

An Evaluation of the Interior Design of the Stockholm Bypass Tunnel – A Driving Simulator Study

Ruggero Ceci, Christopher Patten, and Selina Mårdh

VTI – Swedish National Road and Transport Research Institute, Sweden
{ruggero.ceci, christopher.patten, selina.mardh}@vti.se

Abstract. Maintaining high levels of road traffic safety is always important and when the road is in a tunnel, and especially in a long tunnel, maintaining the highest possible level of safety is paramount. In Sweden, the Stockholm bypass tunnel has been scheduled to commence construction in 2013. The tunnel will be approximately 18 km in length. The length of the tunnel is expected to affect the drivers' experiences pertaining drowsiness, arousal, distraction and feelings of safety and security. The study included 24 participants, 12 men and 12 women, aged 30-45. All of the participants drove two versions of the tunnel, one version with a decoration design in terms of string lighting in the ceiling of the tunnel and one version of the tunnel without any decoration design. Eye tracking behaviour was measured during the study. CR10 ratings of four subjective dimensions (distraction, visually cluttered, visually stimulating/arousal and safety and well-being) during the drive were also measured. The results revealed that 58 per cent of the participants preferred the tunnel with the strings of light in the ceiling and 29 per cent preferred the tunnel without the ceiling lighting. 13 per cent prefer neither one design more than the other. The participants perceived feelings of their driving through the tunnel suggested that the tunnel with the ceiling light design was experienced as being more "visually cluttered" than the tunnel without the light strings but at the same time it was also experienced as more "arousing/stimulating". Mean glance duration times suggested that although there was a significant main effect of the tunnel with the string lighting and in specific areas of the tunnel, the drivers were looking at the ceiling lighting but using short glances (445.3 ms with lighting and 234.3 ms without lighting). The negative safety implications of the elaborate interior lighting features would appear to be minimal in terms of distraction and irritation whereas the safety benefits in this particularly long road tunnel, in terms of subjective feelings of visual stimulation is encouraging. Based on the participants' experiences of the interior design concept of the 18 km long tunnel, having stimulating lighting features in different locations along the length of the tunnel is recommended.

Keywords: tunnel safety, tunnel interior design, driving simulator, category ratio scale (CR-10), eye tracking, string lighting, Stockholm bypass tunnel.

1 Introduction

Maintaining high levels of road traffic safety is always important and when the road is in a tunnel, and especially in a long tunnel, maintaining the highest possible level of

safety is paramount (Patten & Mårdh, 2012). The Stockholm By-pass (FSS) project is a new road project that will create a new bypass of central Stockholm. The entire project includes motorways, bridges and two tunnels; one of which will be 18 km. The FFS is the largest infrastructure project in Sweden to date. The planning of the project includes the choice of the exact route, the road geometry and also the interior design of the 18 km tunnel, including the aesthetics of all aspects of the tunnel. Earlier studies have suggested that the drivers' ability to gauge speed can be affected by visual design concepts (Manser and Hancock, 2007). Other forms of driver behaviour, such as eye-glance behaviour and mental workload has also been suggested as being affected by the lighting colours and patterns of the tunnel walls as well as the strength of the lighting (Kircher and Ahlström, 2012; Kircher and Lundkvist, 2011; Patten, Ceci, Engström and Anund, in press). Based on these studies, the interior design and decoration of the tunnel is expected to affect drivers. The drivers' subjectively perceived experiences pertaining drowsiness, arousal, distraction and feelings of safety and security were studied in VTI's advanced driving simulator in Linköping, Sweden.

In this study, two versions of the tunnel's interior design have been meticulously created from the blue prints of the real tunnel (this hasn't been built yet); one version with ceiling lighting and the other version without. The real tunnel's construction starts in 2013 and is expected to take about ten years to complete. The research questions ask if the ceiling string lighting and other visual design features have a negative effect on vehicle based performance (not reported in this paper), eye tracking data and subjectively rated experiences of tunnel design according to the following:

- Subjective rating of distraction.
- Subjective rating of visual clutter or messiness.
- Subjective rating of arousal/vigilance.
- Subjective rating of safety and well-being.

