verbalize a traffic sign's content aloud as soon as the sign becomes readable.

Finally, there is 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 (Dingus et al., 2006). 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 ongoing projects such as SHRP2 (Gordon et al., 2013) are expected to be used for this purpose in the future. A major challenge for such projects is 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. Carlson & Hawkins, 2003). 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 that the cost of implementing a realistic test track can be very high. Also missing is the interaction with other road users which makes the driving experience more artificial than on the public road.

2.5 Driving simulator studies

In driving simulator studies, participants are seated 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 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°) (Fisher et al., 2011). 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. Driving simulators can be combined with an eye tracking system to synchronically log visual behavior. This set up was used by for instance Dutta et al. (2004), who explored possibilities to maximize road users' understanding of variable message signs. Lidström (1998) and Upchurch et al. (2002) used a driving simulator as a tool for determining traffic sign positions in road tunnel design. They concluded that the driving simulator was a useful tool for improving freeway guide signing.

Interestingly, leading institutions and organizations worldwide such as The Transportation Research Board, indicate that recent innovations in computerized design assistance tools and techniques should be used to improve the understanding of how road geometry and infrastructural-related aspects (including positioning and design of traffic signs) affect traffic safety and operation (TRB, 2007). Driving simulators are shown to be a useful tool in this respect (Bella, 2009, Keith et al., 2005). Besides the high level of detail of the collected driving data, 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 (Godley et al., 2002).

A major issue is the extent to which behavior in the simulated environment corresponds to participants' actual driving behavior in a real-life environment (Fisher et al., 2011). 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) (e.g. Bella, 2009; Godley et al., 2002; Tornos, 1998; Yan et al., 2008). Kaptein et al. (1996) show that overall, absolute validity of route choice behavior is obtained in driving simulator studies. Also, a study by Bella (2005) has specifically shown that the driving simulator is a valid technique to assess drivers' behavior in work zones by comparing speed measurements on highways near workzones with participants' driving speed in a virtual replication of those sites.

The realism of a driving simulator scenario can be improved by replicating as exactly as possible the scenario from existing road environments (e.g. Ariën et al., 2012; Bella, 2005; Yan et al., 2008), or from road plans (e.g. Santiago-Chaparro et al., 2013). However, even in high-fidelity driving simulators, there are limits to the visual realism that can be offered (Bella, 2009; Bella et al., 2007; Klee et al., 1999), which is an important limitation compared to on-field studies and applications using video footage. In addition, there is a risk of participant drop-out due to simulator sickness.

Driving simulator – video footage based
Video footage based driving simulations offer a more realistic driving scene than traditional driving simulator studies where the road environment is virtually represented. Charlton (2006) used such a tool to study conspicuity, memorability, comprehension and priming of a number of different road hazard warning signs. Lai (2010, 2012) 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 represented 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. Indeed, participants are not really controlling their driving through the road scene, and thus not autonomously interacting with the road environment. Essentially, the vehicle mock-up is mainly used as a context feature for the creation of 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 (Lai, 2010, 2012) 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.

3. Traffic sign simulator – design

Since all methods have their advantages and drawbacks, it is recommended to combine several research methods when experimentally investigating traffic sign effectiveness (Martens, 2000). The Traffic Sign Simulator described in this paper is an innovative research tool that combines a number of techniques thereby allowing 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 participants' understanding and general evaluation of the traffic signs, and their suggestions for improvement. As such, this combined approach ensures that the strengths of different research techniques are fully exploited.

