INTERIOR TUNNEL DESIGN AND ROAD TRAFFIC SAFETY

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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 (FFS), has been scheduled to commence construction in 2013. The tunnel will be approximately 16.5 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 strings of lights in the ceiling of the tunnel and one version of the tunnel without any decoration design. 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”.

The results also 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 did not prefer either one design over the other. 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 16 km long tunnel, having stimulating lighting features in different locations alone the length of the tunnel is recommended.

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 16.5 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 16 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 effected 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 (that 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 eight years to complete. The research questions ask if the ceiling lighting and other visual design features have a negative effect on vehicle based performance (not reported in this paper) and subjectively rated performance and experiences of tunnel driving and design:

- Subjective rating of distraction.
- Subjective feeling 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.

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 unease 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 & Materials

2.2.1. Simulator

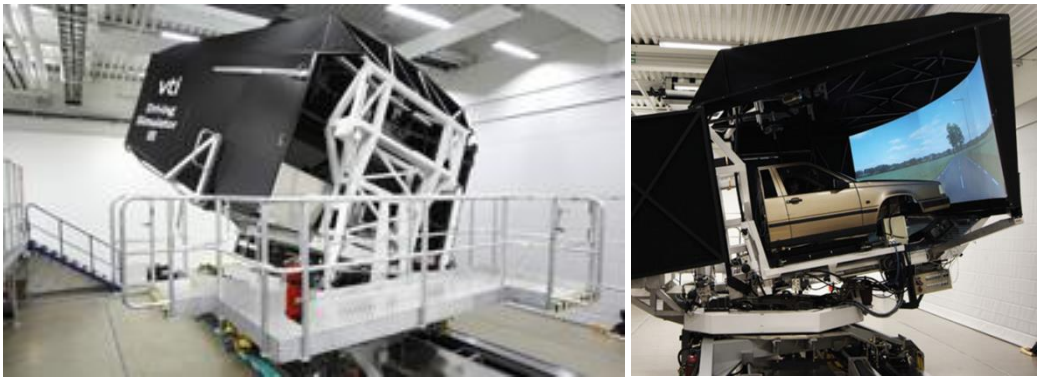


Figure 1: Simulator III, VTI in Linköping, Sweden.

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.

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 (not reported in this paper). 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. The whole process took approximately 1.5 hours. All participants received 300 SEK in compensation.

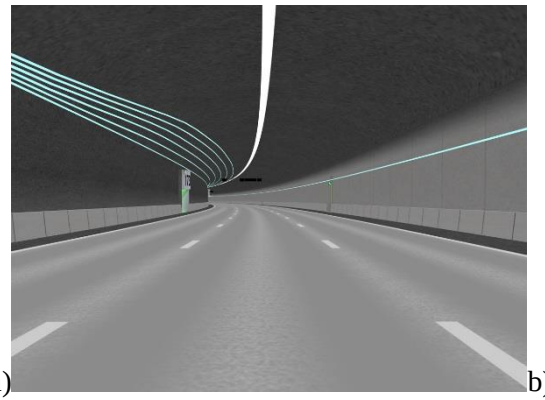
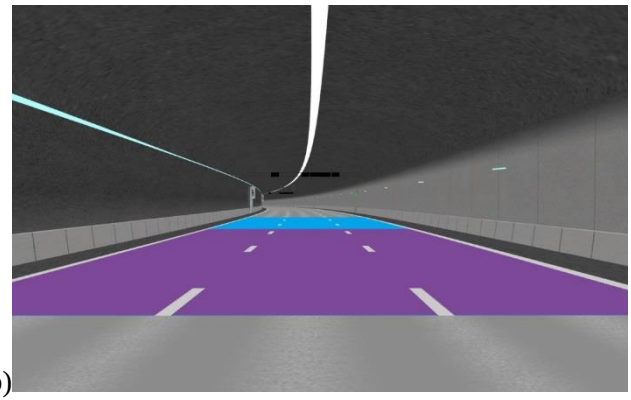
a)  b) 