Moreover, the opinions of specific design features were also rated in a post experimental survey (not reported here).

2 Method

2.1 Participants

The study included 24 participants, 12 men and 12 women, aged between 30-45 years and were recruited to the study from VTI's database of voluntary participants. Their mean age was 38 years and they had held their licences for 18.5 years. The selection criteria for the participants were 1) an annual mileage > 5000 km, 2) a full category B (car) driving licence held for at least 5 years, 3) no spectacles (contact lenses were fine), and 4) no predispositions to motion sickness.

Four of the participants indicated in a pre-experimental survey that they feel uneasy when driving in tunnels. One of these participants specified the reason as being that the GPS stopped working in a tunnel; another submitted reasons for this unease as being due to darkness and the possibility slipperiness in winter. Three other participants thought that driving in tunnels was interesting and fun whilst the remaining 18 participants held no specific opinions of driving in real-life tunnels. All of the participants had previous experience of driving in real-life tunnels.

2.2 Equipment and Materials

Simulator. The study was performed in VTI's driving simulator III in Linköping, using the car set-up pictured in Figure 1. The simulator utilises all of the controls of a real car and is mounted on a full motion based platform. The visual experience is created using six projectors with a forward field of view of 120 degrees. There are also three rearward facing LCD screens instead of mirrors that provide images of the road scene behind the simulator-vehicle.

Eye Tracking. The SMI IviewX is a helmet mounted eye tracking device. The device records the position of the pupil and predicts the eye's direction with a cross-hair. The device also films the direction of sight. All of the participants were donned with the eye tracker before entering the simulator and individual calibration is required for all participants.

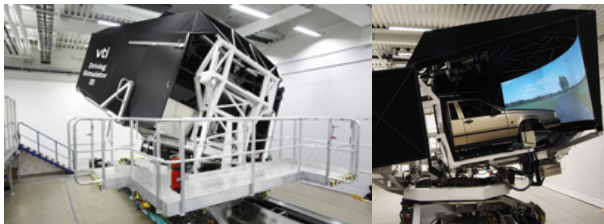


Fig. 1. Simulator III, VTI in Linköping, Sweden

2.3 Procedure

A motorway tunnel replica based on the blue-prints of the Stockholm Bypass tunnel was recreated in the VTI advanced driving simulator no. III. The simulated tunnel included all of the original road topography, including curvature, gradient, length and breadth. It also included the planned surface texture of the walls, road signage, emergency exits and other road furniture such as extraction fans and standard lighting fixtures. The simulated tunnel comprised a three lane motorway. The visual design feature comprised a series of ceiling lighting strings that travelled the length of the tunnel and varied from one line to five or six. The position of the string of ceiling lights also varied and could travel from left to right and vice versa, as well as travelling down the upper section of the tunnel wall (approx. ≥ 2.5 m). The visual design concept also includes special artistic lighting features at certain points in the tunnel such as the subterraneous junctions at Ekerö, the Mid-way point, the Lung and Vällingby.

For the purpose of this study, two versions of the tunnel were used; one with the string lighting feature and one without. The other design features were identical thus isolating the pros and cons of the string lighting feature in the tunnel. The study design was a within-subject design where all of the participants drove all of the different experimental conditions. The order was balanced for lighting design and gender. All participants drove the route in the same direction (from south to north) through the tunnel. The study procedure started when the participants arrived at VTI in Linköping, Sweden whereupon written instructions and informed consent forms were signed. The participants were also drilled with the rating scales as well as completing background questionnaires before being allowed to enter the driving simulator.