3.1 Scenario production

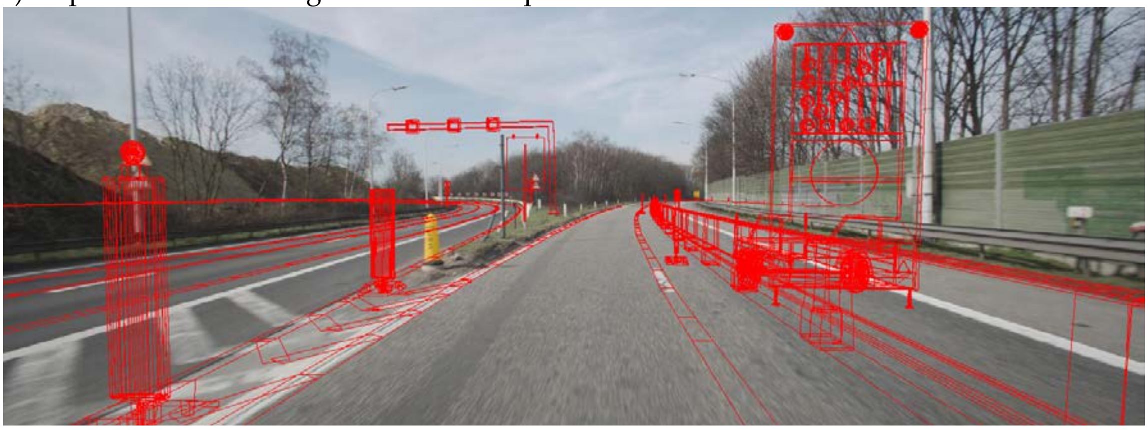
First, the route(s) of interest are filmed using a high-resolution RED-cam camera with a wide-angle lens that allows to collect video footage in full-HD resolution (4096 x 2304 pixels in 16:9 aspect ratio). The camera is mounted on the hood of a minivan, so that the footage is filmed from the viewpoint of a normal car driver. The minivan navigates at a constant driving speed as much as possible. 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 increased; the camera registers at a constant rate of 25 frames per second, but the distance traveled between two frames taken by the camera is reduced by recording at a lower speed. This procedure improves the quality of the final scenario film. For safety reasons, it is sometimes necessary to have a police escort accompany the camera vehicle for instance when recording at lower speeds on a motorway.

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. This is a semi-automatic process that is executed 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 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 can be created.

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 traffic signs of interest in video.

3.2 Driving mock-up 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. Readability of traffic signs at longer distances ahead can be a point of concern due to limitations in the resolution of the visual system. Therefore, if needed, participants can press a button to display an enlarged picture of a specific traffic sign. The availability of the enlarged picture is determined in function of the theoretical reading time and set at the point where the driver would be able to read the sign in the actual road environment while driving at the maximum allowed speed.

In terms of options to analyze driving data, an indication of participants' driving speed can be calculated 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. Also, 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 can be evaluated.

Eye movements are recorded by faceLAB 5.0 (Seeing Machines, Canberra, Australia) which is a camera-based, dash-mounted eye tracking system. The FaceLAB system can track eye movements via the relationship between the pupil and the reflection of infrared light that is projected on the cornea. The system runs at a sampling rate of 60Hz and an accuracy of approximately 0.5° of visual angle (~1° at the periphery). With the current configuration, the system can accommodate head rotations of +/-45° and gaze rotations of +/-22° 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 6 and 7 further down this paper for an illustration). Eye Works software is used to carry out these analyses.

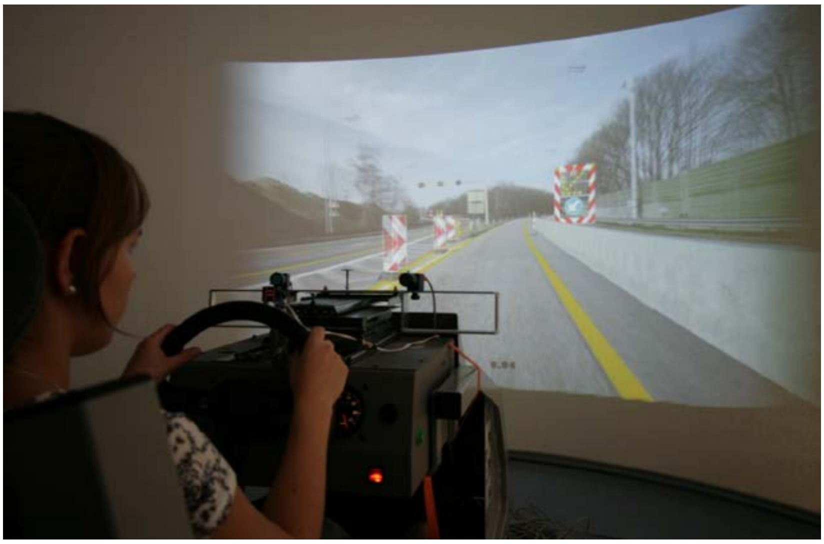


Figure 3. Traffic Sign Simulator mock-up with eye tracking system

3.3 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 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 to which they have been exposed in order to investigate how easily the signs can be recalled. Participants' comprehension of traffic signs can be tested by asking them to paraphrase 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 regarding 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.

