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The influence of lighting, wall colour and inattention on traffic safety in tunnels
A simulator study

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Abstract (background, aim, method, result) max 200 words:

Even though the crash risk in tunnels is rather lower than on the open road network, crash consequences can be very severe. Therefore it is of high importance to assure high safety standard in tunnels, which includes, but is not limited to, an appropriate illumination. The aim of this study was to investigate in which way different levels of illumination and brightness of the tunnel walls influence the behaviour of attentive and inattentive drivers.

The study was conducted in the Simulator III at VTI, which is a high-fidelity simulator with linear motion in lateral direction. A within-subjects design was employed, and 24 participants took part in the tests. Illumination was varied on three levels and tunnel wall colour and driver attention were varied on two levels each. Driving data, eye tracking data and subjective data were collected and analysed for an overtaking event and for an event-free driving situation.

Bright walls were more important for experienced safety and comfort than high illumination level, as long as the illumination was sufficiently bright. Further, driving behaviour and gaze behaviour were heavily influenced by driver state, with distracted drivers showing more unsafe behaviour. Additionally, bright walls received slightly lower demand ratings than dark walls.

Keywords:
tunnel, illumination, driving behaviour, eye tracking, gaze, distraction, attention, inattention

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Även om olycksrisken i tunnlar är lägre än på landsvägar kan skadeföljden bli allvarlig. Därför är det viktigt att säkerställa en hög säkerhet i tunnlar, vilket bland annat ställer krav på belysningen. Denna studie har syftat till att undersöka hur belysningsnivån och tunnelväggarnas ljushet påverkar beteendet hos uppmärksamma och mindre uppmärksamma förare.

Studien genomfördes i VTI:s simulator III, som är en avancerad simulator med linjär rörelse i sidled. I studien deltog 24 försökspersoner, som alla fick köra samtliga kombinationer av belysningsnivå, tunnelväggar och distraktion. Belysningsstyrkan hade tre nivåer, medan tunnelväggarnas ljushet och graden av distraktion hade vardera två nivåer. Kördata, ögonrörelsedata och subjektiva data samlades in och analyserades både för en omkörningssituation och under fri körning.

Ljusa tunnelväggar är viktigare för upplevd säkerhet och komfort än hög belysningsnivå så länge denna nivå är tillräcklig. Körbeteendet och ögonrörelserna påverkades starkt negativt av distraktion på så sätt att försökspersonerna körde mindre säkert då de tvingades lösa en sekundär uppgift. Ljusa väggar innebar en något mindre mental belastning.

Nyckelord:
tunnel, belysning, körbeteende, blickbeteende, blick, distraktion, uppmärksamhet, ouppmärksamhet

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Preamble

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Katja Kircher

Cover: VTI/Hejdlösa bilder and Katja Kircher, VTI

Quality review

Review seminar was carried out on 29 April 2011 where Carina Fors, VTI, reviewed and commented on the report. Katja Kircher has made alterations to the final manuscript of the report. The research director of the project manager Jan Andersson, VTI, examined and approved the report for publication on 19 May 2011.

Kvalitetsgranskning

Granskningsseminarium genomfört 2011-04-29 där Carina Fors, VTI, var lektör. Katja Kircher har genomfört justeringar av slutligt rapportmanus. Projektledarens närmaste chef Jan Andersson, VTI, har därefter granskat och godkänt publikationen för publicering 2011-05-19.

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The influence of lighting, wall colour and inattention on traffic safety in tunnels – A simulator study

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Summary

Even though the crash risk in tunnels is rather lower than on the open road network, crash consequences can be very severe. Therefore it is of high importance to assure high safety standard in tunnels, which includes, but is not limited to, an appropriate illumination. Too low illumination levels may compromise safety, while unnecessarily high levels waste resources. In this study it was investigated in which way different levels of illumination and brightness of the tunnel walls influence the behaviour of attentive and inattentive drivers.

