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Tunnel Driving and the Effects of Visual Design

ViP Simulator Study

Technical Report

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FINDING A BETTER WAY

Preface

This study is the result of a well-developed and highly professional collaboration between authorities, researchers and industry in Sweden. It originated from an idea and a need to look further into the problem of human factors and tunnel safety related to tunnel design issues within the framework of the ViP Centre (centre for Virtual Prototyping and Assessment by Simulation). A successful collaboration often involves many professionals and that is the case also for this project. Many people have been involved in this project; Lena Nilsson who, as the director of ViP, supported the study and ideas behind it with helpful comments in its initial phase, Carina Fors for valuable input regarding the measurement of monotony and sleepiness, Ann Bolling for her help during the planning of the study, Anders Andersson, Björn Blissing and Mats Lidström for their great patience and invaluable work with the planning and programming of our model of the future Stockholm Bypass tunnel. From Volvo Technology Corporation, Rasmus Nisslert has greatly contributed to the analysis of the simulator driving parameters. The results from this study may be of significance for tunnel safety improvements in general and in particular for the on-going work of the Stockholm Bypass project in Sweden.

Ruggero Ceci
Project leader
Swedish Transport Administration

Quality review

Internal peer review was performed on 2011-06-29 by Dr Lars Eriksson (VTI) and Mr Carl Johan Andhill (Dynagraph) who reviewed and commented on the report. Dr Christopher Patten has made alterations to the final manuscript of the report. The research director of the project manager Assoc. Prof. Jan Andersson (VTI) examined and approved the report for publication on (2011-11-09).

Kvalitetsgranskning

Intern/extern peer review har genomförts den 2011-06-29 av Dr Lars Eriksson (VTI) och den 2011-09-22 av Herr Carl Johan Andhill (Dynagraph). Dr Christopher Patten har genomfört justeringar av slutligt rapportmanus. Projektledarens närmaste chef Docent Jan Andersson vid VTI har därefter granskat och godkänt publikationen för publicering (2011-11-09).

Content table

Sammanfattning

Tunnel körning anses vara farligare än körning på andra vägtyper på grund av att eventuella räddningsinsatser är mycket svårare i en tunnel och dessutom för att alla som befinner sig i en tunnel kan vara i fara vid exempelvis en fordonsbrand. Tunnlar kan dock lösa vissa problem med uppköp av stora markytor för vägbyggare i redan trångbodda städer som exempelvis Stockholm. Huvudsyftet med detta projekt har varit att utvärdera effekter av tunnel design på körförmåga samt även att studera trötta förare i olika vägmiljöer. Resultaten tyder på att det faktum att man befinner sig i en tunnel hade i sig mer effekt på prestationen än olika visuella designegenskaper i själva tunnelröret. Förarens tillstånd (pigg eller trött) hade också betydelse för körningen.

Försöksdeltagare (n= 24) fick köra två gångar; i ett trött tillstånd och i ett normalt alert eller piggt tillstånd. Det fanns fyra olika scenarier. En motorväg (BL), en tunnel med minimal belysning och design egenskaper (T1), en tunnel med stödjande takbelysning (T2) vilket liknar en modern tunnel där belysningen följer vägens geometri, och en tunnel som hade vilseledande takbelysning (T3). Ordningen för förartillståndet och scenarierna var balanserad. Tunnlarna var 17 km långa.

Effekter av olika visuell design från denna studie tyder på att 1) mentala belastningen blev högre mot slutet av tunneln jämfört med i början. Kvinnor hade högre mental belastning (peripheral detection task (PDT) och category ratio scale 10 (CR10)) än männen och i synnerhet för tunnel 3; och 2) laterala kontrollen ökade generellt mellan motorvägen och tunnel scenarier. Största skillnaden var dock mellan könen där kvinnor verkade påverkas mer av ändringar i den visuella designen än männen som var tämligen oberörda; och 3) effekten av förarens tillstånd var tydligt skilt mellan trötta och pigga men inga interaktionseffekter mellan trötta och vägtyp hittades.

Summary

Driving in tunnels is generally considered to be more *dangerous* than other type of road because, in the event of an accident in the tunnel, emergency and rescue teams are hampered by the tunnel environment. Moreover, a relatively minor incident such as a vehicle fire on the hard shoulder of an *open-air* motorway can have devastating consequences for everyone in the tunnel such as the Mont Blanc tunnel fire in 1999 where 39 people died (Luchian, 1999). Tunnels can, however, solve a number of traffic management problems in cities such as Stockholm. The main purpose of this study is to test the hypothesis that enhanced optical cues increase lateral control and reduce driver workload in tunnel driving. In addition, it is suggested that tunnel driving in general requires more mental effort than driving on an open road; that drowsiness leads to impaired lateral control performance; and also leads to impaired visual detection performance.

Participants (n = 24) were run twice; in a tired state and in a normal alert state. There were four different scenarios. A Highway (BL), a tunnel with minimal lighting and design characteristics (T1), a tunnel with supporting ceiling lights (T2) which is similar to a modern tunnel where the lights follow the road geometry, and a tunnel that had misleading ceiling lights (T3). The order for the driver's state and the scenarios was balanced. The tunnels were 17 km long.

Effects of different visual design of this study suggest that 1) the mental workload was higher towards the end of the tunnel compared to the beginning. Women exhibited higher mental load (peripheral detection task (PDT) and the category ratio scale 10 CR10)) than men, and especially for tunnel 3 (with misleading visual cues), and 2) lateral control generally increased between the highway and tunnel scenarios. The biggest difference was between the sexes, where women would appear to be affected more by changes in the visual design than the men who were relatively uninvolved, or 3) The effect of driver state (alert and drowsy) was clearly discernible but no interaction effects were found for driver state and road type (tunnel design).

1 Introduction

There are a few long road tunnels in existence, the longest of which is the Lærdal tunnel in Aurland, Norway at 24.5 km, constructed in 2000, followed by the Zhongnanshan tunnel in China at 18 km, constructed in 2007 and the Gotthard Road Tunnel in the Lepontine Alps, Switzerland at 16.9 km, constructed in 1980. A new tunnel project is underway in Sweden. The Stockholm By-pass Tunnel (SBT) is planned to be 17 km in length and completed in 2020. Safety measures are a high priority in long tunnels because the consequences of an accident can be far more devastating than in open-air surroundings; fire and asphyxiation are major concerns. By far the best countermeasure for this type of situation is to avoid the accident all together. Inattention, distraction, drowsiness (including monotony which may precede a drowsy state) are common factors that can cause accidents (Klauer, et al. 2006).

Tunnel driving increases driving demand experienced by the drivers. Tunnel driving increases exertion required for lateral control and increases eye fixation to the centre of the road. Thus increasing road centre gaze-concentration; increasing steering micro-corrections; and reducing lateral position variability (cf. Beall & Loomis, 1996; Chatziastros et al. 1999).

When driving there are numerous cues that the driver will use to control the trajectory of the vehicle; many of these cues are visual. Splay angle, parallax, visual ambient texture density, angular movement or optical flow all pertaining longitudinal and lateral control or speed and lane position. There is still no real consensus as to exactly which cues are used, however, splay angle seems to dominate for lateral control in straight-line driving. Splay angle is illustrated and explained on page 13 and in figure 1. Active eye movements and optical flow are important when cornering (Wilkie & Wann, 2002).

Compensatory behaviour that occurs as an effect of increased driving effort created by the tunnel environment, which is typically characterised in the form of e.g. reduced speed and increased headway are expected (cf. Patten, et al. 2004; Recarte & Nunes, 2002). The compensatory effect is, however, also expected to deteriorate the more a driver acclimatises to the tunnel environment. There are a number of theoretical mechanisms that explain the general trend towards desensitisation to potentially threatening objects viz. risk homeostasis or risk allostasis theory (cf. Fuller, 2005, 2008; Lewis-Evans & Rothengatter, 2009; Wilde, 1976, 1982, 1988). Vehicle speed in particular, is expected to increase and headway is expected to reduce the longer the participants drive in the tunnel environment.

Driver impairment, in terms of fatigue, is an integral and potentially dangerous part of everyday driving that all drivers are exposed to at one time or another. This study focuses on drivers with ‘normal’ levels of alertness as well as sleep deprived drivers in the context of long tunnel driving.

The design of the study is a within subject design with a balanced order for driving during daytime and night time. The night before the day time session the participants slept 7-8 hours. The night before the night time session the participants reduced their sleep to 4h (02h-06h).

1.1.1 Hypotheses

Differences between males and females were analysed pro forma and where no differences were found, the groups were merged.

H1

Tunnel driving requires more effort than baseline motorway driving.

$H1_{null}$ The tunnel environment does not require more effort than the baseline condition.

H2

Enhanced optical cues increase lateral control and reduce driver effort.

$H2_{null}$ Enhanced optical cues have no effect on lateral control or driver effort.

H3

Misleading optical cues impair lateral control and increase driver effort.

$H3_{null}$ Misleading optical cues have no effect on lateral control or driver effort.

H4 Initial compensatory behavioural effects resultant of tunnel driver gradually declines throughout the tunnel driving sections.

$H4_{null}$ The compensatory driving behavioural effects remain constant.

H5 The monotonous character of tunnel driving exacerbates the effects of sleepiness compared to non-tunnel driving.

$H5_{null}$ Tunnel driving does not give increased KSS scores when compared to non-tunnel driving.

Scope

The scope of this simulator study is to create a methodological framework of a 17 km (+ 2 km) long tunnel environment. The features are based in part on the planned Stockholm By-pass Tunnel (SBT). The tunnel’s direction is northbound only.

2 Method

2.1 Participants

Age:
The age groups range was 25-46 years, with a mean age of 36 years and a standard deviation of 6.56 years.

Driving experience:
Min 5 yrs. Category B (car) licence with a mean annual mileage of 1857 km.

Participant sample size:
n = 24 (12 male, 12 female)

2.2 Apparatus

- VTI’s Driving Simulator III in Linköping; car cabin.
- Peripheral detection task (PDT) equipment with a headset made according to TNO’s specifications The peripheral detection task (PDT) apparatus used in this study was designed according to the TNO specifications (van der Horst, 2010) that specified a head-mounted LED instead of the traditional head-up windscreen display.
- Vitaport for electro-oculogram (EOG) eye movement measure (Jammes, Sharabaty & Esteve, 2008).

2.3 Procedure

A journey of 20 km at 90 km/h requires approximately 12 minutes. A within subject design would require approximately 1:10 hrs. (60 minutes driving + 10 minutes break) simulator time per participant including familiarisation time. Gross time requires approx. 2 hrs. per participant including prepping and post questionnaires, debriefing and departure. The experimental conditions and the baseline section order were balanced. All drives started with a familiarisation drive (FD) of 17 km of non-tunnel, motorway driving. Short breaks of up to 2 minutes between conditions were used for four CR10 questions on monotony, frustration, sleepiness and mental effort. The participants remained in the simulator. After each break, irrespective of the impending condition, the following drive started from the lay-by stop with a short non-tunnel motorway section of approximately 500 m to bridge the gaps between conditions. The procedure prescribed in Table 1 below was applied to both participant groups.

Table 1: Procedure for the ViP tunnel study.

Participant preparation	Road environment								
	Familiarisation drive (FD)	Break	Baseline (BL)	Break	Tunnel 1 (T1)	Break	Tunnel 2 (T2)	Break	Tunnel 3 (T3)
Measures: 1. PDT 2. SWRR 3. Speed 4. MeanLP 5. KSS 6. EOG 7.CR10									

2.3.1 Participant instruction

- Participants had a short break (2 minutes) between each road scenario section (experimental conditions) where they were instructed to leave the motorway and

drive into the lay-by and complete the modified CR-10 questions (2-3 questions).
- The KSS scale (Anund, 2009) was answered verbally twice for each condition (every four minutes of experimental time and should reflect to the previous four minutes of driving).
- The PDT signals are responded to throughout all of the conditions.
- Drivers are instructed to drive in the centre lane and to otherwise drive as they would normally, but adhering to basic traffic rules and regulations.

The peripheral detection task (PDT) consists of a reaction time metric measured in seconds (s) and a miss rate metric measured in per cent (%). A missed PDT signal is when the participant fails to react (by pressing the PDT button) to the illuminated diode within two seconds (see Appendix 1).

Pre-experiment instructions:
Three days before the test the participants were requested to complete a sleep and wake diary. They were also requested to complete a questionnaire about their background and their general health.

Before the day of the experiment, the participants were requested to:
- Avoid consuming alcohol 72 hrs before the experiment.
- Avoid using makeup on the morning of the experiment (because of the EOG electrodes).
- Avoid coffee, tea and soft drinks with caffeine (e.g. Coke Cola, Red Bull etc.) 3 hrs before arriving at VTI.

Before the daytime experiment the participants were requested to:
- Sleep at least 7 hrs the two previous nights before the experiment.
- Go to bed no later than midnight and to wake up no later than 09:00 hrs.
- Avoid daytime napping the three days preceding the experiment.

Before the night time experiment the participants were requested to:
- Only sleep between the hours of 02-06:00 the night before the night time drive.
- Sleep at least 7 hrs the previous night (i.e. two nights before the night time drive) and to go to bed no later than midnight and to wake up no later than 09:00 hrs.
- Avoid daytime napping the three days preceding the experiment.
- The staff on duty were able to make sure that nobody nodded off to sleep.
- Make their own way to VTI (Linköping) if their appointment was at 22:00 hrs. All participants with appointments after 01:00 were collected by taxi. All of the night time participants were taken home by taxi.

All participants were informed of the possibility of opting out of the experiment in accordance with the ethics board recommendations. Informed consent forms were also completed by all participants including permission to use video recording from the experiments.

2.3.2 Testing

The drivers’ state and gender were balanced in a within subject design as shown in table 3 below.

The participants were donned with electrodes for vertical and horizontal electro-oculogram (EOG) for recording of eye blinks (only on one eye) . The PDT device was fitted with a micro-switch and headset.

2.4 Design

Table 2: Experimental design for simulated tunnel driving. A 2 x 4 within-group design was used.

Within-subject design		Road environment			
		Baseline (BL)	Tunnel 1 (T1)	Tunnel 2 (T2)	Tunnel 3 (T3)
Driver state	Alert				
	Sleepy				

Note: Short breaks of up to two minutes between road environment conditions were used. The participants remained in the simulator. After each break, irrespective of the impending condition, the following drive started from a lay-by or roadside pit stop with a short non-tunnel motorway section of approximately 500m to bridge the gaps between conditions.

The order of the experimental conditions and driver state were balanced. All participants started with a familiarisation drive (FD) of 12 km of non-tunnel, rural driving. The sleepy drivers followed the same experimental design as shown in Table 2 in an evening/night setting to utilise the circadian rhythm of participants.

Table 3: Order of conditions. FD = familiarisation drive, BL = baseline, T1 = tunnel 1, T2 = tunnel 2, T3 = tunnel 3.