4. Results from an illustrative test case

This section presents the results from a study applying the Traffic Sign Simulator to a test case where a work zone as well as a deviation route signalization plan was to be implemented in a real-life setting. This section is meant to be no more than a show case and is therefore purely illustrative with a description of the study set-up and an overview of some of the most important results obtained with the traffic sign simulator. Due to the specificity of the test case, one should be cautious in generalizing the reported findings as well as the test design used in this case study to other situational contexts in which comparable signalization plans would be used.

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) (Brijs et al., 2011). More precisely, we have evaluated the temporary traffic sign plan for the reconstruction works before they were implemented in field. 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. A study by Khattak et al. (2002) indicates that the number of crashes during the work zone period is around 20 per cent higher than during the pre-work zone period. Work zones mainly increase the occurrence of rear-end and fixed-object crashes (Campbell et al., 2012). 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 is operational 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. In that time frame 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.

The aim of using the Traffic Sign Simulator in this project is more precisely to actively contribute to designing the most optimal lay-out for all traffic signs that are used. Specific research questions that need to be answered in this optimization problem are the following:

- How well do drivers understand the meaning of the main announcement sign of the time-dependent detour?
- Is it necessary to repeat the main announcement sign multiple times?
- Is there a high risk that drivers make incorrect route choices?

- Which lane do drivers choose when approaching the usual entry lane towards the fly-over?
- Are there specific suggestions for improvement to the traffic signs in the test scenarios identified by participants?

Figure 4. Vilvoorde fly-over detour.

4.1 Sample

Twenty-three volunteers participated in the study. The participants are 47 years old on average (s.d.=13.72, range=24-66). 70% are male, 30% female. 13% of the participants are professional truck drivers. The sample includes both infrequent and very frequent drivers, as appears from the self-reported annual number of kilometers driven (mean=33174 km/y, s.d.=32620 km/y, range=1000-140000 km/y).

4.2 Test procedure and data collection

Each of the participants individually executes an identical test procedure, consisting of five parts, i.e. introduction, pre-test, test drive, post-test and final comments. In the introduction phase, participants are asked to give formal consent to allow that data about their driving behavior is anonymously collected and analyzed. Furthermore, some background information about the participants is collected, such as age, gender, and number of kilometers driven per year.

In the pre-test, the scenario set-up is first explained to the participants. They are informed that they need to remember that they are driving on the E19 in the direction of Brussels (coming from Antwerp), and that they are on their way to Ghent. Next, the participants are briefly (4 seconds) exposed to the main announcement sign twice (see figure 5 for the main announcement sign). The duration of 4 seconds is chosen because it corresponds with the approximate time that such a traffic sign would be readable for a driver driving at 120 km/h (Campbell et al., 2012). After each exposure, the participants are asked to replicate the announcement sign as detailed as possible by means of a drawing task. After the second exposure, the participants are also asked to formulate the meaning of the sign in their own words. The aim of the pre-test is to see what participants can remember and understand from the sign after a short exposure. This already gives a first meaningful indication of whether repetition of the announcement sign is required.

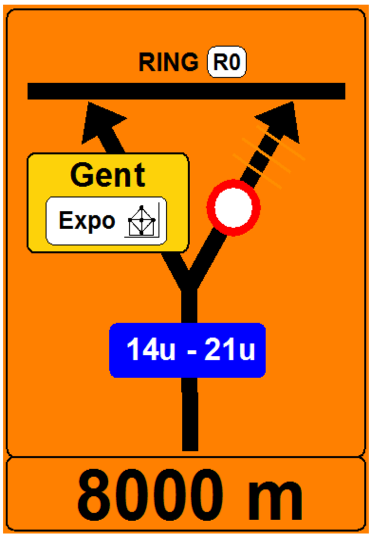


Figure 5. Announcement sign.