The study was conducted in the Simulator III at VTI, which is a high-fidelity simulator with linear motion in lateral direction. A within-subjects design was employed, and 24 participants took part in the test. Illumination was varied on three levels and tunnel wall colour and driver attention were varied on two levels each. This yields twelve different combinations, which meant that each participant drove through twelve tunnels with a length of 4 km. The order was randomised with certain restrictions between participants. The tunnels were separated by 2 km long open motorway sections. In each tunnel the participant encountered an overtaking situation, which demanded a decision on the tactical level.

The collected data consisted of driving behaviour data as logged from the simulator, eye tracking data, secondary task performance data, subjective demand ratings while driving, and subjective ratings and comparisons post-test. The data collected during driving were analysed for the situation with the overtaking event and in addition for an an event-free driving situation further down the tunnel.

The main results were:

- Bright walls are more important for experienced safety and comfort than high illumination levels, as long as the illumination is sufficiently bright.
- Driving behaviour and gaze behaviour were heavily influenced by driver state, with distracted drivers showing more unsafe behaviour.
- A larger percentage of long glances away from the forward roadway and lower attention levels were found for tunnels with dark walls.
- The participants experienced a higher task demand during the distracted condition as compared to non-distracted. They also experienced the overtaking event as more demanding than driving freely.
- Bright walls received slightly lower demand ratings.
- Secondary task performance did not vary across conditions.

It can be concluded that bright walls enhance traffic safety and are conducive to the drivers' to feel safe and comfortable, provided an acceptable level of illumination. Absolute levels are difficult to come by based on a simulator study, as the range of illumination is much more limited in the simulator than in reality. For detailed results on

absolute illumination levels it is indispensable to run real world trials, even though the simulator proved useful for the evaluation of relative levels.

As performance was degraded for distracted drivers, it is recommended to address the issue of attention in future studies, because inattention and monotony are known risks especially in longer tunnels. It is also recommended to evaluate design features related to visual guidance, and to investigate other architectural measures, which might help decrease energy consumption without compromising traffic safety.

Trafiksäkerhet i tunnlar – inverkan av belysning, väggarnas ljushet och förarens uppmärksamhetsgrad – en simulatorstudie

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Sammanfattning

Även om olycksrisken i tunnlar är lägre än på landsvägar kan skadeföljden bli allvarlig. Därför är det viktigt att säkerställa en hög säkerhet i tunnlar, vilket bland annat ställer krav på belysningen. Alltför låg belysningsnivå kan medföra försämrad säkerhet, medan alltför hög nivå innebär slöseri med resurser och onödig miljöpåverkan. Denna studie har syftat till att undersöka hur belysningsnivån och tunnelväggarnas ljushet påverkar beteendet hos uppmärksamma och mindre uppmärksamma förare.

Studien genomfördes i VTI:s simulator III, som är en avancerad simulator med linjär rörelse i sidled. I studien deltog 24 försökspersoner, som alla fick köra samtliga kombinationer av belysningsnivå, tunnelväggar och distraktion. Belysningsstyrkan hade tre nivåer, medan tunnelväggarnas ljushet och graden av distraktion hade vardera två nivåer. Detta ger 12 olika betingelser, vilket innebar att varje försöksperson körde genom 12 tunnlar, vardera med en längd av 4 km. De 12 betingelserna presenterades i slumpmässig ordning, med vissa restriktioner. Mellan tunnlarna körde man på 2 km vanlig motorväg i öppet landskap. I varje tunnel kom försökspersonen ifatt ett annat fordon samtidigt som denne blev upphunnen av ett tredje fordon. Denna arrangerade trafiksituation framtvingade ett beslut på taktisk nivå.

Från simulatorns logg har körbeteendedata registrerats. Vidare registrerades ögonrörelser, förmåga att lösa sekundära uppgifter samt subjektiv mental belastning. Med hjälp av en enkät efter körningen registrerades försökspersonernas subjektiva bedömning av säkerhet och komfort i tunnlarna. Data från körningen analyserades för två situationer – dels för körning utan påverkan från övrig trafik, dels för omkörning i samband med upphinnande.