Participant no.	Order					Drive 1	Drive 2	Male=0 Female=1
1	FD	BL	t1	t2	t3	Dagtid	Kväll	1
2	FD	BL	t1	t3	t2	Kväll	Dagtid	0
3	FD	BL	t2	t3	t1	Dagtid	Kväll	0
4	FD	BL	t2	t1	t3	Kväll	Dagtid	1
5	FD	BL	t3	t1	t2	Dagtid	Kväll	1
6	FD	BL	t3	t2	t1	Kväll	Dagtid	0
7	FD	t1	BL	t2	t3	Kväll	Dagtid	1
8	FD	t1	BL	t3	t2	Dagtid	Kväll	0
9	FD	t1	t2	BL	t3	Dagtid	Kväll	1
10	FD	t1	t2	t2	BL	Kväll	Dagtid	0
11	FD	t1	t3	BL	t2	Kväll	Dagtid	1
12	FD	t1	t3	t2	BL	Dagtid	Kväll	0
13	FD	t2	t1	t3	BL	Kväll	Dagtid	0
14	FD	t2	t1	BL	t3	Dagtid	Kväll	1
15	FD	t2	t3	t1	BL	Dagtid	Kväll	0
16	FD	t2	t3	BL	t1	Kväll	Dagtid	1
17	FD	t2	BL	t1	t3	Kväll	Dagtid	0
18	FD	t2	BL	t3	t1	Dagtid	Kväll	1
19	FD	t3	t1	t2	BL	Dagtid	Kväll	0
20	FD	t3	t1	BL	t2	Kväll	Dagtid	1
21	FD	t3	t2	t1	BL	Kväll	Dagtid	0
22	FD	t3	t2	BL	t1	Dagtid	Kväll	1
23	FD	t3	BL	t2	t1	Kväll	Dagtid	1
24	FD	t3	BL	t1	t2	Dagtid	Kväll	0

2.4.1 Scenario descriptions

The simulated scenarios that constitute five different scenarios include three experimental tunnel conditions (T1-3), one baseline condition (BL) and a familiarisation driving (FD) section. The general features of the tunnel scenario environments are intended to be a general replica of the planned tunnel construction of the Stockholm By-pass project. Road dust and dirt impairing retro-reflection from standard lane markings is a common problem in tunnels and are therefore included into the simulated tunnel design. Audio cues are also valuable characteristic of tunnel driving and in particular because these cues change when in tunnels due in part to audio reflection, however, due to budget constraint, was not possible to simulate.

Figure 1 below is an illustrated example of the angular movement and splay angle. Angular movement and splay angle are geometrical properties of the optical flow from road texture. This may more or less coincide with the splay angle and angular movement of the road markings, depending mainly on the trajectory of the car.

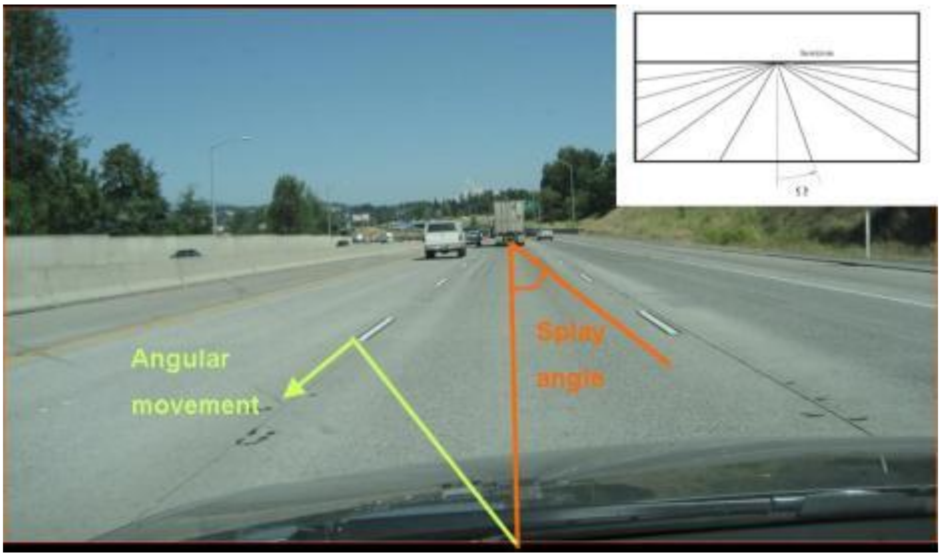


Figure 1: An illustration of angular movement and splay angle which is relevant for lateral control when driving straight ahead.

Baseline

The baseline (BL) scenario condition comprised:

- A simulated motorway section, Swedish motorway with six lanes (three in each direction).
- A speed adjusted road noise (tyres and road surface)
- An autonomous traffic model (the Weaving road user algorithm model, Olstam, 2009) was activated (at approx. 4 sec. level of traffic intensity) in each lane.
    - Only passenger cars will be used in the autonomous traffic to reduce obscuring visual cues.
- The distance driven was approximately 20 km.
- Each road scenario section ended with a short lay-by stop (max 2 minutes).
- A car with daylight running lights in dipped-beam mode was simulated.
- The sign posted speed limit was 90 km/h.

Tunnel 1

The tunnel 1 (T1) scenario condition comprised the following:

- A simulated motorway section in a tunnel, with three lanes travelling in the same direction.
- Road curvature and gradient in approximate accordance with the Stockholm By-pass blueprints.

    - This did not include entrance and exit ramps and other possible design features from the blueprints.
- The distance driven was approximately 18 km for each tunnel.
- Each road scenario section ended with a short lay-by stop (max 2 minutes).
- A standard (Södra länken) ceiling lighting.
- A wall and roof visual-texture of a typical Stockholm blasted bedrock surface.
- Traffic intensity was at the Weaving Model’s 4 sec. level of intensity.
- A road noise (tyres and road surface) was duplicated for respective speed limits from a real tunnel.
- There were no redundant entry and exit ramps in the present study.
- Road dust and dirt impairing retro-reflection from standard lane markings.
- The sign posted speed limit is 90 km/h.

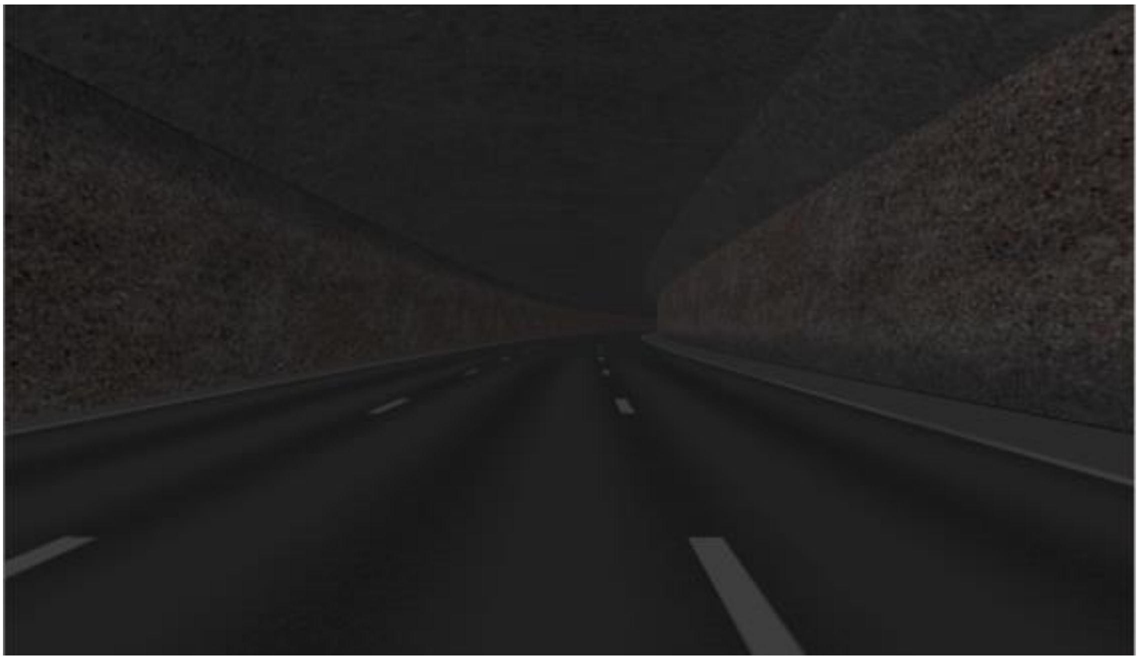


Figure 3: An illustration of tunnel 1 (T1) with toned down optical cues.

Tunnel 2

The tunnel 2 (T2) scenario condition comprises the following:

- The same as T1 above with the exception of:
    - A ceiling lighting design that provides optical information emphasising and utilising splay angle and velocity cues (e.g. angular movement, visual surface texture) to support appropriate speed, appropriate lane position alignment and reduce driver effort.

Figure 4: An illustration of tunnel 2 (T2) with supporting optical cues.

Tunnel 3

The tunnel 3 (T3) scenario condition comprises the following:

- The same as T1 above with the exception of:
    - a misleading optical design
        - by exaggerating splay angles and angular movement providing subtle false alignment cues to exasperate driver effort.

Figure 5a: An illustration of tunnel 3 (T3) with misleading optical cues.

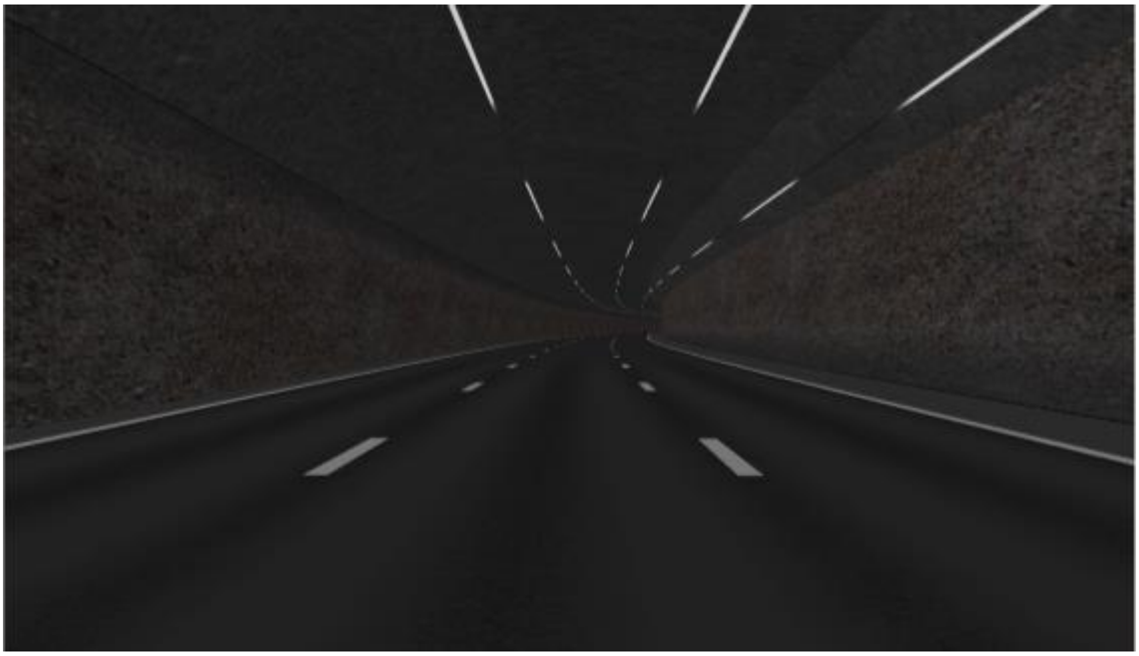


Figure 5b: An illustration of tunnel 3 (T3) with misleading optical cues.

Familiarisation drive

The familiarisation drive (FD) scenario comprises the following:

- A motorway route, non-tunnel driving scenes.
- Other vehicles were phased in successively.
- The distance to be driven is approximately 12 km.
- Each road scenario section ends with a short lay-by stop (max 2 minutes).
- The FD phase is not an experimental condition per se; the purpose was to provide participants with simulator familiarisation.


Figure 6a: An illustration of the baseline condition (BL).

Figure 6b: An illustration of the baseline condition (BL).

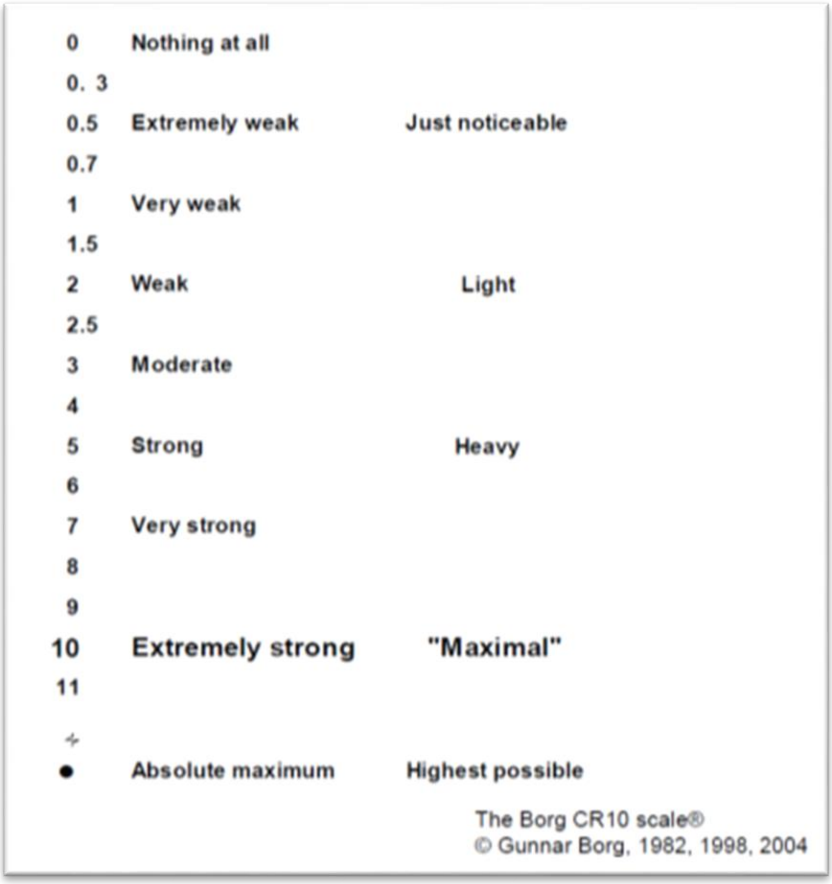
2.4.2 Dependent variables

An external PDT-system was used (cognitive workload). The PDT is invasive where participants are required to react to the PDT stimuli and depress a micro-switch which is attached to the left index finger.