Before the start of the test drives, participants adjust the car seat to their preferred position, and the FaceLAB software is calibrated to allow the eye tracker to accurately register the participants' eye movements. Two test drives are completed by each participant. Before the start of route 1, participants receive the clear instruction that they drive on the E19 towards Brussels with their destination being Ghent, and that the time is 16h00 (4.00PM). This implies that the exit towards the Vilvoorde Flyover is closed at that moment (which is not mentioned to the participants for obvious reasons). Route 1 starts approximately 9 km before the entry lane towards the Vilvoorde flyover, and follows the left junction towards the R0 inner ring road. Next the detour over Woluwe is taken (indicated in green on figure 4). The drive ends at the Vilvoorde flyover and takes approximately 20 minutes. For the second route, participants get the same instruction, but this time with the indication that it is 10h00 (10.00AM). This implies that the entry lane towards the Vilvoorde flyover is open for traffic. The second route is substantially shorter than the first. It starts approximately 1.5 km before the entry lane exit towards the Vilvoorde flyover, and ends shortly after taking this entry lane. This drive takes approximately 3 minutes.

During the test drives, participants' visual scanning and driving behavior are saved in an overlay video that combines the input of multiple measuring devices. A recording screen of the eye movements is merged with a simultaneous recording screen of the test drive. Also the display speed of the video (operated by the gas and brake pedal), direction indicator and requested enlargements of traffic signs are included in the overlay video. Based on this overlay video, the data analyst can register for each moment of the drive to which point in the road environment the driver is looking, which traffic signs are being fixated (or not), how often and for how long a traffic sign is being fixated upon, which lane and route choices are made, etc. An example of such an overlay video can be seen in figure 6. The green dot indicates participants' gaze. At the bottom of the screen, the display speed is shown. Furthermore, it can be seen that the participant is using the left indicator in this example to indicate a lane change.

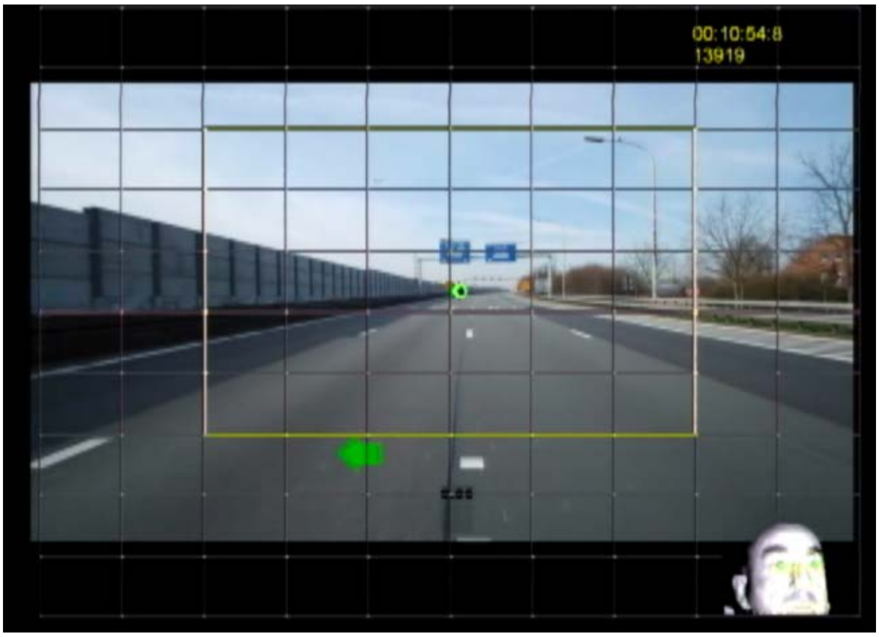


Figure 6. Example of overlay video.

In the post-test, as in the pre-test, the participant is briefly exposed to the announcement sign, and asked again to describe the meaning of the sign. Next, the exact meaning of the sign is explained by the researcher. Afterwards, participants are asked to evaluate how clear and comprehensible they find the sign. Next, two slightly different designs of the announcement sign are shown to the participant, and they are asked to indicate their personal preference.

The final comments phase aims to collect qualitative information about possibilities to improve the planned traffic signs. The two drives are played on a laptop, and the participants are asked to freely indicate any comments to the traffic signs.

4.3 Results

Understanding of main announcement sign and need for repeated exposure

Different aspects in the test procedure show that repeated exposure to the announcement sign is required.