Resultaten visar bland annat följande:

- Ljusa tunnelväggar är viktigare för upplevd säkerhet och komfort än hög belysningsnivå så länge denna nivå är tillräcklig
- Körbeteendet och ögonrörelserna påverkades starkt negativt av distraktion på så sätt att försökspersonerna körde mindre säkert då de tvingades lösa en sekundär uppgift
- Förarna tog bort blicken från vägen framöver oftare och under längre tid samt var allmänt mindre uppmärksamma i de tunnlar som hade mörka väggar
- Deltagarna upplevde en högre mental belastning då de distraherades och i omkörningssituationerna
- Ljusa väggar innebar en något mindre mental belastning
- Förmågan att utföra den sekundära uppgiften varierade inte över de olika betingelserna.

Slutsatsen är att ljusa tunnelväggar förbättrar trafiksäkerheten och bidrar till en känsla av säkerhet och komfort under förutsättning att belysningsnivån är tillräckligt hög. Det är svårt att från en simulatorstudie avgöra vad ”tillräckligt hög” är eftersom nivåerna i

verkligheten inte kan översättas direkt till vad simulatorn visar. Belysningsnivåer måste därför sannolikt studeras i en verklig tunnel där dessa kan varieras.

Eftersom körbeteendet försämrades vid distraktion bör detta undersökas närmare i framtida studier, framförallt som monotoni och ouppmärksamhet är kända riskfaktorer i långa tunnlar. Vidare bör samband mellan tunnelutformningen och den visuella ledningen undersökas, då detta kan leda till minskad energikonsumtion utan att ge avkall på trafiksäkerheten.

1 Introduction

There are many reasons for using tunnels in road traffic, amongst those are that tunnels can help reducing the travel time, they can connect areas, and they improve the urban environment. Additionally they can keep corridors open in inclement weather by eliminating risks for landslides and avalanches across roads, and by avoiding road closures in winter. In some areas they are also built to avoid the risk of rock fall.

However, there are also some disadvantages connected to tunnels. There is a lack of daylight and of visible escape routes. Walls are close to the road, hard and unforgiving. The air is not as clean as outside, and there are usually no landmarks, making navigation more difficult and instilling a feeling of "not getting anywhere" in the driver. Related to this is the lack of variation, which can lead to boredom and fatigue, especially in longer tunnels. Furthermore, tunnels with plain walls make it more difficult for the driver to estimate one's own speed.

What makes tunnels special is the potential for catastrophes, examples for which are the Tauern tunnel fire in 1999 (Leitner, 2001), the Channel tunnel fire in 1996 (Kirkland, 2002), the Gotthard tunnel fire in 2001 (Carvel & Marlair, 2005), and the Mont Blanc tunnel fire in 1999, killing 39 people (ibid.).

1.1 Illumination and energy consumption

The illumination of a tunnel can change the impression it makes on the driver quite substantially, and it would appear obvious that a brighter tunnel should be a safer tunnel. Of course tunnels have to be safe, but is it the illumination, and the illumination alone, which determines how safe a tunnel is? Illumination consumes energy and if energy consumption could be reduced it would be good for the environment and the tunnel budgets. This, in turn, could make it possible to invest in other safety features which are more effective.

The relationship between illumination and energy consumption is not linear. Roughly, for a high pressure sodium lamp, a 50% cut of the illumination level will save 35% energy. As an example, a typical tunnel lighting fulfilling the Swedish regulations will use 20 kW per kilometre. As the lighting is on 24 hours, this means that the energy consumption is almost 180,000 kWh per year and kilometre. If this could be reduced by 35%, without affecting traffic safety or comfort, approximately 60,000 kWh per kilometre would be saved every year, which with today's energy price is a significant saving.

Furthermore, as the regulations put a demand on the luminance of the road surface, even more energy could be saved by the use of a bright road surface. The luminance of the road surface is the product of the illumination and the luminance coefficient of the road surface. The latter describes the reflection properties of the surface; a high coefficient means that the luminance in the regulations can be achieved with less illumination. Consequently, energy consumption in tunnels might be reduced if both the lighting and the road pavement are adapted to the needs of the driver.