Dependent variables:

- Simulator III vehicle measures
    - Steering wheel reversal rate (SWRR)
    - Mean speed
    - Headway (HW)
    - Mean lane position (MLP)
- Peripheral detection task (PDT) workload measure
    - PDT reaction time (PDT rt)
    - PDT miss rate (PDT %)
- Subjective workload scale
    - A CR-10 subjective scale based upon two NASA-TLX dimensions (questions on ‘effort’, ‘frustration’).
- Subjective sleepiness/alertness scale
    - Karolinska sleepiness scale (KSS)
- Physiological measures
    - Blink duration

The CR10 scale was developed as a category ratio scale and was analysed accordingly using the ten point scale with verbal anchors (Borg & Borg, 2008). The CR10 is a subjective scale that can be used to convey subjectively experienced factors such as effort. The CR10 was originally developed for psychophysical measuring of physical exertion.



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

Figure 7: English version of the Borg CR10 scale with verbal anchors from Borg & Borg (p. 2, 2008). Printed with permission.

Blink duration was extracted from the vertical EOG channel by using an automatic blink detection algorithm (Jammes, Sharabaty et al. 2008).

Mean Lane Position (MLP) – The mean distance measured perpendicular from the right front wheel to the closest right lane. Lane changes are excluded. A mean lane position of 0.8775 m is in the centre of the lane.

The mean speed calculated when there is no lead vehicle or when the time headway (THW) to the lead vehicle is greater than 4 seconds. Lane changes are excluded.

Time Headway (THW) – The mean time headways (distance To Lead Vehicle/ego Vehicle Speed) calculated for each lead vehicle when the THW <= 4 seconds. Lane changes are excluded. A lane change is defined to begin 200 meters before the first wheel crosses the lane marker and to end 200 meters after all wheels are within the new lane.

The following metrics are used as an indirect measure of effort:

Peripheral detection task (PDT) reaction time
PDT miss rate
CR10 scale (questions on ‘effort’, ‘monotony’ and ‘frustration’)
Mean speed

The following metrics are used as an indirect measure of lateral control:

Steering wheel reversal rate (SWRR) 0.1 degrees
SWRR 3.0 degrees
Mean lane position

The following metrics are used as an indirect measure of the initial compensatory behavioural effects:

Entry-Exit data for 500m and 1750m:
- Mean speed
- Mean lane position

The entry-exit data is the first and last 500m or 1750m sections of road that are included in the analyses of the various metrics.

Dependent variables:
The following metrics are calculated for each of the scenarios:

Mean Speed – The mean speed calculated when there is no lead vehicle or when the time headway (THW) to the lead vehicle is greater than 4 seconds. Lane changes are excluded.

Mean Lane Position (MLP) – The mean distance measured perpendicular from the right front wheel to the closest right lane. Lane changes are excluded. A mean lane position of 8.775 m is in the centre of the lane.

Time Headway (THW) – The mean of the mean time headways (distanceToLeadVehicle/egoVehicleSpeed) calculated for each lead vehicle when the THW <= 4 seconds. Lane changes are excluded.

Steering Wheel Reversal Rate (SWRR) – The number of reversals per minute calculated after first applying a low pass filter to the steering wheel signal with a cut off frequency of 0.6 Hz. The gap size is set to three degrees and 0.1 degrees.

PDT Reaction Time – The mean reaction time to the PDT stimuli. Reaction times lower or equal to 200 ms and greater or equal to 2 seconds are not considered.

Missed PDT stimuli – A missed stimuli is defined as when a PDT stimuli is not responded to or if the reaction time to the stimuli is greater than 2 seconds.

Scenarios
BL: Baseline, no tunnel
T1: Tunnel 1 (no optical cues)
T2: Tunnel 2 (optical cues)
T3: Tunnel 3 (misleading optical cues)

2.4.3 Statistical analysis

The data was analysed using a General Linear Model repeated measures analysis of variance and Students t-test. A pro forma control of sphericity was done on all analyses and appropriate action was taken where sphericity was not assumed (e.g. a Greenhouse-Geisser or a Huynh-Feldt adjustment).

Alpha was set at .05 unless adjusted for e.g. multiple comparisons (i.e. Bonferroni). ‘Tendencies’ were reported where the significance levels were close to alpha. The exact p-values were reported, however, so that the reader could form their own opinion.

In terms of analysis of the driving data the road/tunnel was segmented because of known and/or expected effects in different sections or segments of the driving such as acclimatisation phases, initial tunnel entry effects, monotony effects in mid and end segments of the drives etc.

3 Results

The results are divided up according to the metrics or dependent variable used and at the end of the Results section, the results are summarised by the hypotheses.

3.1 Peripheral detection task (PDT)

The peripheral detection task (PDT) consists of a reaction time metric measured in seconds (s) and a miss rate metric measured in per cent (%). A missed PDT signal is when the participant fails to react (by pressing the PDT button) to the illuminated diode within two seconds.

In figure 8, the main effect of driver state was significant (F (1, 22) 12.414, p < .01) with sphericity assumed for the mean PDT reaction times. The PDT reaction times are significantly longer for the drivers when they are drowsy. The main effect of road type was not significant. One-tailed t-test planned comparison of road types BL-T2 for drowsy drivers (t (1, 23) 1.871, p= .05) showed a significant but small effect of a 'normal' tunnel (T2) and standard motorway driving when drowsy.

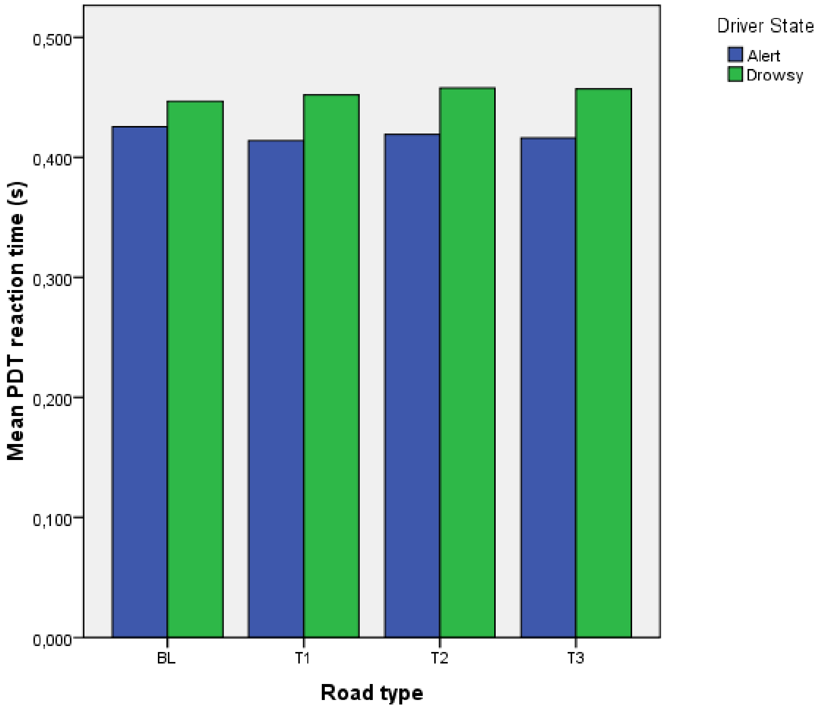


Figure 8: Effects of road type and driver state on PDT reaction time (s).

In figure 9 below, there was a significant main effect of driver state (all drivers) (F (1, 22) 4.173 p= .05). Road type was not significant. There was not a statistically significant interaction between road type and driver state (F (3, 66) 1.823 p = .15).

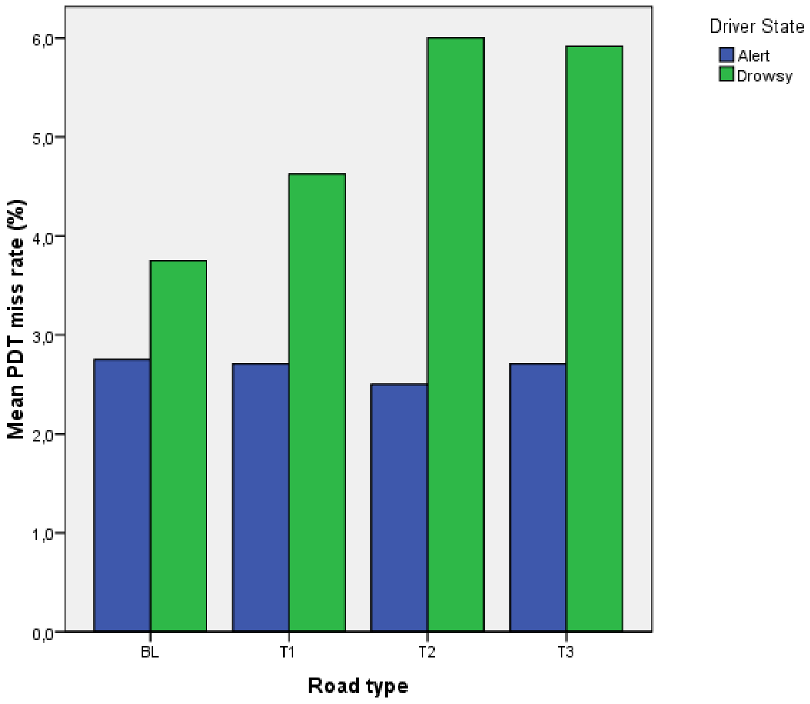


Figure 9: Effects of road type and driver state on PDT miss rate (%).

3.1.1 Entry-Exit Analysis 500m

In figure 10 below, the PDT reaction times (all drivers) for the first and last 500 m of each entry-exit section had a significant main effect (F(1, 22) 41.586 p= < .001). Road type was not significant. The reaction times were lower in the first 500m section than the last 500 m suggesting increased workload.

The road type order was balanced whereupon one would not expect the Baseline (BL) condition to be different between entry and exit reaction times (in figure 10 below) unless there is an effect of the short stop for subjective scales that preceded every new condition, including the baseline condition.

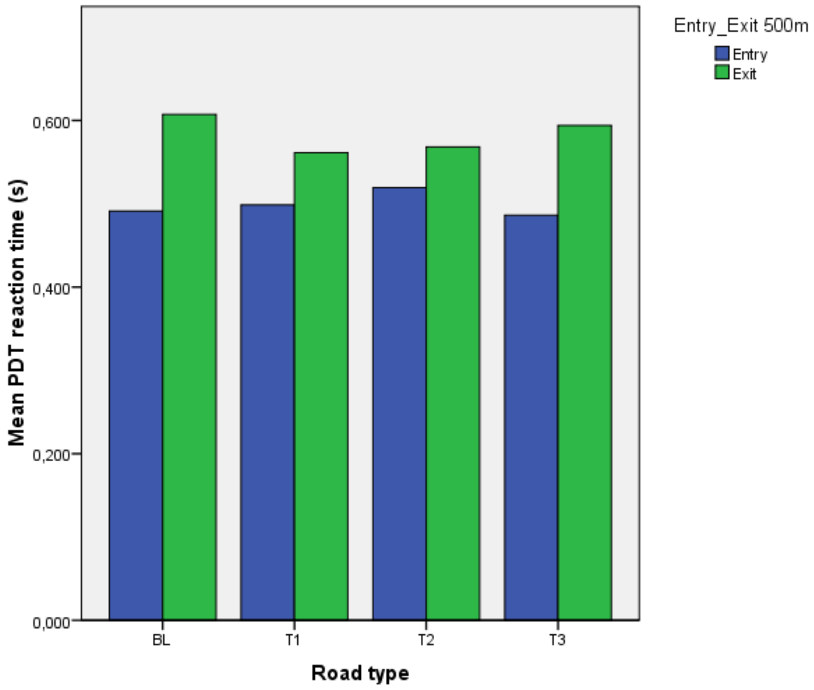


Figure 10: Effects of road type and Entry-exit 500m on PDT reaction time (s), both driver states (alert and drowsy).

3.1.2 Entry-Exit Analysis 1750m

In figure 11 below, the PDT reaction times for the first and last 1750 m of each entry-exit section had a significant main effect (F(1, 22) 79.726 p< .001) for driver state (alert and drowsy) (F(1, 22) 5.133 p< .05). Road type was not significant. The reaction times were lower in the first 1750 m than the last 1750 m of each road type-section suggesting increased workload.

The PDT reaction times for the first and last 1750 m of each entry-exit section and the drivers' state (alert and drowsy) with a significant interaction effect (F(1, 22) 5.693 p< .05). Figure not shown.

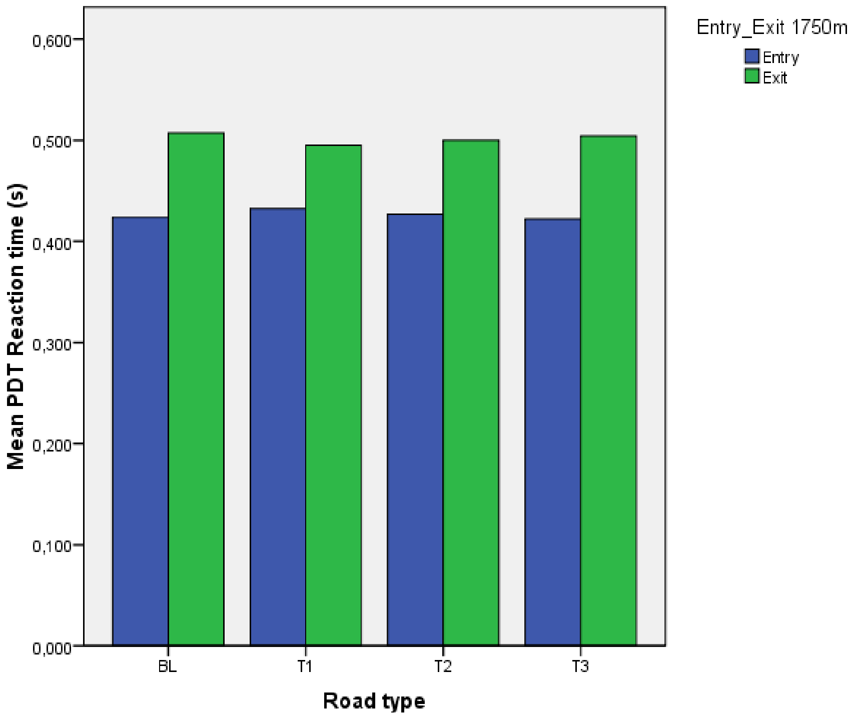


Figure 11: Effects of road type and Entry-exit 1750m on PDT reaction time (s), both driver states (alert and drowsy).

In figure 12 below, the PDT reaction times for the first and last 1750 m of each entry-exit section and the drivers' state (alert and drowsy) had a significant main effect (F(1, 22) 5.133 p= .034) for both driver states (alert and drowsy). Road type was not significant. The reaction times were lower in the first 1750 m than the last 1750 m of each entry-exit section suggesting increased workload.