The pre-test indicates that there is a need for repeated exposure to the announcement sign. The number of elements of the announcement sign that are drawn by the respondents, and that are correctly explained by the participants increases after repeated exposure. Both the participants' drawings and their description of the meaning of the sign are assessed by subdividing the traffic sign in a number of components. The researcher then assesses whether the component is recalled/explained correctly, incorrectly or whether it was missed. The total score (number of correct components minus number of incorrect components) for correctly drawing the sign increases from 9.3 to 13.7 (out of a maximum of 22 components). The total score for correctly describing the meaning of the sign increased from 5.7 to 6.9 (out of a maximum of 9). When we look more in detail, there seems to be a recall problem for two of the most important components of the sign, i.e. the timeslot and the distance indications. Recall and interpretation of these components however strongly increased during the second exposure to the sign, indicating the importance of repeated exposure to the sign.

From the test drives, it appears that the mean number of glances per participant is high for each of the announcement signs on the route, as can be seen from figure 7. This fairly stable parameter is an indication of the fact that participants benefit from repeated exposure to the sign. If this would not be the case, a decrease in the number of glances per participant would be expected.

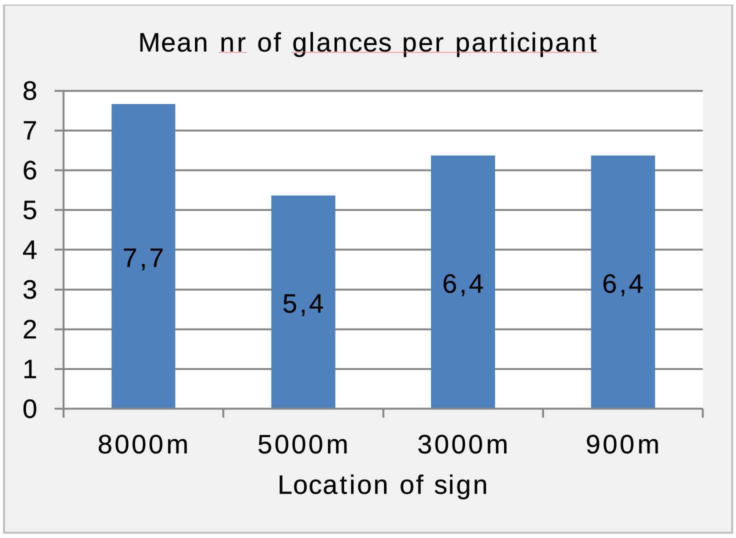


Figure 7. Number of glances at announcement sign.

The post-test shows that participants prefer the announcement sign as presented in the scenarios over the two alternative designs that are shown during this test. During the final comments, half of the participants explicitly indicate that they think it is useful to repeat the announcement sign multiple times.

Route and lane choice

When driving the first scenario (where the detour route applies), no incorrect route choices were made. This suggests that the detour indications are sufficiently clear and understandable in general. It is noteworthy however that near the (closed) entry lane towards the Vilvoorde viaduct, nearly all participants chose to drive on the middle lane, rather than the rightmost lane. The Belgian traffic code indicates that drivers should keep to the right side, except in busy traffic or when overtaking. This can be interpreted as an indication of the fact that some drivers may be in doubt about the status of the rightmost lane. Therefore, it can be expected that the capacity of the rightmost lane may not be optimally used, especially during the start of the road works.

During the second scenario however, 7 participants made an incorrect route choice by taking the detour while the normal connection was open. Also, four participants changed to the right-most lane fairly late. This indicates that it is likely that some drivers will take an unnecessary detour during the road works. This finding also stresses the importance of repeating the announcement sign.

Specific points of improvement

A number of specific points of improvement to the traffic signs in the test scenarios were identified by combining participants' suggestions from the final comments phase with observations from the test drives. Some of the most notable suggestions are mentioned below.

A first point of attention is that interference between temporary route guidance signs (orange sign panels in figure 8) and regular traffic signs (blue sign 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. From the eye tracking data it appears that the number of glances to temporary traffic signs that are positioned close to regular traffic signs is lower compared to stand-alone temporary signs because participants divide their glances over both the temporary and regular signs. To make sure that drivers spend enough attention to the temporary signs, it is therefore recommended to avoid such interference.

Figure 8. Interference between temporary and permanent traffic signs.