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

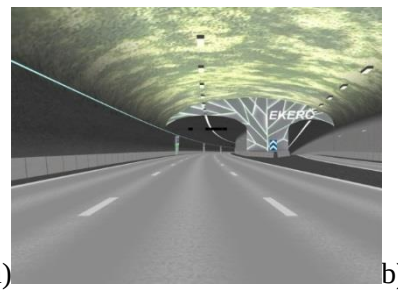
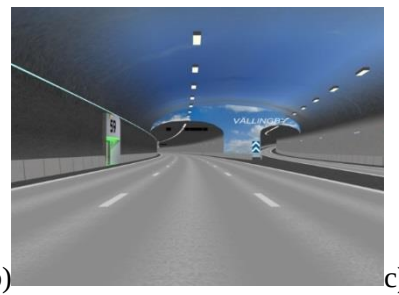
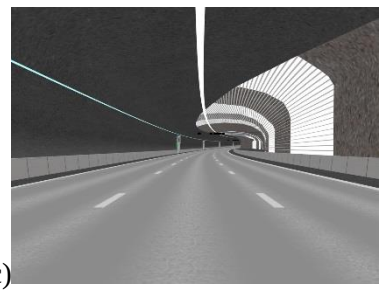
a)  b)  c) 

Figure 3: A screen capture of the exit ramps a) "Ekerö", b) "Vällingby" and c) the Lung segment.

2.3.1. Questionnaire 1

Questionnaire 1 contained questions regarding the participants' background details, e.g. age, gender, experience, as well as questions of the participants' view of tunnel driving in general.

2.3.2. Questionnaire 2

Questionnaire 2 contained many detailed questions about the participants' experiences of driving in the tunnel conditions. Questionnaire 2 was completed in post-experiment phase. The questions used a seven-point Likert scale where 1 represented "strongly disagree" and 7 represented "strongly agree".

The participants were informed in questionnaire 2 that the string lighting design feature that ran along the upper walls and ceiling of the tunnel was only present in one of the two tunnels through which they drove. The participants were asked to indicate a number on the seven-point scale that most accurately reflected their experiences for each of the statements (reported in Table 1).

2.3.3. 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 figure 4 below). 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?

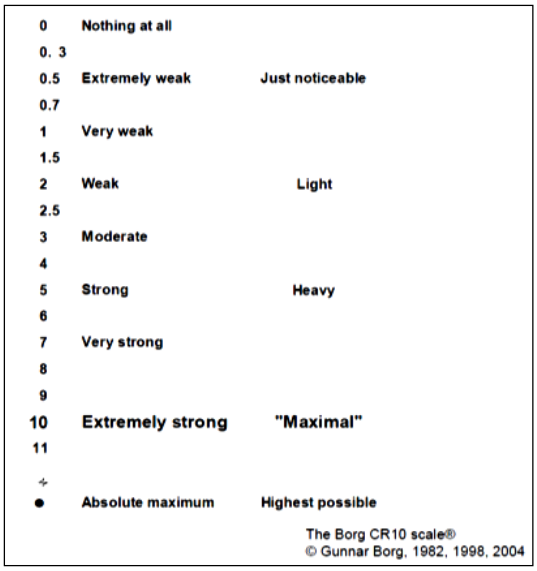


Figure 4: CR10 rating scale with verbal anchors.

2.4. Data analysis

There were 24 participants that completed the study. There were 12 men and 12 women with an age range of 30-45 years, a mean age of 38 years and had on average held a full car driving licence for 18.5 years. The order of presentation was balanced and interaction effects from order were also investigated between the conditions. The tunnel design, including the specifics details of subterraneous 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)

The additional five special visual design features were (in order of appearance when driving) Ekerö (a subterraneous junction), the Middle section (mid-way point), the Lung, Vällingby (a subterraneous junction) and the Main Exit.

One-Sample Kolmogorov-Smirnov non parametric tests (two-tailed) were used to analyse distribution of the responses to Questionnaire 2.

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 5.