Once inside the simulator the participants would familiarise themselves with the basic controls. The eye tracking equipment was also calibrated. The participants then started their familiarisation or practice drive. The speed limit in the tunnel was signposted at 100 km/h. The participants were instructed to drive ‘normally’ and to drive in the centre lane (there were three lanes). There was also simulated light traffic in the tunnel. There were no overtaking situations where the vehicle to the left of the participant maintained slightly slower and the vehicles to the right of the participant drove slightly faster (driving in right-hand traffic). After each tunnel condition, the participants stopped to rate four CR10 questions. After the final tunnel condition, a post-questionnaire was answered (not reported in this paper). The whole process took approximately 1.5 hours. All participants received 300 SEK in compensation.

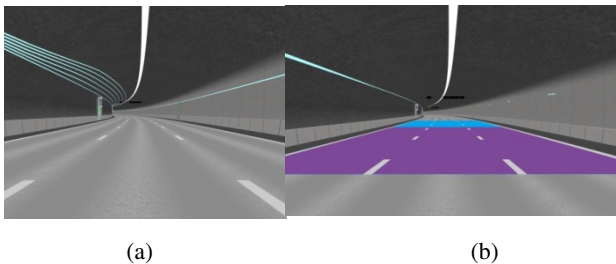


Fig. 2. A screen capture of a) the string lighting visual design feature and b) the Middle section or mid-way point in the tunnel

2.4 Rating Scale CR10

The rating scale used in this study was the Category Ratio Scale 10 (CR10). The scale ranges from 0 to >11 although in practice 11 is the highest rating (see Appendix 1). More importantly with the CR10 scale that was developed by Borg (2008), is the verbal anchors associated with each ratings. Moreover, all of the CR10 ratings were measured directly after exiting the different experimental conditions to reduce the likelihood of confusion and memory loss regarding the ratings of the conditions. The four dimensions were rated whilst the participants remained seated in the stationary vehicle. The questions were read aloud on the loudspeaker from the simulator control room and recorded by the operator. The following four ratings were rated by the participants:

- How distracting did you experience the tunnel’s interior design features?
- How visually cluttered did you experience the tunnel’s interior design features?
- How stimulating or arousing did you experience the tunnel’s interior design features?
- How safe did the tunnel’s interior design features make you feel?

2.5 Data Analysis

There were 24 participants that completed the study. The order of presentation was balanced and interaction effects from order were also investigated between the conditions.

The tunnel design, including the specific details of subterranean junctions was not altered as their location, design and geographic position are all fixed. All of the separate road sections with visual design features (seven with string lighting and five junctions or other special features) were analysed as separately due to their uniqueness's. The statistical analyses used were with ANOVA repeated measures and t-tests using SPSS (version 17.0). Due to technical problems with the eye tracking equipment and its calibration, only data from 12 of the participants was valid (7 women and 5 men).

The string lighting design features in the tunnel was divided into seven episodes or segments as well as the additional five junctions or other special features. The seven separate segments of string lighting was present either on the left (L) or the right (R). Alternatively, the string lighting was present on first the left and then the right (LR) of the ceiling or vice versa (RL). The seven string lighting segments were as follows:

- Segment 1 (string lighting LR)
- Segment 2 (string lighting LR)
- Segment 3 (string lighting L)
- Segment 4 (string lighting RL)
- Segment 5 (string lighting RL)
- Segment 6 (string lighting L)
- Segment 7 (string lighting R)

3 Results

3.1 CR10 Borg Scale

The participants were asked to rate four dimensions on the CR10 scale (0 - >11) in regard to the tunnel they had just driven through (one with string lighting design features and one without the design features). The results are shown in figure 3.