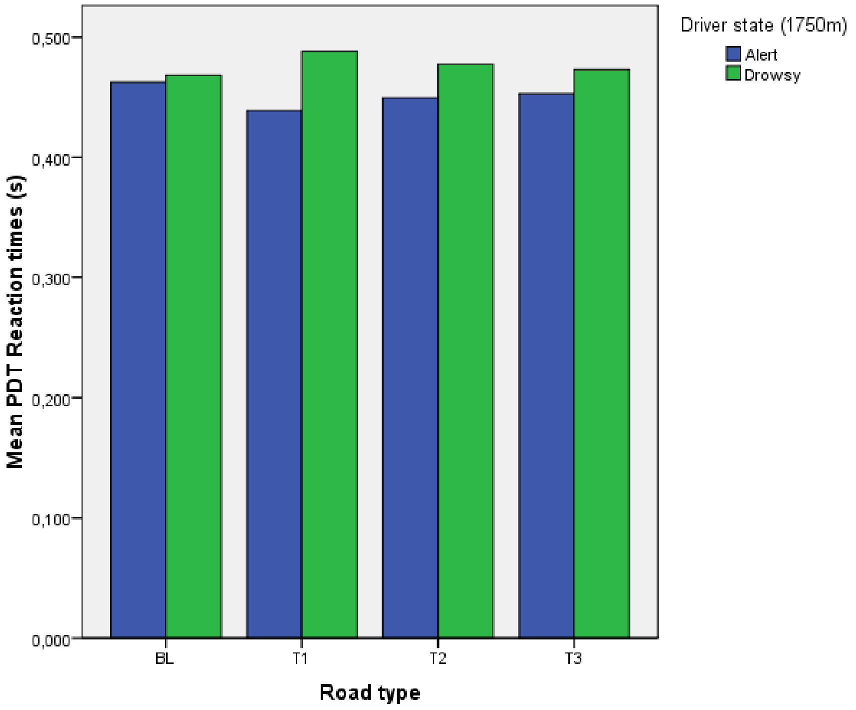


Figure 12: Effects of road type and driver state (alert and drowsy) using Entry-exit 1750m data selections.

In figure 13 below, the PDT reaction time metric had an interaction tendency for road type and sex (F (3, 63) 2.602 p= .06) with the sphericity assumption not violated (alert and drowsy drivers condensed).

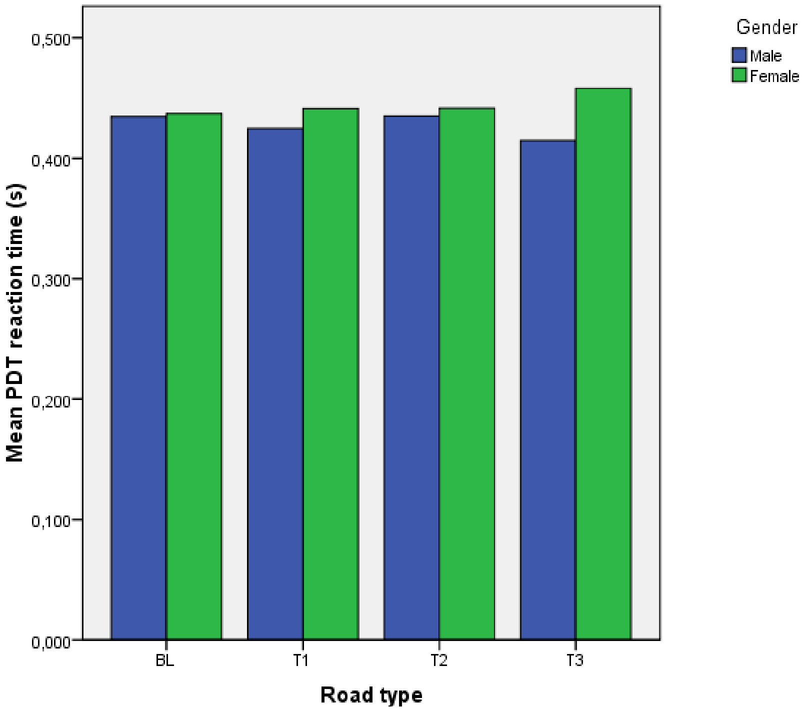


Figure 13: Effects of road type and gender on PDT reaction time (s), both driver states (alert and drowsy).

3.2 CR10

Monotony

In figure 14 below, the main effect for road type was significant (F (3, 64) 6.176 p < .01) for the CR10 Monotony question (alert driver group only). The verbal description between a CR10 3.6 score is verbalised as ‘moderate’ whereas a CR10 score of 5.0 is verbalised as being ‘strong’. Using a Bonferroni multiple comparisons adjustment, the pairwise comparisons between Baseline-Tunnel 1 and Baseline-Tunnel 4 were statistically significant.

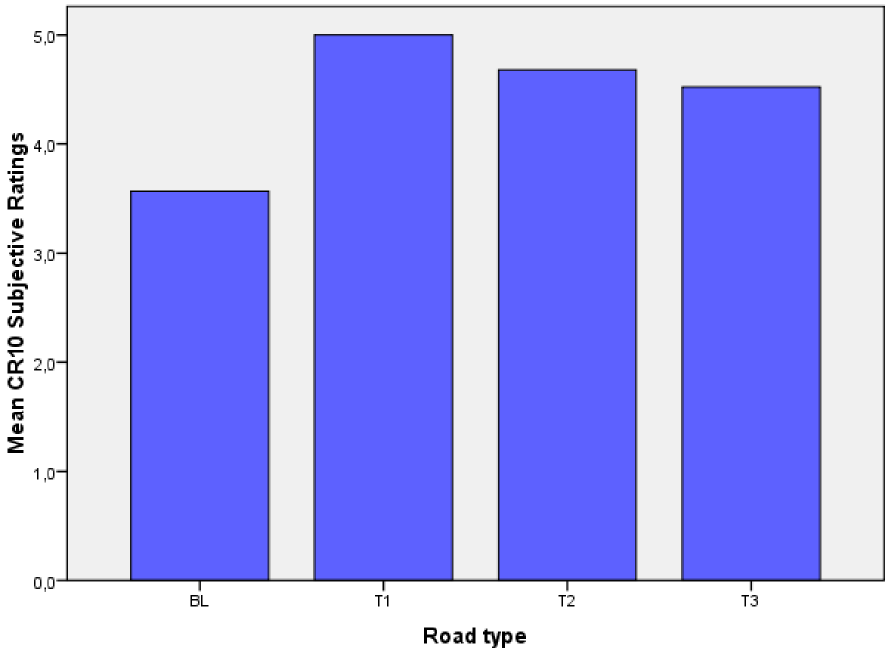


Figure 14: Effects of road type on CR10 Monotony (subjective scale), alert driver state only.

In figure 15 below, the main effect for road type was significant (F (3, 54) 4.863 p < .01) with sphericity assumed for the CR10 Monotony question for both driver state groups. Driver state *per se* was not significant.

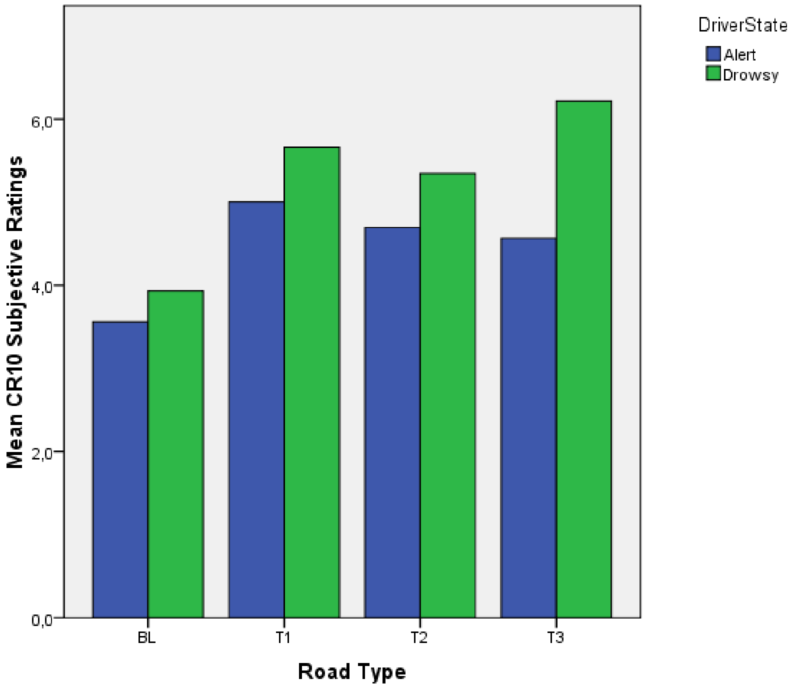


Figure 15: Effects of road type and driver state (alert and drowsy) on CR10 Monotony (subjective scale).

In figure 16 below, the CR10 monotony question (all drivers) had a significant main effect for road type (F (3, 51) 5.812 p< .01) and a main effect of gender as a between subject variable (F (1, 17) 7.346 p< .05) with adjustment for multiple comparisons (Bonferroni) for both driver groups (alert and drowsy).

There were also tendencies for driver state (alert and drowsy) (F 1, 17) 3.516 p=.078) and an interaction tendency for road type and sex (F (3, 51) 2.365 p= .082).

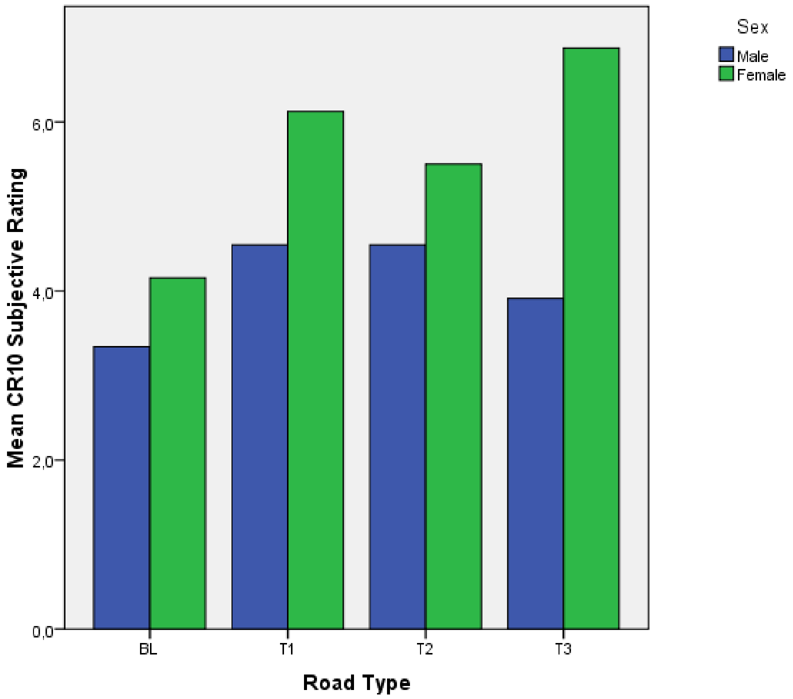


Figure 16: Effects of road type and sex on CR10 Monotony (subjective scale) both driver states (alert and drowsy).

Frustration

In figure 17 below, the main effect was not significant (alert drivers only), however, using a Bonferroni multiple comparisons adjustment, the pairwise comparison between the baseline (BL) and tunnel 3 (T3) was significant for the CR10 Frustration question.

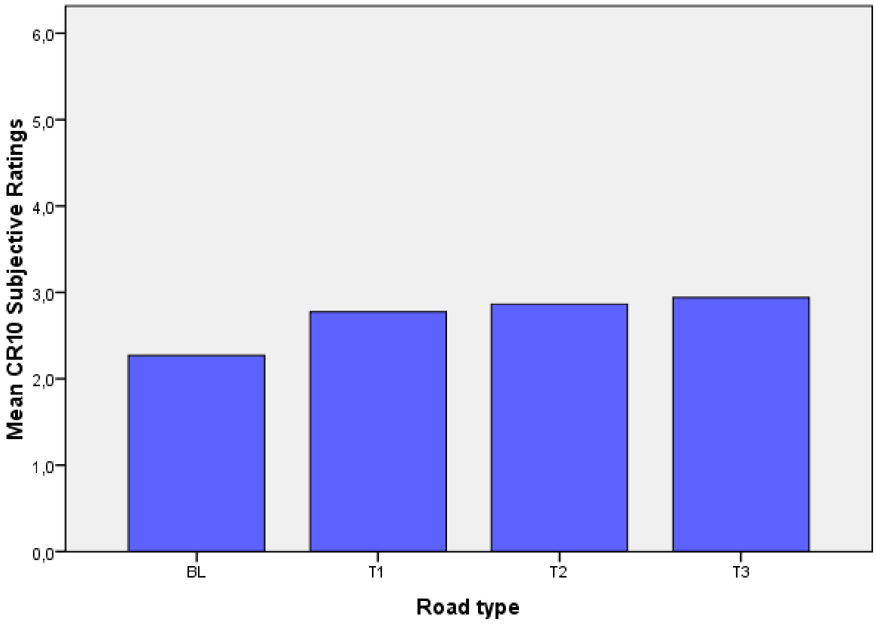


Figure 17: Effects of road type on CR10 Frustration (subjective scale), alert driver state only.

In figure 18 below, the CR10 frustration question (all drivers) had a significant interaction effect for road type and sex (F (3, 51) 2.979 p< .05) and a main effect of gender as a between subject variable (F (1, 17) 5.618 p< .05) with adjustment for multiple comparisons (Bonferroni) for both driver groups (alert and drowsy).

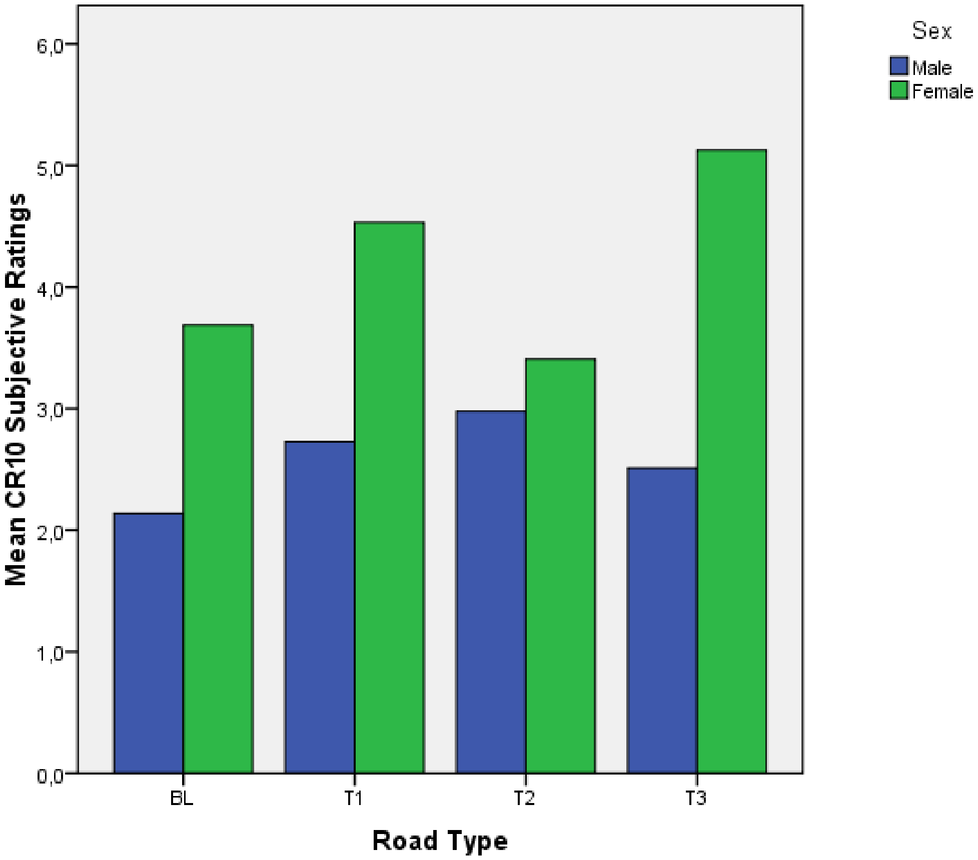


Figure 18: Effects of road type and sex on CR10 Frustration (subjective scale) both driver states (alert and drowsy).