1.2 Regulations in different countries

The tunnel lighting regulations are rather complex, using different lighting levels in different zones of the tunnel. Furthermore, the requirement on lighting may be dependent on the traffic intensity, the speed limit and the outdoor conditions (day/night). As a base, many countries use CIE Report 88-1990 with or without small changes. Table 1 summarises the regulations in the interior zone of the tunnel in some Nordic countries and the UK.

Table 1 Requirement on road surface luminance [cd/m2] in the interior zone of the tunnel.

Country	Low speed, low traffic	High speed, high traffic
Sweden	3–6	5–10
Denmark	1	12
Norway	0.5	4
United Kingdom	1.5–3	4–10

Table 1 shows a large variation between the luminance level requirements in the four countries. A reasonable question is if the Swedish requirement is too high? Or maybe the Norwegian too low?

Common for all regulations is that there is a requirement on the luminance of the road surface, never on the walls or roof. Some regulations recommend the use of white walls up to a certain height, but without mentioning any figure. It may be that a light wall is more important than a bright road surface.

1.3 Safety

Norwegian data, which consider almost 800 tunnels adding up to a total distance of 779 km show that the crash risk in tunnels is comparable to the crash risk on normal roads (Amundsen, 1994; Amundsen & Engelbrektsen, 2009). More precisely, it can be said that there occur slightly fewer crashes in tunnels (0.11 crashes per 1 000 000 driven km) than on normal roads (0.13 crashes per 1 000 000 driven km), but they tend to have more severe consequences. While on normal Norwegian roads 0.03 fatalities occur per one million driven km, in tunnels the frequency more than doubles to 0.07. Generally the crash risk is higher in the entrance zone of the tunnel than further into the tunnel. This applies to both the first 50 m inside of the tunnel and the last 50 m before the tunnel. The fatality risk, however, increases dramatically from 0.02 just outside of the tunnel to 0.06 on the first 50 m inside of the tunnel. The risk increases further to 0.09 in the section of 50 m to 150 m into the tunnel, while it then sinks slightly to 0.07 in the middle section of the tunnel. There is an indication that the risk might increase with increasing tunnel length, but so far only tunnels up to a length of 3,000 m have been investigated. In comparison to normal roads, the risk to get involved in a crash with a vehicle travelling in the same direction is almost doubled, while the risk to crash in connection to a junction or with a pedestrian are much lower. This is easily explained by the general lack of junctions and pedestrians in tunnels. Crashes with vehicles driving in the same direction account for approximately 43% of all tunnel crashes in Norway. Next highest rank single vehicle crashes with 36% of all crashes, which roughly corresponds to the number for normal roads. The highest likelihood for crashes is during rush hours, even when taking the higher traffic volumes into account.

It was found, too, that tunnels with higher speed limits account for a relatively lower crash frequency, but the consequences when involved in a crash are far worse than at lower speeds.

Similar data were obtained from Austria (Nussbaumer, 2007). In tunnels the likelihood of crashes was lower, but the risk of fatalities given a crash was higher than on the open road network. Additionally it was found that the probability of being injured or killed is 19% higher in tunnels with bi-directional traffic than in tunnels with uni-directional traffic (Robatsch & Nussbaumer, 2004). Nussbaumer (2007) mentions that the main reasons named for tunnel crashes in Austrian police reports were lacking vigilance (fatigue, distraction, inattention) and wrong behaviour (issues with safety distance, lane keeping, overtaking).

To conclude, it can be stated that tunnels are not more dangerous in terms of accident frequency than normal roads, rather to the contrary, in fact, but once a crash has happened the probability for severe injuries to occur is greater in tunnels than on normal roads. Single-tube tunnels are more dangerous than double tube tunnels, and boredom and related factors are a concern in tunnels, which is probably aggravated in long tunnels.

1.4 Comfort

However, driving is not only about objective facts. Tunnel anxiety is a phenomenon widespread enough to be of relevance, especially if it is so pronounced that the person in question avoids driving through tunnels altogether. It is related to claustrophobia and appears often in combination with other types of phobia.