The difference in the mean CR10 rating scores for the "distraction" dimension between the tunnel with the visual string light design feature was 2.4 and 1.97 for the tunnel without the design features. This was tested with a t-test and was not

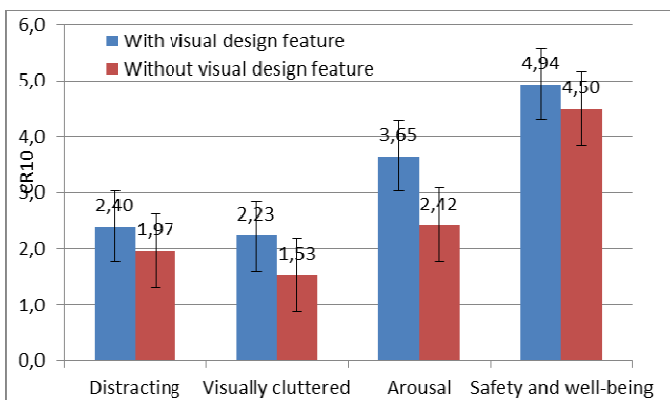


Fig. 3. CR10 rating scale. There were four dimensions that were rated by the participants. Standard error bars and the mean CR10 rating are indicated (n = 24).

statistically significant ($t(23) = 1.54, p = .137$). The verbal anchors for the different scores can be found in figure 2.

The difference in the mean CR10 rating scores for the “visually cluttered” dimension between the tunnel with the visual string light design feature was 2.23 and 1.53 for the tunnel without the design features. This was tested with a t-test and was statistically significant ($t(23) = 2.232, p = .036$).

The difference in the mean CR10 rating scores for the “visually stimulating/arousal” dimension between the tunnel with the visual string light design feature was 3.65 and 2.42 for the tunnel without the design features. This was tested with a t-test and was statistically significant ($t(23) = 2.612, p = .016$).

The difference in the mean CR10 rating scores for the “safety and well-being” dimension between the tunnel with the visual string light design feature was 4.94 and 4.5 for the tunnel without the design features. This was tested with a t-test and was not statistically significant ($t(23) = .968, p = .343$).

3.2 Mean Glance Duration

In table 1 below, the mean glance durations (total glance time/total glance frequency). String number 4 was statistically significant, $F(1, 10) 7.782 p = .019$ with a large effect size ($\text{Eta}^2 = .438$) according to Cohen’s guidelines (1988). String 7 was also significant, $F(1, 10) 8.92 p = .014$ with a large effect size ($\text{Eta}^2 = .471$) according to Cohen’s guidelines (1988), whilst strings 1, 2, 3, 5 and 6 were not significant. There was a significant main effect between the tunnel with the design concept (445.34 ms) and the tunnel without (234.33 ms), ($F(1,11) = 9.81, p = .01$) and the effect size was large ($\text{Eta}^2 = .471$) according to Cohen’s guidelines (1988).

Table 1. Mean glance duration for the different segments of tunnel with the string light design concept and an identical tunnel segment without the string lighting feature. ($n = 12$).

Lighting string	With design concept (ms)	Without design concept (ms)	p value	Effect size (Eta^2)
String 1	420.6	206.1	n.s.	-
String 2	404.4	266.3	n.s.	-
String 3	533.8	263.7	n.s.	-
String 4	403.9	186.0	*	.438
String 5	375.0	211.1	n.s.	-
String 6	360.2	168.4	n.s.	-
String 7	619.4	338.7	*	.471

* significance at .05 level; n.s. = not significant.

3.3 Correlations between Mean Glance Durations and CR-10 Ratings

In order to further analyse the correlations between eye-tracking data (mean glance durations) and the four different perceived dimensions according to the CR-10 scale a Pearson Correlation analysis was performed over the range of lighting string (1-7). A significant correlation only between mean glance duration (1-7) with string lighting and CR-10 ratings of *distraction* was found ($p < 0.05, 1$ -tailed). This could be interpreted as a support for the assumption that the string lighting features in this condition

affect the visual (glance) behaviour while driving through the simulated tunnel in a somewhat distracting manner. However, the magnitude of this perceived distraction seems fairly low according to the CR-10 scale (about 2 with the verbal anchor *weak*).