In figure 19 below, the CR10 frustration question had a significant main effect for driver state (alert and drowsy) (F (1, 17) 6.936 p< .05). Gender was not significant.

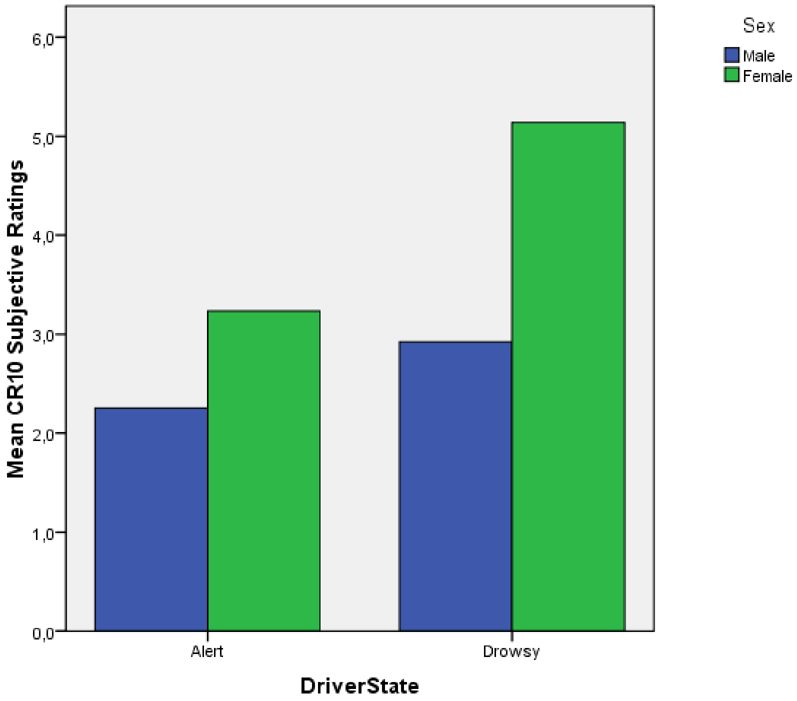


Figure 19: Effects of driver state (alert and drowsy) and sex on CR10 Frustration (subjective scale).

Mental effort

In figure 20 below, the main effect was significant for driver state (F (1, 18) 6.171 p< .05) for the CR10 Mental Effort question. Road type was not significant.

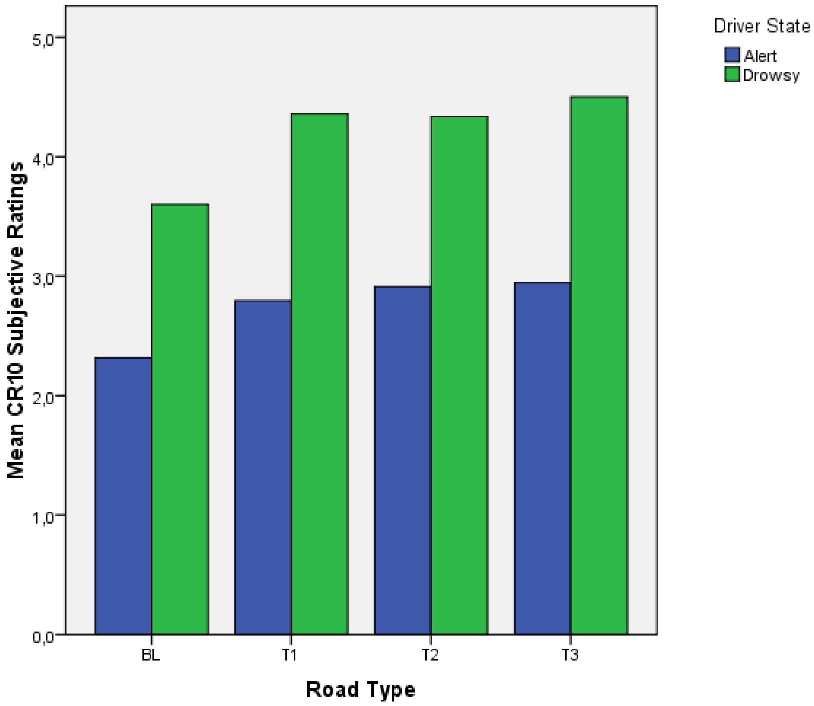


Figure 20: Effects of road type and driver state (alert and drowsy) on CR10 Mental Effort (subjective scale).

In figure 21a below, the CR10 mental effort question had a significant main effect of gender as a between subject variable (F (1, 17) 6.871 p= .018) with adjustment for multiple comparisons (Bonferroni) for both driver groups (alert and drowsy). Road type was not significant. The verbal description between a CR10 2.5 score is verbalised as being between ‘weak’ and ‘moderate’ whereas a CR10 score of 4.5 is verbalised as being just under ‘strong’.

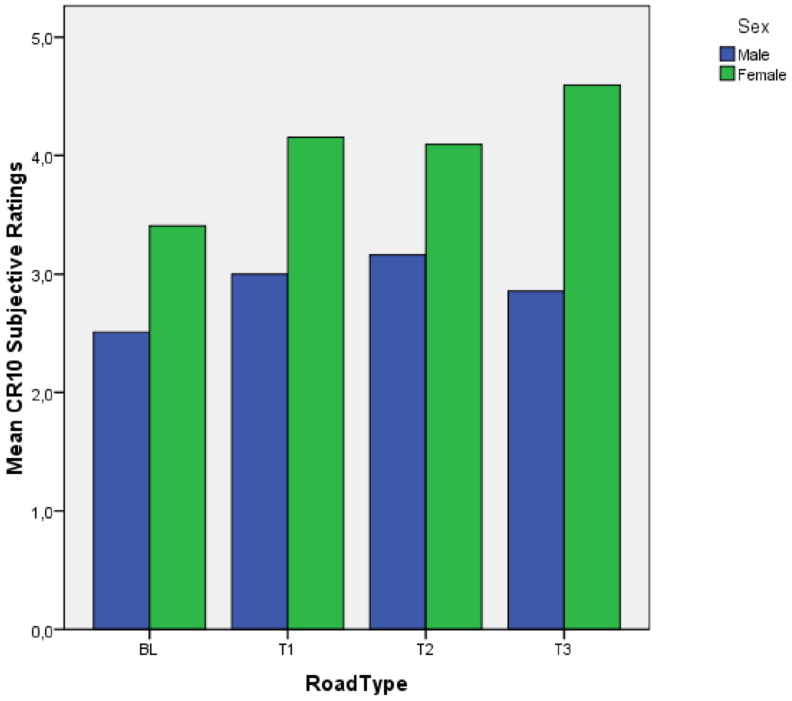


Figure 21a: Effects of road type and sex on CR10 Mental Effort (subjective scale) both driver states (alert and drowsy).

Sleepiness

In figure 21b below, the CR10 sleepiness question had a significant main effect of driver state as a within-subject variable (F (1, 16) 24.597 p< .001). The mean CR10 rating in the ‘alert’ driver state group was 3.8 and 6.0 in the ‘drowsy’ driver state group. Neither road type nor sex was statistically significant. The verbal description between a CR10 2.5 score is verbalised as being between ‘weak’ and ‘moderate’ whereas a CR10 score of 6.0 is verbalised as being between ‘strong’ and ‘very strong’.

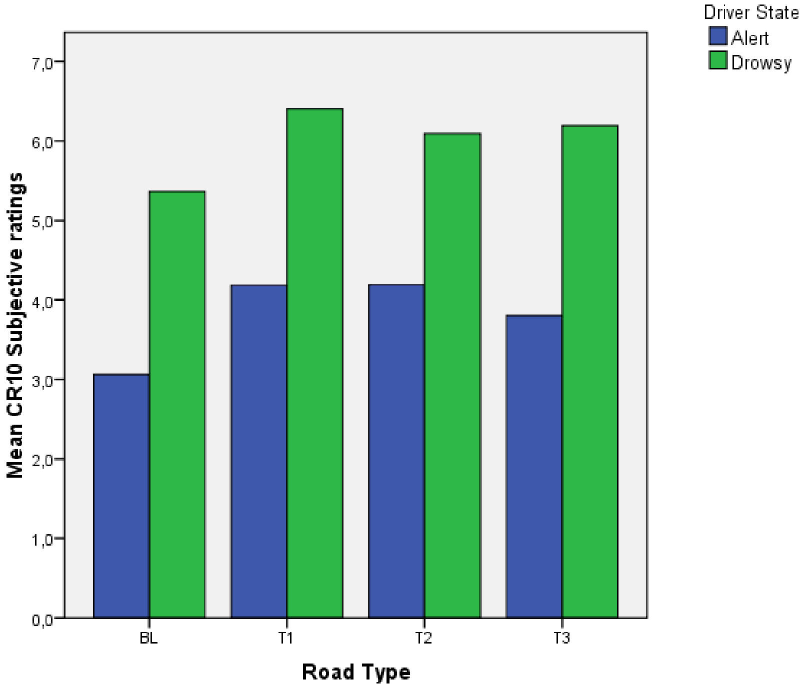


Figure 21b: Effects of road type and driver state on CR10 Sleepiness (subjective scale).

3.3 Mean Lane Position

Mean Lane Position (MLP) – The mean distance measured perpendicular from the right front wheel to the closest right lane. Lane changes are excluded. A mean lane position of 0.8775 m is in the centre of the lane.

In figure 22 below, there was a significant main effect of road type on mean lane position (F(3, 69)=7.716, p<.001), where the tunnel conditions induced a significant shift towards the right in the lane compared to baseline (no tunnel; see Figure 2). Among the contrast BL vs. T1, T1 vs. T2 and T2 vs. T3 the first contrast (BL vs. T1) was significant (F(1, 22)=12.84, p<.01). Drowsiness or drowsiness order did not affect mean lane position and there were no significant interactions.

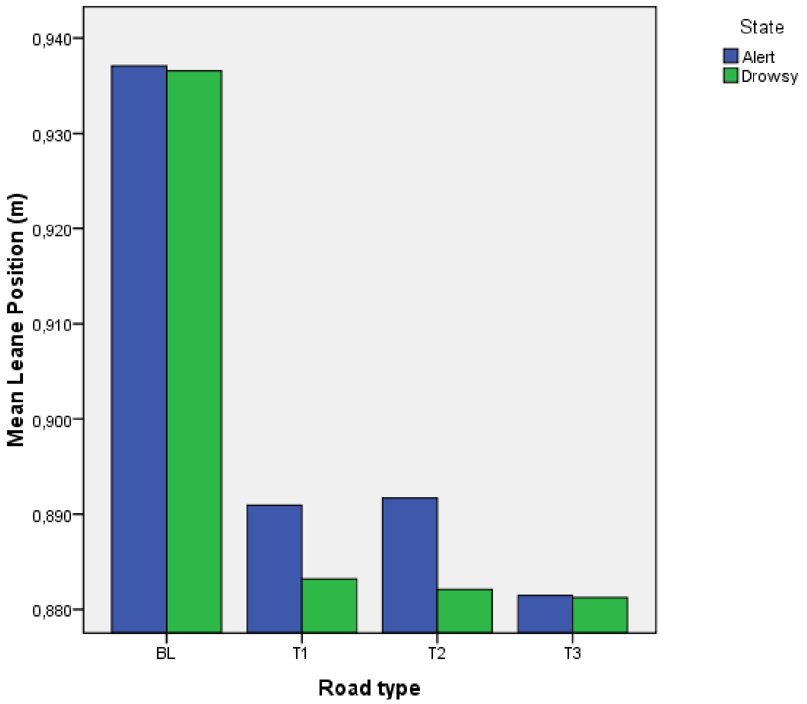


Figure 22: Effects of road type and driver state (alert and drowsy) on mean lane position (m). A mean lane position of 0.8775 m is in the centre of the lane.

In figure 23 below, there was a main effect of road type for mean lane position for alert drivers only (F (3, 66) 4.511 p< .01) and an interaction tendency of road type and gender (F (3, 66) 2.395 p= .076).

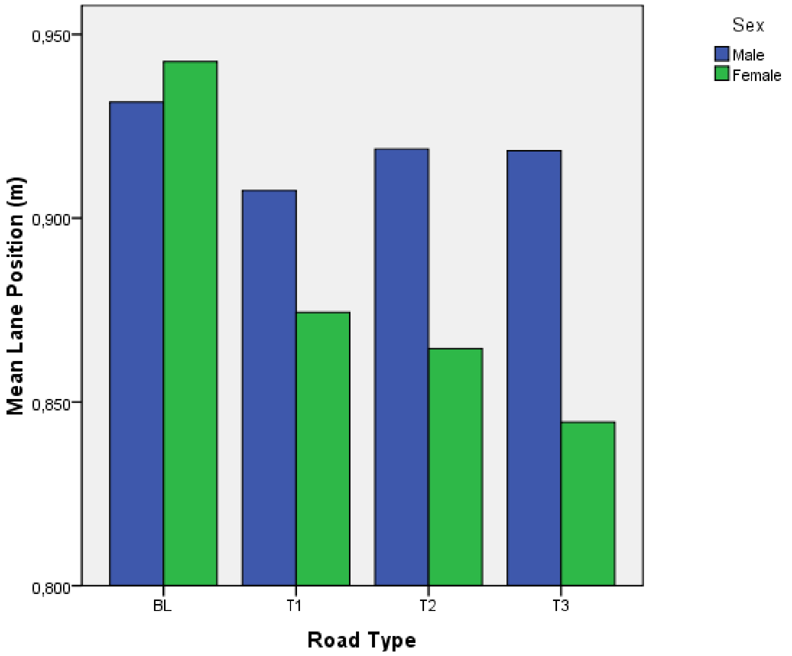


Figure 23: Effects of road type and sex on mean lane position (m), both driver states (alert and drowsy). A mean lane position of 0.8775 m is in the centre of the lane.

3.4 Mean Speed

The mean speed calculated when there is no lead vehicle or when the time headway (THW) to the lead vehicle is greater than 4 seconds. Lane changes are excluded.