A Norwegian survey (Flø & Jenssen, 2007) revealed that 2–3% of the population experience severe claustrophobia in tunnels, 20% feel anxious and another 15% experience unpleasant feelings and are afraid in tunnels. Thus, more than a third of the population experience anxiousness to some degree while in tunnels. The anxiousness levels are higher for subsea tunnels, with seven per cent of the Norwegians participating in the survey stating they would never drive through such a tunnel.

These facts make it very clear that objective safety is not the only parameter to consider when designing tunnels that are supposed to be and feel safe. There have been some initiatives to make tunnels less uniform and boring visually. In the design of the Laerdals Tunnel in Norway, which is more than 24 km long, both driver fatigue, anxiousness and boredom were taken into account. Three big caves are placed at intervals of 6 km. These caves are lit with blue light and some yellow light at the fringes, giving an impression of sunrise, while the remaining parts of the tunnel are lit with white light (Flø & Jenssen, 2007).

Preceding trials with Norwegian and Chinese drivers showed that a red colouring should be avoided, as it can give rise to the fear of fire in the tunnel. Similarly, for tunnels that have subsea sections it is not recommendable to remind the drivers of their being underneath a body of water by designing the tunnel accordingly (Flø & Jenssen, 2007).

1.5 Purpose of the study

Given the obvious demand for safe tunnels on the one side, and the very realistic costs for the environment as well as of monetary character, it is important to establish scientific support for the question whether it is possible to reduce the illumination in tunnels below the levels demanded today by Swedish regulations. As interactions both with the brightness of the tunnels walls and with the attentional state of the driver were considered to be possible, these factors were included in the study. Bright walls might increase visibility as compared to dark walls at equal levels of illumination. Attentional state can play a role when it comes to tunnel driving, as it is a comparatively monotonous type of driving. Therefore, in the present study three levels of illumination were investigated in combination with light versus dark tunnel walls and attentive versus visually distracted drivers.

To ensure high levels of control over the situation and enable strict reproducibility it was decided to conduct a simulator study, which should deliver the first answers in what hopefully is going to be a series of connected experiments. The specific questions that were raised for the study at hand to answer were:

- Does the illumination level in a tunnel influence traffic safety? If so, in which way?
- Does the brightness of the wall in a tunnel influence traffic safety?
- Is there an interaction with distraction, in the way that brightness might get crucial first when drivers are not fully attentive?
- Do the factors mentioned above influence experienced comfort and safety, and if so, in which way?

2 Background

Only very limited research effort has been devoted to the analysis of driver behaviour in tunnels. Manser and Hancock (2007) addressed the issue of how speed can be influenced with the help of patterns and texture on the roadside. The possibility to use the tunnel walls to convey information to the drivers was already investigated earlier by Carmody (1997). In the Manser and Hancock study a tunnel scenario was used, as it allows the isolation of visual factors. The study was conducted in a driving simulator, with the tunnel wall design as a four-level within-subjects factor and texture as a two-level between subjects factor. The different tunnel wall designs were 1. wide stripes that gradually became thinner, 2. thin stripes that gradually became wider, 3. thin stripes throughout and 4. no stripes at all. For half of the participants the walls carried an additional texture, while it was smooth for the other half of the participants. The main findings were that was, in fact, possible to influence driving speed via tunnel wall design, with the participants slowing down when stripe width decreased and speeding up with increasing stripe width. The effect was attenuated by a texture in the wall, which can most likely be explained by the additional peripheral speed information provided by the texture. This indicates that structure or texture in the tunnel walls is beneficial if the aim is to help the driver keep his or her speed, while measures to influence speed with patterns work best without an underlying structure.

As mentioned, these studies were conducted in a simulator, and even though it can be expected that the results can be transferred to real-world settings, a systematic validation would strengthen them.