The yellow temporary pavement markings with destination names (as shown in figure 9) require only few and short glances. Participants also indicate that they find these markings very clear and useful because they confirm the correct lane choice in unfamiliar and complex weaving areas where there is a potential of making incorrect lane or route choice decisions.

Figure 9. Temporary pavement markings with destination names.

Finally, participants indicate that context-dependent traffic signs (e.g. by adding location-specific additional road elements such as median position and other lanes) improve the readability and the understanding of the signs. Therefore, it is recommended to not only display the aspects that are of direct importance to the drivers, but also more location-specific details. An example of such improvement is shown in figure 10.

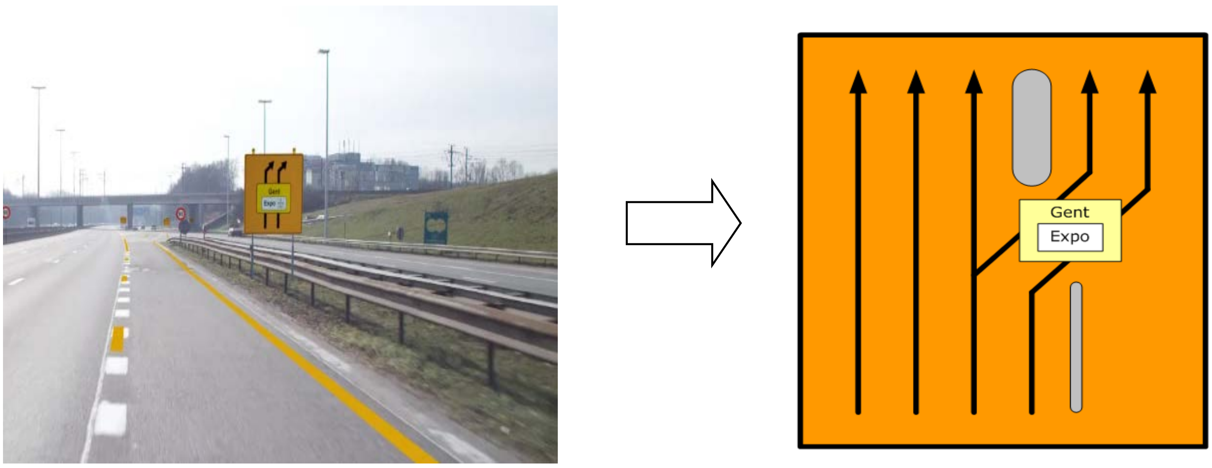


Figure 10. Example of context-dependent traffic sign design.

4.4 Impact

The conclusions of the Traffic Sign Simulator study have led to more than 20 specific changes to the final traffic signs that have been implemented on the road. The changes relate to traffic sign position and lay-out, and the number of times certain signs are repeated. Also, additional road markings with destination names were added.

A formal scientific assessment of the impact that these changes have had on road safety and on traffic flow has not been carried out. It is therefore difficult to quantify the impact of the study.

Some empirical findings suggest however that the optimization of the traffic signs in line with the findings of the study has had a positive impact:

- No serious injury crashes have occurred during the road works
- The levels of congestion were lower than expected
- The Flemish Roads and Traffic Administration indicates that the number of received complaints about the work zone signalization was remarkably low. The Administration indicates that the number of complaints is usually much higher for road works of a such an extent

While the absence of a formal scientific impact evaluation makes it impossible to show the precise impact of the Traffic Sign Simulator study, we believe that the accumulation of these observations indicates that the application of this new method has led to useful improvements in the traffic signs for this project.

5. Discussion

5.1 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 (too) 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 has 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. The Traffic Sign Simulator can therefore be a useful active design tool for temporary and for permanent traffic sign plans.

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 take into account as much as possible 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 (Hakamies-Blomqvist & Peters, 2000; Hunter-Zaworski & Stewart, 1999).

5.2 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 (virtual road traffic) would be another possibility to reduce the differences 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 path is fixed, and some behavior of the participant will not be visually supported (e.g. incorrect route choices). By having a more flexible camera path, lane changes can be visualized more realistically.

In summary, it can 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.

5.3 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 for 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. Discetti & Lamberti, 2011), the effect of different messages displayed on VMS (e.g. Lai, 2010), 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. Iida et al., 1992) or the impact of advertisement panels on driving behavior and visual attention (e.g. Beijer et al., 2004; Crundall & Underwood, 2001).

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