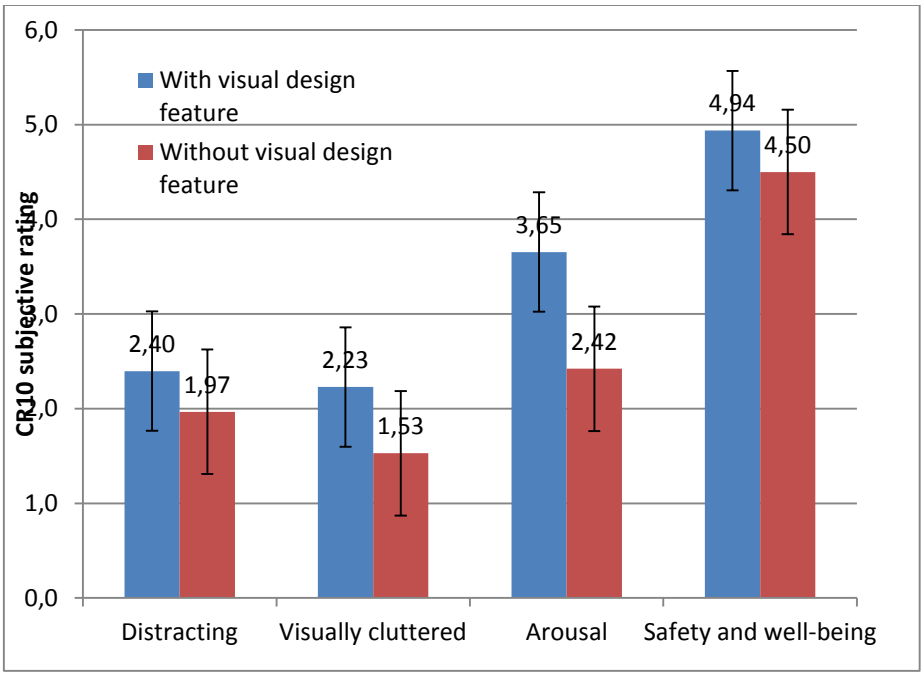


Figure 5: CR10 rating scale. There were four dimensions that were rated by the participants. They drove through two tunnels; one with the visual design features and one without. Standard error bars and the mean CR10 rating are indicated (n = 24).

The difference in the mean CR10 rating scores for the "distraction" dimension between the tunnel with the visual 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 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 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 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 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. Questionnaire 2

Questionnaire 2 contained many detailed questions about the participants' experiences of driving in the tunnel conditions. Questionnaire 2 was completed in post-experiment phase. The questions used a seven-point Likert scale where 1 represented "strongly disagree" and 7 represented "strongly agree". There were also seven open questions. All of the translated questions and responses can be found in table 1.

The questionnaire poses questions regarding the following topics that are subsequently superimposed on all of the different visual design features:

General attitudes towards tunnel driving

Perceived feeling of safety and well-being when in the tunnel

Feeling of orientation when in the tunnel

Feeling of speed

Monotony/under stimulation

Opinion regarding the tunnel entrance

Opinion regarding the optical cues (string lighting)

Opinion regarding the subterraneous junctions, the Middle section and the Lung

In the questionnaire, screen captures from the simulator were taken and used to remind the participants of the specific locations in the tunnel that the topics were related to. The screen capture pictures are also found below in conjunction with the relevant questions below.

The questionnaire responses are found in table 1 below. One-Sample Kolmogorov-Smirnov non parametric tests (two-tailed) were used to analyse distribution. Significant results are also reported in table 1.

Table 1: The participants indicated a number on the seven point Likert scale that most accurately reflects their experiences for each of the statements where 1 represented "strongly disagree" and 7 represented "strongly agree". The questions were posed in Swedish but are translated below.

Question number	Mean rating	Standard deviation	Frequency of responses	Question
Question 1†	-	-	24	"Did you notice the string lighting design features?"
Question 2	3.38	1.69	24	"I experienced the string lighting as distracting and that it took my attention away from driving"
Question 3	3.83	1.76	24	"I experienced the string lighting design features as visually stimulating/arousing"
Question 4	2.42*	1.21	24	"I experienced the string lighting design feature as monotonous/dull"
Question 5	2.92	1.91	24	"I experienced the string lighting design features as supportive when driving in the tunnel"
Question 6	3.38	1.88	24	"I experienced the string lighting as contributing to my feeling of safety and well-being".
Question 7†	-	-	10	"Do you have any additional comments regarding the string lighting design feature?"
Question 8	3.25	1.57	24	"I experienced the design of the exit ramps as distracting and they took my attention away from driving"
Question 9	5.21	1.62	24	"I experienced the design of the exit ramps as visually stimulating/arousing"
Question 10	4.71	1.97	24	"I experienced the design of exit ramps as aiding my feeling of orientation when in the tunnel"
Question 11	4.67	1.76	24	"I experienced the design of exit ramps as contributing to my feeling of safety and well-being"
Question 12†	-	-	11	"Do you have any additional comments regarding the design of the exit ramps?"
Question 13	4.0	2.25	24	"I experienced the Middle section-feature as distracting and that it took my attention away from driving"
Question 14	3.96	2.05	24	"I experienced the Middle section/mid-way point as visually stimulating/arousing"
Question 15	2.63	1.93	24	"I experienced the Middle section/mid-way point as aiding my feeling of orientation when in the tunnel"
Question 16	2.67*	1.61	24	"I experienced the Middle section/mid-way point as contributing to my feeling of safety and well-being"