4 Discussion

The main research question addressed in this study was whether or not the string lighting design feature that ran along the upper walls and ceiling of the conceptualised Stockholm Bypass tunnel had an adverse effect on driver performance and road safety. Moreover, the participants' opinions and subjective ratings of the tunnel's visual design features were explored in detail. Based on the overall results of the present study, the effects of the design with light strings in the ceiling of the tunnel was considered to be more beneficial from a traffic safety point of view as compared to the tunnel design without light strings. This conclusion is based on the fact that the light string design did not significantly change the driver behaviour but was perceived as breaking the monotony of the tunnel. The results of the study can be used as a basis for further design aspects of long tunnels.

The participants' experiences, opinions and comments regarding the visual design features in the tunnel were measured with different rating scales. The first rating scale was the CR10 scale that was used to rate four dimensions of the tunnel, directly after experiencing the design features. The CR10 was easy and quick to administer, as well as being tangible because of the verbal anchor words, for the participants' when putting a number to a feeling or experience. It is also generally advantageous to record the rating as soon as possible after the event, to avoid memory/recollection issues or confusion regarding the object being rated when there are potentially several conditions to choose from. The CR10 dimensions for "visually cluttered" and "visually stimulating/arousing" were statistically significant between the two conditions (with the string lighting and without). The tunnel with the string lighting design feature was rated as being more visually cluttered than the tunnel without. It was however, also significantly rated as being more visually stimulating than the tunnel without the string lighting which was deemed as a positive result because the aim of the string lighting was, in part, to break the visual monotony of an 18 km long tunnel wall/ceiling.

The post study questionnaire revealed that 58 per cent of the participants preferred the tunnel with the strings of light in the ceiling and 29 per cent preferred the tunnel without the ceiling lighting. 13 per cent preferred neither one design more than the other. The eye tracking data was extracted and analysis for the sections of tunnel where the string lighting was present as well as an equivalent section of the tunnel without string lighting. The participants' visual behaviour was studied to see whether or not the drivers looked at the string lighting, and if they did, how often and how long? The safety threshold for non-road related vehicle design glance times and visual distraction varies. In the USA, a maximum of 2.0 second (or 2000 ms) glance times are stipulated (AAM, 2003). The mean glance time ranged between 360 ms and 619 ms in the tunnel with the string lighting (mean 445.3 ms) and was significantly longer than the tunnel without the string lighting (234.3 ms). It should be noted, however, that the mean glance durations are unlikely to pose any serious safety concerns.

5 Conclusions

The construction of long tunnels brings issues regarding driver behaviour and traffic safety into focus. In Sweden, the Stockholm Bypass tunnel (FFS), has been scheduled to commence construction in 2013. The tunnel will be approximately 18 km in length and the length and stretch of the tunnel is expected to affect the drivers' experiences pertaining drowsiness, arousal, distraction and feelings of safety and security. An attempt to meet these issues was made by focusing on the interior design of the tunnel. The present study was performed at VTI's driving simulator III in Linköping. A tunnel based on the blue-prints of the FFS tunnel (version FST Plan 2011-11-08) was designed in the simulator. The study included 24 participants, 12 men and 12 women, aged 30-45. All of the participants drove two versions of the tunnel, one version with a decoration design in terms of strings of lights in the ceiling of the tunnel and one version of the tunnel without any decoration design. Measures of lateral position, speed, eye movement data (mean glance duration), perceived feelings of distraction, arousal/stimulation, drowsiness, safety and security as well as perceived design preferences were collected.

The participants perceived feelings of their driving through the tunnel suggested that the tunnel with the ceiling light design was experienced as being more "visually cluttered" than the tunnel without the light strings but at the same time it was also experienced as more "visually stimulating/arousing".

Appendix 1

0	Nothing at all	
0.3		
0.5	Extremely weak	Just noticeable
0.7		
1	Very weak	
1.5		
2	Weak	Light
2.5		
3	Moderate	
4		
5	Strong	Heavy
6		
7	Very strong	
8		
9		
10	Extremely strong	"Maximal"
11		
↕		
●	Absolute maximum	Highest possible

The Borg CR10 scale®
© Gunnar Borg, 1982, 1998, 2004

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