In figure 24 below, the mean speed metric had a significant main effect of road type (F (1, 22) 5.169 p= .033) and an interaction effect for road type and gender (F (1, 22) 7.563 p= .012) for alert drivers only. Tunnel 2's (T2) design was the most similar to a conventional Swedish road tunnel. Females reduced their speed in tunnel 2 whereas males' speed remained relatively constant. The speed limit was 90 km/h.

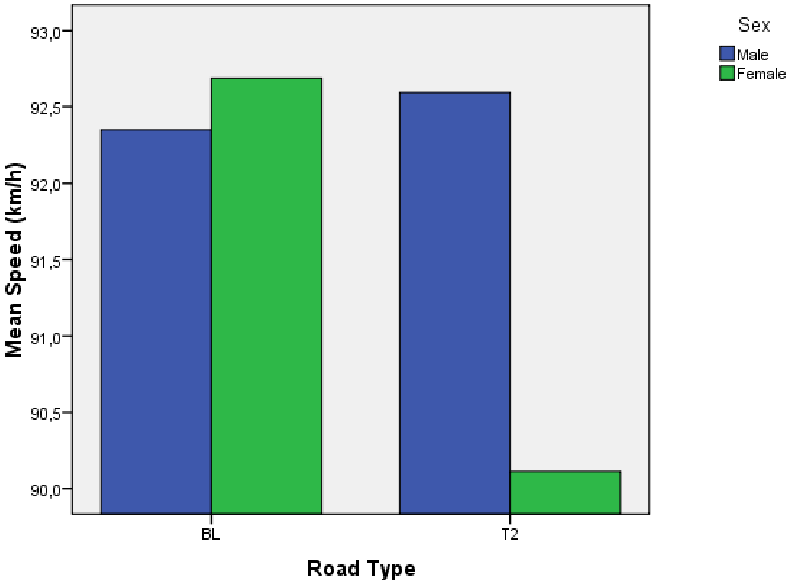


Figure 24: Effects of road type and sex on mean speed (km/h), alert driver state only. The road type comprised baseline (BL) and Tunnel 2 (T2) only. The speed limit was 90 km/h.

In figure 25 below, the mean speed metric had an interaction tendency for road type and gender with sphericity not assumed (Huynh-Feldt F (1.936, 42.595) 2.472 p= .098) for both driver states (alert and drowsy). There were no main effects.

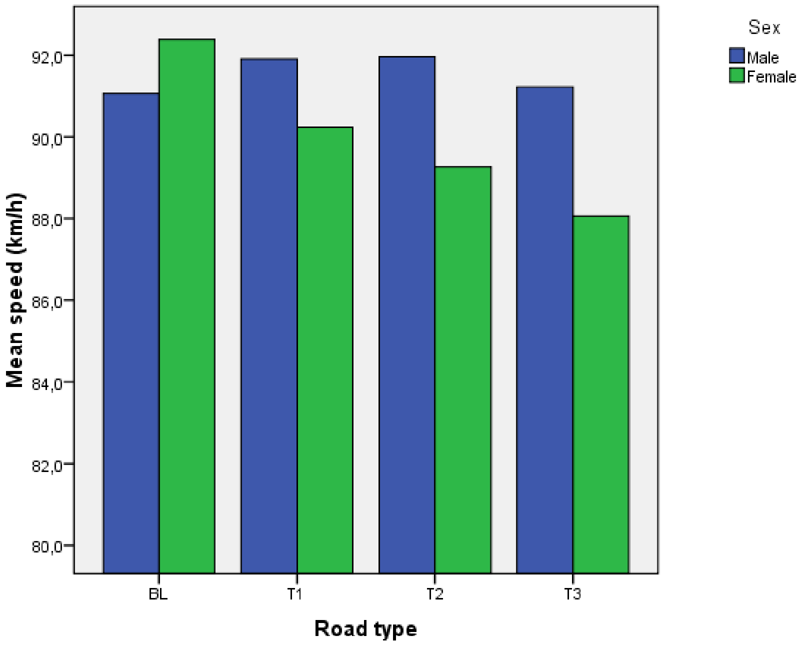


Figure 25: Effects of road type and sex on mean speed (km/h), both driver states (alert and drowsy).

3.4.1 Entry-Exit Analysis 500m

In figure 26 below, the mean speed (entry-exit 500 m) metric had a significant interaction for road type and entry-exit with sphericity assumption violated and adjusted using Huynh-Feldt (Huynh-Feldt F (2.149, 49.438) 3.130 p= .049) for all of the drivers (alert and drowsy). There were no main effects. The number of missing values varied for the variables included in the general linear models repeated measures analysis and caution is advised when interpreting these results.

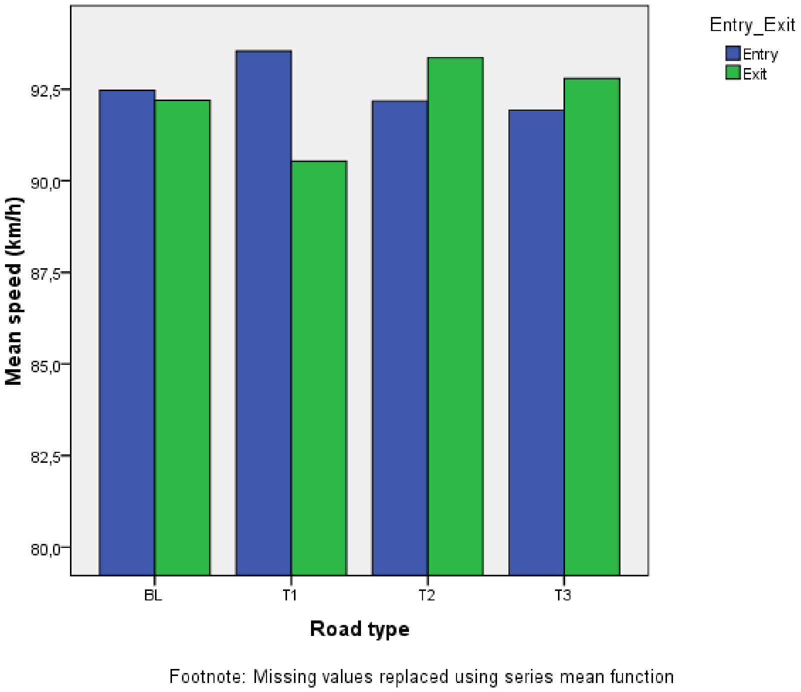
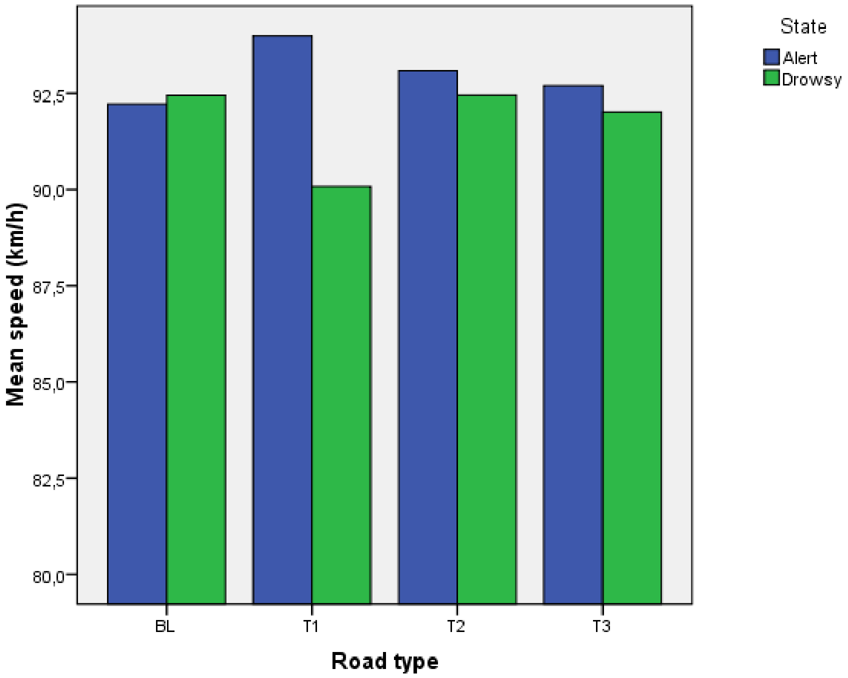


Figure 26: Effects of road type and entry-exit 500m on mean speed (km/h), both driver states (alert and drowsy).

Figure 27 below, the mean speed (entry-exit 500 m) metric had a significant main effect of driver state (F (1, 23) 4.650 p= .042). There was also an interaction for road type and driver state with sphericity assumed (F (3, 69) 5.243 p= .003). The number of missing values varied for the variables included in the general linear models repeated measures analysis and caution is advised when interpreting these results.



Footnote: Missing values replaced using series mean function

Figure 27: Effects of road type and driver state on mean speed (km/h), both driver states (alert and drowsy) using entry-exit 500m data.

3.4.2 Entry-Exit Analysis 1750m

In figure 28 below, the mean speed (entry-exit 1750 m) metric had a significant main effect of road type for drowsy drivers only (F (3, 21) 7.359 p= .001). Using a Bonferroni multiple comparisons adjustment, the pairwise comparisons between Tunnel 1-Tunnel 2 was statistically significant and Baseline-Tunnel 1 showed a tendency (p= .07) when adjusted for multiple comparisons.

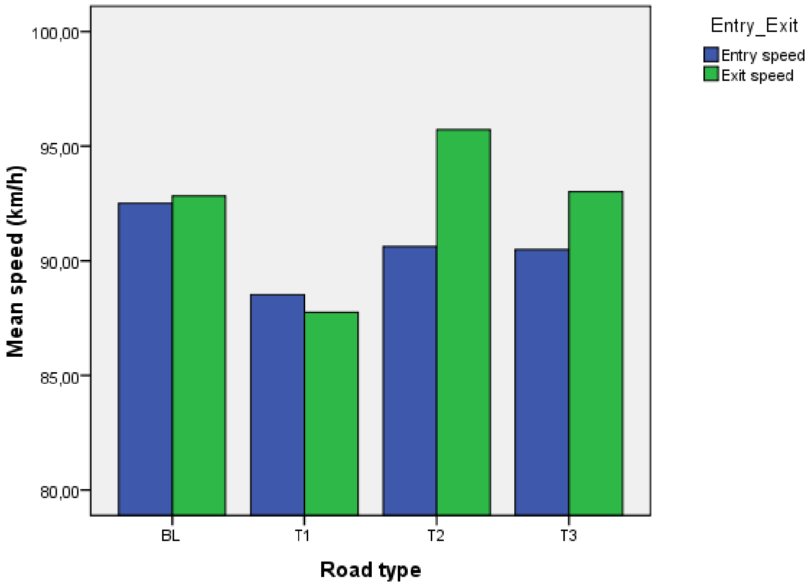


Figure 28: Effects of road type and entry-exit 1750m on mean speed (km/h), drowsy driver state only.

3.5 Time Headway

Time Headway (THW) – The mean time headways (distance To Lead Vehicle/ego Vehicle Speed) calculated for each lead vehicle when the THW <= 4 seconds. Lane changes are excluded.

In figure 29 below, the mean time headway dependent variable (alert drivers only) had a significant main effect of gender (F (1, 22) 7.122 p= .014) with adjustment for multiple comparisons (Bonferroni). Road type was not significant.

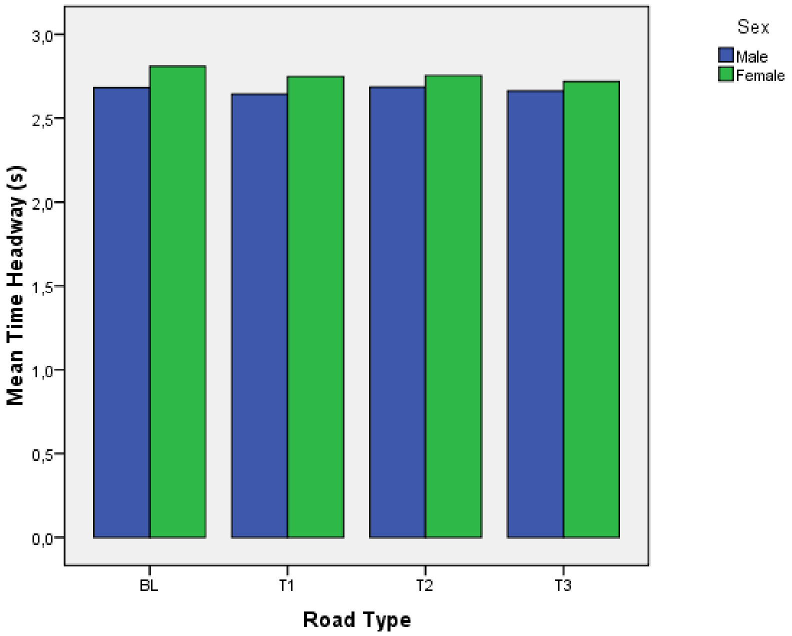


Figure 29: Effects of road type and sex on time headway (s), alert driver state only.

3.6 Steering Wheel Reversal Rate

Steering Wheel Reversal Rate (SWRR) – The number of reversals per minute calculated after first applying a low pass filter to the steering wheel signal with a cut off frequency of 0.6 Hz. The gap size was set to 3.0 degrees, 1.0 degrees and 0.1 degrees.

Different effects were obtained for different gap size settings for steering wheel reversal rate (SWRR). For gap size 0.1, there was a significant main effect of road type (F (3, 66) 3.616, p=< .05). See figure 29b below. Planned analysis of repeated contrasts revealed that only the difference between baseline (BL) and tunnel 1 (T1) was significant (F (1, 22) 10.63, p=.004).

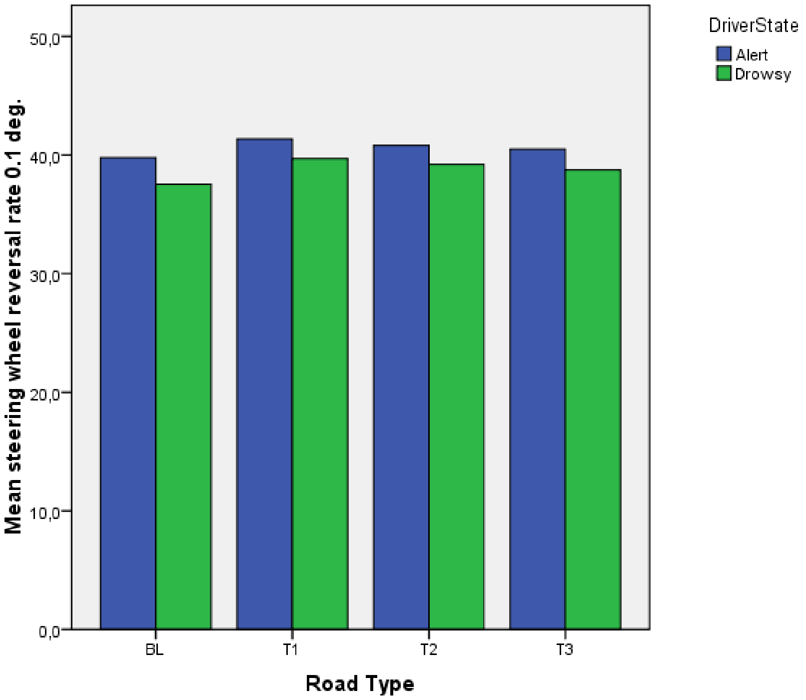


Figure 29b: Effects of road type and driver state on steering wheel reversal rate (SWRR) gap size 0.1 degrees.