Question 17†	-	-	8	”Do you have any additional comments regarding the Middle section/mid-way point?”
Question 18	3.54	1.77	24	”I experienced the design of the Lung design feature as distracting and it took my attention away from driving”
Question 19	4.71	1.63	24	”I experienced the Lung design feature as visually stimulating/arousing”
Question 20	4.17	1.61	24	“I experienced the string lighting as contributing to my feeling of safety and well-being”
Question 21†	-	-	5	”Do you have any additional comments regarding the design of the Lung design feature?”
Question 22	4.21	1.82	24	”I felt that it was easy to know roughly how far I had travelled in the tunnel”
Question 23	6.21*	1.47	24	”I thought that it was easy to see where the emergency exits were in the tunnel”
Question 24	3.92	1.5	24	”I thought that it was easy to keep to the legal speed limit in the tunnel”
Question 25	”Without”		7	”Which type of tunnel design did you prefer? (With string lighting; without; or neither).”
	”With”		14	
	”Neither”		3	
Question 26†	-	-	15	”Do you have any suggestion on how to improve the tunnel’s interior design?”
Question 27†	-	-	8	”Did you experience any particular problems when driving in the tunnels that you would like to comment?”
Question 28†	-	-	8	”Do you have any final comments that you would like to share?”

† Verbal responses/comments to open questions

* Statistical significance $p < 0.05$ (two-tailed)

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 16 km long tunnel wall/ceiling. Thus implying that a visually *rich* or cluttered environment is perceived as more stimulating/arousing and may then allay the onset of boredom.

The results reported from Questionnaire 2 should be viewed with a degree of caution due to the small sample size (n= 24). The ratings for questions 4, 16 and 23 are worth noting where the participants rated the string lighting as not being monotonous or dull (no. 4); the Middle section/mid-way point did not contributing to their feeling of safety and well-being (no. 16); and that they agreed strongly that it was easy to see where the emergency exits were in the tunnel (no. 23).

The results from question number 25 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.

5. CONCLUSIONS

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". This is a positive trait.

One of the major concerns with driving in long tunnels is that drivers will become inattentive due to the featurelessness of long road tunnel. Attentive drivers are essential to maintain acceptable levels of road safety in all road driving, but this is even more essential in road tunnel driving because of the dire consequences of even a small collision in a tunnel (especially if there is a vehicle fire) and the extraordinary difficulties for the emergency and rescue services. A tunnel with a vehicle fire should be closed to all traffic until such a time as the emergency services can extinguish the fire and expel the toxic fumes (unlike a surface vehicle fire). Collisions in tunnels have a far greater negative effect on road users' finances, health and mobility. In conclusion, it is recommended that road authorities pay particular attention to driver needs and driver limitations when designing long road tunnels.

6. REFERENCES

Alliance of Automobile Manufacturers (2003). *Statement of Principles, Criteria and Verification Procedures on Driver Interactions with Advanced In-Vehicle Information and Communications Systems*. Washington, DC: Alliance of Automobile Manufacturers.

Borg, G. & Borg, E., (2008). *Borg CR Scales Folder*. Stockholm, Borg Perception

Dingus, T. A., Antin, J. F., Hulse, M.C., & Wierwille, W. W. (1989). Attentional demand requirements of an automobile moving map navigation system. *Transportation Research, A23* (4), p. 301-315.

Green, P. (1999). *Visual and task demands of driver information systems* (Technical Report No. UMTRI-98-16). Ann Arbor, MI: UMTRI (The University of Michigan, Transportation Research Institute).

Kircher, K. & Ahlstrom, C. (2012). The impact of tunnel design and lighting on the performance of attentive and visually distracted drivers. *Accident Analysis and Prevention*, 47, 153-161.

Kircher, K. & Lundkvist, S.-O. (2011). *The influence of lighting, wall colour and inattention on traffic safety in tunnels – A simulator study*. Linköping, Sweden: VTI rapport 724A.

Maner, M.P. & Hancock, P.A. (2007). The influence of perceptual speed regulation on speed perception, choice, and control: Tunnel wall characteristics and influences. *Accident analysis*, 39, 69-78.

Patten, C., Ceci, R., Engström, J. & Anund, A. (2012). Tunnel Driving and the Effects of Visual Design. In press.

Patten, C & Mårdh, S. (2012). *Förbifart Stockholm Tunnel Utvärdering 2012*. VTI Rapport R759. VTI, Linköping.

Wierwille, W. (1993). Visual and manual demands of in-car controls and displays. In B. Peacock, W. Karkowski (Eds.) *Automotive Ergonomics* (pp. 299-320.) Washington, DC: Taylor & Francis.