In figure 30 below, there was a significant interaction effect of driver state and sex with 0.1 degree gap size (F (1, 22) 4.229 p= .05) where females when drowsy (during night time) had fewer micro reversals compared to their alert state (during day time).

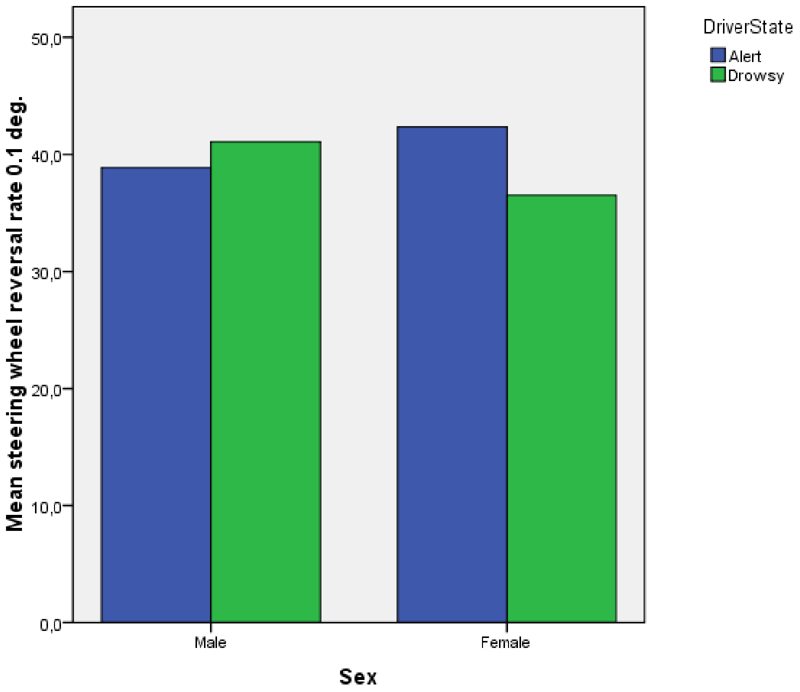


Figure 30: Effects of sex and driver state on steering wheel reversal rate (SWRR) gap size 0.1 degrees.

In figure 31 below, the SWRR results were generally reversed between a gap size 0.1 degrees compared to 3 degrees as an effect of driver state (drowsy or alert). There was no effect of road type although there was a trend for the contrast between T1 and T2 (p=.063). However, there was a main effect of drowsiness (F (1, 22) 7.354, p< .05) where the number of reversals increased in the drowsiness condition.

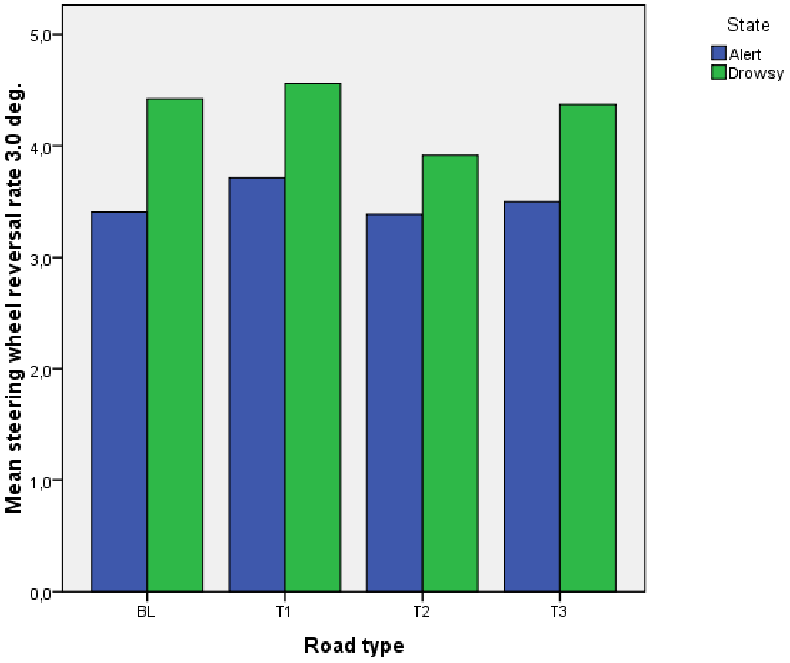


Figure 31: Effects of road type and driver state on steering wheel reversal rate (SWRR) gap size 3 degrees.

3.7 Standard deviation of lane position (SDLP)

In figure 32 below, the road type was not significant, however, there was an interaction effect of road type by sex (F (3, 66) 3.069 p= .034) and a significant main effect of driver state (F (1, 22) 7.170 p= .014).

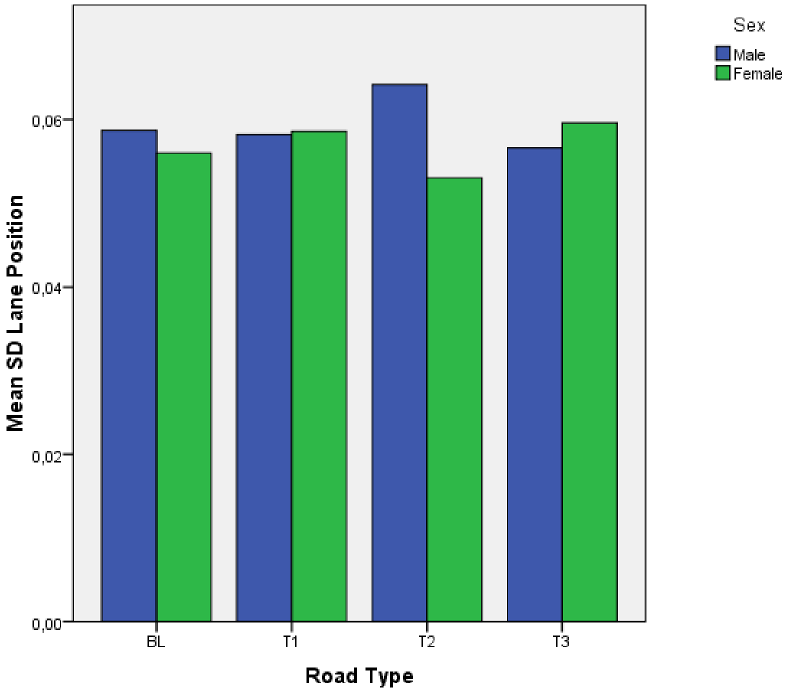


Figure 32: Effects of road type by sex on standard deviation of lane position (m), both driver groups by sex.

3.8 Sex, age & mileage

Table 4: A cross tabulation between mileage groups and the participants' sex. There were three missing values.

			Sex		
			Male	Female	Total
Mileage Group	0-10 000 km	Count	1	5	6
		% of Total	4,8%	23,8%	28,6%
	10 001-15 000 km	Count	4	4	8
		% of Total	19,0%	19,0%	38,1%
	15 001-20 000 km	Count	2	0	2
		% of Total	9,5%	,0%	9,5%
	>20 001 km	Count	5	0	5
		% of Total	23,8%	,0%	23,8%
Total		Count	12	9	21
		% of Total	57,1%	42,9%	100,0%

In table 4 there was a significant correlation between sex and the mileage group (Pearson's R= .651**) where females tended to have a lower annual mileage than males (Chi square p= .024).

Ages of females and males were evenly distributed.

3.9 Sleep deprived drivers & tunnel driving

3.9.1 KSS

In figure 33 below, there was no effect of road type on the Karolinska Sleepiness Scale (KSS) for drowsy drivers.

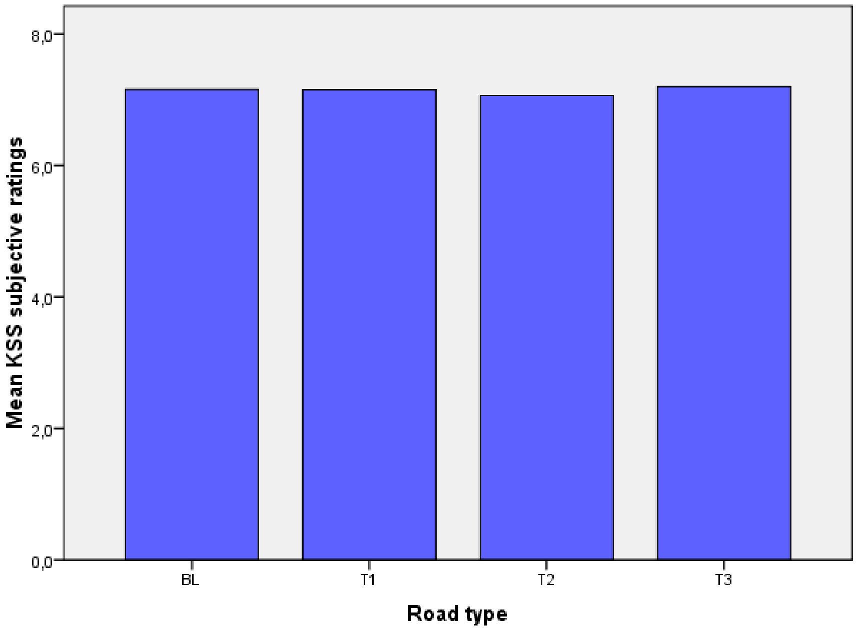


Figure 33: Effects of road type on Karolinska Sleepiness Scale (KSS), drowsy driver state only.

In figure 34 below, there was a significant effect of driver state (F (1, 23) 64.757 p= <.001), sphericity assumed, as shown in figure 34 below.

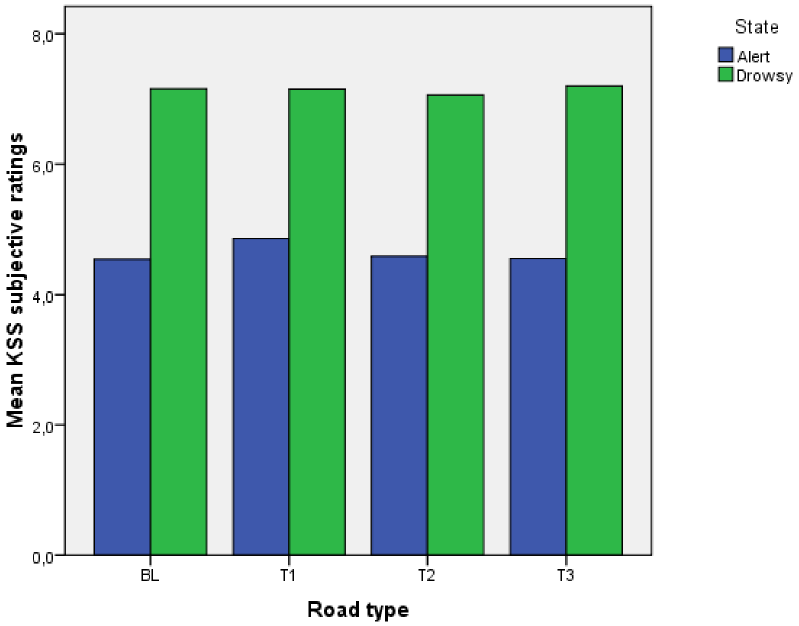


Figure 34: Effects of road type and driver state on Karolinska Sleepiness Scale (KSS), both driver states (alert and drowsy).

3.9.2 Blink duration(EOG)

During the experiment the electro-oculogram (EOG) metric was scored for blink duration. There was a significant effect for time on task (the first or second part of each 8 minute block) for blink duration (First 0.122 vs. Second 0.127). No significant interactions on the first level were identified for blink duration.

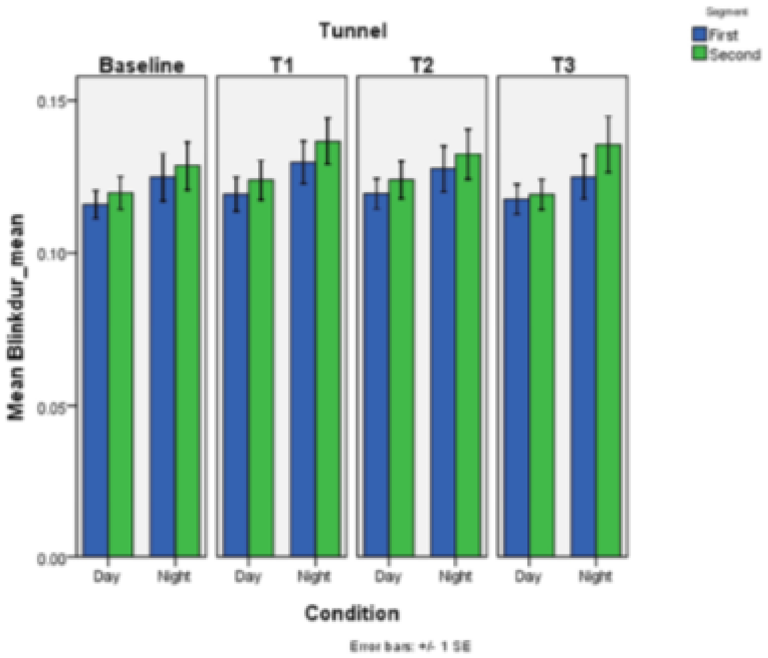


Figure 35: Effects of road type and driver state on blink duration measured at two four minute intervals per road type condition.

3.10 Results summarised in terms of hypotheses and metrics

The results are summarised by hypotheses and metrics in the following section. The different metrics are also categorised for each measure i.e. ‘effort’ or ‘lateral control’.

The following metrics are used as an indirect measure of effort:

Peripheral detection task (PDT) reaction time
PDT miss rate
CR10 scale (questions on ‘effort’, ‘monotony’ and ‘frustration’)
Mean speed

The following metrics are used as an indirect measure of lateral control:

Steering wheel reversal rate (SWRR) 0.1 degrees
SWRR 3.0 degrees
Mean lane position

The following metrics are used as an indirect measure of the initial compensatory behavioural effects:

Entry-Exit data for 500m and 1750m:
  Mean speed
  Mean lane position

The entry-exit data is the first and last 500m or 1750m sections of road that are included in the analyses of the various metrics.

A lane change is defined to begin 200 meters before the first wheel crosses the lane marker and to end 200 meters after all wheels are within the new lane.

3.10.1 Hypothesis 1:

Tunnel driving requires more effort than baseline motorway driving.

$H1_{null}$: The tunnel environment does not require more effort than the baseline condition.

Hypothesis 1 requires the following metrics:

Peripheral detection task (PDT) reaction time
PDT miss rate
CR10 scale (subjective effort, monotony and frustration)
Mean lane position
Steering wheel reversal rate (SWRR) 0.1 degrees
SWRR 3 degrees
Mean speed

Analyses of the PDT data (reaction times and miss rates) have not shown any statistically significant differences between the baseline (BL) motorway driving and the most typical tunnel which was tunnel two (T2) in accordance with hypothesis 1. There was, however, an interaction tendency between road type and gender where females generally had longer PDT reaction times and in particular in tunnel 3 (T3). The PDT metric provided little support for hypothesis 1.

Analyses of the CR10 scale (subjective effort, monotony and frustration) provided support for hypothesis 1 where drowsy and alert drivers both experienced a greater degree of monotony when driving in tunnel compared to the baseline scenario. Alert drivers experienced through the CR10 “frustration” question, that tunnel 3 (T3) was significantly more frustrating than the baseline (BL). There was also a significant interaction effect between road type and gender for the CR10 “frustration” question. Females generally experienced a greater degree of frustration than males. The CR10 “mental effort” question also suggests that females experience a greater degree of mental effort than males when driving in tunnels (in simulators). Drowsy drivers also expressed a greater degree of mental effort than alert drivers in general irrespective of simulated road type. The CR10 subjective ratings provide some support for hypothesis 1.

Analysis of the mean time headway metric was only significant between males and females where females generally kept a greater distance to the autonomous vehicles in the simulated environment. Road type was not, however, statistically significant thus not supporting hypothesis 1.

Analyses of the mean lane position metric suggest that the lateral position of the vehicles generally centralises within the lanes when driving in tunnels when compared to the baseline (motorway) condition. There was an interaction tendency between road type and gender and a significant main effect of road type for alert drivers. The mean lane position tendency was relatively stable for males who were inclined to retain the same lateral position irrespective of road type, whereas females were more affected by the tunnel conditions. The general mean lane position analyses provide some support for hypothesis 1.

Analyses of the mean speed metric did suggest a significant main effect that supported hypothesis 1 when comparing the baseline (BL) with the standard tunnel (T2). There was also an interaction effect between road type and gender. Males generally held a steady mean speed over the different road types, whereas females were affected by the tunnel environment and reduced their mean speeds. The mean speed metric supports hypothesis 1.

Analysis of the steering wheel reversal rate (SWRR) metric set at 0.1 degree gap size (micro steering corrections) suggested that there was a significant main effect of road type, where the reversal rate was higher in the tunnel conditions suggesting high workload or effort. With the SWRR gap size set at 3 degrees (macro steering corrections), there was no effect of road type although there was a trend for the contrast between T1 and T2.

The driver effort measure comprising PDT reaction time, PDT miss rate, and CR10 questions, suggest that there is support for hypothesis 1, however, the differences were generally small. The lateral position measure, comprising mean lane position and steering wheel reversal rate also supports hypothesis 1.

3.10.2 Hypothesis 2:

Enhanced optical cues increase lateral control and reduce driver effort.

$H2_{null}$: Enhanced optical cues have no effect on lateral control or driver effort.

Hypothesis 2 requires the following metrics:

- Mean lane position
- Steering wheel reversal rate (SWRR) 0.1 degrees
- SWRR 3 degrees
- Peripheral detection task (PDT) reaction time
- PDT miss rate
- CR10 scale (subjective effort, monotony and frustration)

Lateral control (mean lane position) was generally greater in all of the tunnels (T1-3) compared to the baseline (BL). Comparisons between tunnel 1 (T1) and tunnel 2 (T2) were not significant. The tunnel per se appeared to provide visual cues either tangibly such as in T2 or subtly such as in T1.

The metrics that are not otherwise specifically mentioned showed no statistically significant effects.

There is little support for hypothesis 2 that stated that enhanced optical cues used in this study would increase lateral control and reduce driver effort in the data and the null hypothesis is therefore accepted. The analyses suggest an unclear relationship between the metrics used and the setup of the simulated tunnel scenarios. These results can be interpretation in a number of ways; some of which are found in the Discussion.

3.10.3 Hypothesis 3:

Misleading optical cues impair lateral control and increase driver effort.

$H3_{null}$: Misleading optical cues have no effect on lateral control or driver effort.

Hypothesis 3 requires the following metrics:

- Peripheral detection task (PDT) reaction time
- PDT miss rate
- CR10 scale (subjective effort, monotony and frustration)
- Steering wheel reversal rate (SWRR) 0.1 degrees
- SWRR 3 degrees
- Mean lane position

Similarly to hypothesis 2, there is little support for hypothesis 3 that stated that the misleading optical cues used in this study would impair lateral control and increase driver effort and the null hypothesis is therefore accepted. The setup of the simulated tunnel scenarios in this study are believed to be too weak to elicit clear results. The metrics that are not otherwise specifically mentioned were not statistically significant.

3.10.4 Hypothesis 4:

Initial compensatory behavioural effects resultant of tunnel driver gradually declines throughout the tunnel driving sections.

$H4_{null}$: The compensatory driving behavioural effects remain constant.

Hypothesis 4 requires the Entry and Exit data with the following metrics:

- Peripheral detection task (PDT) reaction time
- PDT miss rate

CR10 scale (subjective effort, monotony and frustration)
Steering wheel reversal rate (SWRR) 0.1 degrees
SWRR 3 degrees
Mean lane position

Analysis of the PDT reaction time data for the first and last 500m (entry and exit data) of the specific road type had a significant main effect where reaction times were longer towards the exit. Road type per se was not significant. Similarly, entry and exit data analysis for the first and last 1750m was also statistically significant but road type was not significant. The increase in PDT reaction times suggests an increase of driver effort towards the end of the road-type sections.

The metrics that are not otherwise specifically mentioned were not statistically significant.

Analysis of the mean speed entry-exit data for the first and last 500m and 1750m had a significant main effect of entry-exit and was more pronounced for drowsy drivers.

The measures for driver effort provided some support for accepting hypothesis 4.

3.10.5 Hypothesis 5:

The monotonous character of tunnel driving exacerbates the effects of sleepiness compared to non-tunnel driving, expressed in increased Karolinska sleepiness scale (KSS) scores.

$H5_{null}$: Tunnel driving does not give increased KSS scores when compared to non-tunnel driving.

Hypothesis 5 requires the following metrics:
Karolinska sleepiness scale (KSS)
EOG/blink duration

Analysis of the Karolinska sleepiness scale (KSS) was not statistically significant between tunnels and baseline driving and the null hypothesis is therefore accepted. There is a difference in sleepiness indicators between day time and night time simulator driving but there is no difference between motorway and tunnel driving for each of the driving time conditions.

4 Discussion

The main results of this study suggest that tunnel driving to a certain degree, increases driver effort. Increased effort was expressed more in the subjective measure than in the quantitative measures and the differences were generally small. Clear gender differences were found where women reported a higher degree of influence than men.

Clear differences between the different types of tunnel designs were not found which could be explained by the weakness of the optical cues adopted in the scenarios of the present study combined with a potentially stronger impact of naturally occurring optical flow from road and wall textures.

The driver effort measure comprising the metrics PDT reaction time, PDT miss rate and CR10 questions, suggest that there is support for hypothesis 1, however, the differences were generally small. The lateral position measure, comprising mean lane position and steering wheel reversal rate also supports hypothesis 1.

There is little support for hypothesis 2 that stated that enhanced optical cues used in this study would increase lateral control and reduce driver effort in the data and the null hypothesis is therefore accepted. The analyses suggest an unclear relationship between the metrics used and the setup of the simulated tunnel scenarios. The interpretation of the results should consider factors that have not manipulated experimentally such as potentially stronger impact of naturally occurring optical flow from road and wall textures. Relatively dense autonomous traffic flow that was simulated may even have had some effect on optical flow.

Similarly to hypothesis 2, there is little support for hypothesis 3 that stated that the misleading optical cues used in this study would impair lateral control and increase driver effort and the null hypothesis is therefore accepted. The setup of the simulated tunnel scenarios in this study are believed to be too weak to elicit clear results. Misleading optical cues can impair lateral control and increase driver effort. It is important to underline the notion that optical cues usually affect our ability to perceive and control our bodily movements. The process is sometimes referred to as spatial updating which is primarily dependent on visual and kinetic cues to update the brain on our position in relation to movement. This is something humans do continuously whenever we move. Physical movements that are consistent with spatial orientation cues can facilitate accurate performance such as when maintaining an even lane position. Inconsistent movements cues can, however, lead to impaired performance (cf. Presson & Montello, 1994). A visit to an amusement park with a hall of mirrors or a fun house that plays with and manipulates these visual and spatial cues should illustrate their importance to the curious reader.

The measures for driver effort provided some support for accepting hypothesis 4 that stated that initial compensatory behavioural effects resultant of tunnel driver gradually declines throughout the tunnel driving sections. The increase in PDT reaction times suggests an increase of driver effort towards the end of the road-type sections.

There were no hypotheses for gender or sex, however, post hoc analyses of gender as a fixed variable revealed some interesting trends for road type and gender for the dependent variables of mean speed and PDT reaction times. Additional analyses have shown that when gender is factored in to the evaluation, there appears to be differences in the effects of tunnel design. In general terms, there would appear to be an affect or emotional response to tunnel design where female participants (in this study) generally reacted to the changes in tunnel design and the male participants were generally uninfluenced. The metrics that were sensitive to gender differences were time headway, the peripheral detection task and the CR10 subjective scales. There was an even participant age/sex distribution, however, the participant mileage/sex distribution suggested a bias towards males in this study having a greater annual mileage than females. There are too few participants in this study with a high annual mileage (n= 4) to perform any meaningful analyses pertaining mileage. Correspondingly, low annual mileage may be a factor for further investigation in future studies regarding tunnel driving. Annual mileage alone is unlikely to explain the differences completely and may reflect driving habits in general.

There could in essence be a number of different factors that explain the difference between men and women such as anxiety or stress of coming to a simulator per se. These results were, however, somewhat unexpected and more detail research would be necessary to investigate, explain and verify the gender differences in tunnel driving. There could also be a possible interaction between sex and experience/annual mileage.

The drivers’ state of drowsiness was as expected clear-cut. The drivers, when drowsy, performed consistently poorer than when they were alert as one would expect.

The peripheral detection task (PDT) apparatus used in this study was designed according to the TNO specifications (van der Horst, 2010) that specified a head-mounted LED instead of the traditional head-up windscreen display. There are, however, a number of difficulties experienced with the current setup of a head-mounted LED. The main concerns are concerned with use of the PDT in a dimly lit driving simulator. The strength of the diode was probably too strong, making the diode too conspicuous and too intrusive. This may also explain the relatively fast PDT reaction times.

The driving scenarios contained autonomous vehicle algorithms that created a feeling of ‘real’ traffic for the participants. These vehicles consisted of cars and inadvertently also provide visual cues for longitudinal travel and control by their visual presence. This may have had a reduced effect on the lateral control metrics (SWRR and mean lane position) in tunnel 3 (T3) that had continuously misleading visual cues on the ceiling.

In regard to the entry-exit data analyses, there was no statistically significant effect for road type (baseline, tunnels 1-3) using the PDT reaction time. One would expect the two mean baseline measurements for entry and exit to be similar. They were, however, significantly different. The assumption that hypothesis 4 was correctly accepted remains with a caveat for the mechanism that increases the drivers’ effort may not necessarily be the tunnels’ design per se. The road-type order was fully balanced so an order effect should be unlikely. Speculatively one could suggest that there may have been an effect of driving in the simulator per se. Hence the short breaks that were incorporated into the scenarios to respond to subjective rating scale questions, may have generated a noticeable reduction of workload measured with the PDT reaction time metric.

A lesson to be learnt would to be the use of occasionally misleading visual cues instead of continuously misleading cues because it is possible that the drivers quickly adapt and ignore the unreliable (misleading) cues and shift their focus to other more reliable cues such as road markings, the position of the autonomous vehicles, and optical flow information of road and wall textures.

5 Conclusions

The effects of visual design suggest that 1) mental workload (effort) increased as a result of driving in tunnels when compared to the beginning of the tunnel section. Women exhibited higher levels of mental workload (PDT and CR10) than men and particularly in tunnel 3 (T3) with the misleading cues. 2) Lateral control generally increased between motorway driving and tunnel driving. The biggest difference was, however, between men and women where it would appear that women were affected by the visual design whilst men were relatively unaffected. 3) The effect of driver state (alert and drowsy or day vs. night) was clearly discernible but no interaction effects were found for driver state and road type (tunnel design).

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7 Appendix 1

PDT specification excerpt from TNO (van der Horst 2010).

Peripheral Detection Task (PDT) system

For more information, contact Richard van der Horst
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Timing of PDT signal.

```
|
                    |
|____|___________________|__________________|_____________________|
t0   t1                                        t2                              t3
                                   t4
```

t0-t1 (LedActivePeriod) = led on, visible period of stimulus, 1sec typical

t0-t2 (DetectionPeriod) = period reaction is detected, 2 sec typical

t0-t3 (CyclePeriod) = Minimum time of 1 PDT cycle, 3 sec typical

t3-t4 (MaxRandomPeriod) = variable period before next stimulus, 0-2 sec typical

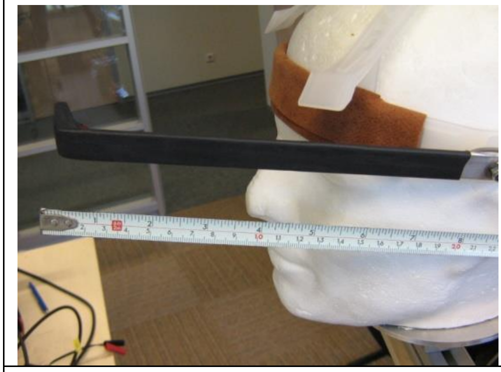
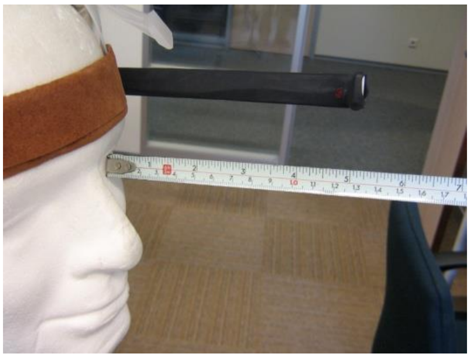
Reaction time is only measured once. The first rising edge of the trigger button is taken to calculate reaction time.

If no rising edge is detected during period t0-t2, -9999 will be send as reaction time.

After a rising edge has been detected, no further rising edges will be detected until a new stimulus is triggered.

If the reaction was within the period of the stimulus t0-t1, the led will be turned off.

A complete cycle will take 3~5 sec typical.

Specs LED: ….

Visual angle: horizontally (to be measured, my estimate about 15 degrees to the left)

Vertically: (to be measured, my estimate 3-4 degrees above the horizon)