Such an effort was made by Törnros (1998), who investigated driver speed and lateral position in a real tunnel and an equivalent simulated tunnel. In this study the wall pattern and structure were not modified. The study featured a within subjects design, where each participant drove through the tunnel twelve times in the simulator and twelve times in the real tunnel. Thus, each driver drove on each of three lanes in both directions through the tunnel, once with the speedometer available and once with the speedometer covered. The general finding was that for speed a relative validity could be observed, that is, the speed profile was similar in the simulator and in the real tunnel, except for an offset with consistently higher speeds in the simulator. The same effect had also been observed for validation studies of open road driving (Alm, 1995; Harms, 1994). Additionally, Törnros observed that drivers tended to position the car in the lane such that they kept some distance to the nearest wall. This effect was greater when the wall was located to the left of the driver, that is, closer to the driver, as left-hand steering was used. The effect could be observed both in the simulator and in the real tunnel, with a slightly greater effect in the latter.

These results are promising, as a confirmed relative validity allows conclusions about which design is likely to be more effective with respect to speed choice or lane positioning in a direct comparison in the simulator. Even though the absolute values can be about 3–7 km/h higher in the simulator than in the field, it can be assumed that the internal order should remain unaffected in real traffic, which is a valuable input to the study at hand.

2.1 Traffic events and situations

Driving alone on a road without junctions is a simple task, which is mainly made up of keeping an appropriate speed and not leaving the own lane, or at least the road. In normal driving, however, it is often necessary to interact with other road users that either cross one's path or block one's way. Many of these manoeuvres are well learned, and rules exist that tell road users who has the right to go first, and who has to yield. In many of those manoeuvres, however, judgement is required on the road users' side. When turning left in right hand traffic, crossing the oncoming traffic lane can be necessary. The driver has to judge whether the gap between vehicles is large enough to allow a safe turn. When overtaking on a motorway, the rear view mirror has to be checked first, and then a judgement has to be made whether a lane change is safe, or whether another vehicle approaches too fast from behind.

In tunnels the number of interactions are rather limited, compared to the open road network, and especially in comparison to inner-city traffic, but nevertheless, interactions are possible. As it is possible that the factors investigated in the present study may influence the drivers' judgements how to handle an event more complex than pure lane tracking, it was decided to include a common overtaking event into the study. It should represent a relatively simple situation, which is frequently encountered on the motorway during regular driving, but which still requires a decision on the part of the driver.

The overtaking event that was selected for the present study required the driver to make a judgement whether he could change lanes to overtake two slower vehicles ahead without getting in conflict with a car approaching from behind. If the driver changed lanes to overtake a slower vehicle ahead he gained a bit of time and reduced his travel time. If the driver did not overtake, he did not risk getting into a conflict with the car approaching from behind, but he had to brake slightly and wait for the car to pass before he could overtake the slower vehicle and proceed at the desired speed.

This situation was selected, as it was not critical, but still required judgement from the driver. As mentioned, it is a very common situation in motorway driving, which is of advantage, as it should be repeated twelve times throughout the test situation, once in every tunnel. Repetition in every tunnel was necessary to allow comparisons of the drivers' behaviour in all tested situations. It was assumed that the participants would learn quickly that the situation was recurring in each tunnel, but this was deemed not to be of major concern, as the behaviour still could vary, depending on other circumstances like lighting, the tunnel wall colour or other activities executed by the driver. It was assumed that a situation that demanded a tactical decision could possibly yield results that allowed conclusions about the driver's ability to judge the situation and his own role in guaranteeing smoothly flowing traffic.

2.2 Level of activation

Both constant high levels and constant low levels of activation can be detrimental for driving. Humans perform best under medium activation levels (cf. Figure 1), as was shown as early as 1908 (Yerkes & Dodson). Much research has been done on driving performance while conducting secondary tasks (see McCartt, Hellinga, & Bratiman, 2006; Young, Regan, & Hammer, 2003 for reviews), and also on complex driving situations (Horberry, Anderson, Regan, Triggs, & Brown, 2006). When the mental workload becomes too high, performance breaks down, and the risk for an incident and a crash increases.

Maybe not as obvious, but nonetheless important, also longer periods of very little activation are dangerous, as they can lead to boredom and fatigue. Driving becomes more a vigilance task than a continuous activity. The driver can get into a state of stupor, not really realising any more when he or she has to get back into the loop and act (Thiffault & Bergeron, 2003; Ting, Hwang, Doong, & Jeng, 2008). Alternatively, the driver might look for other activation, starting to make phone calls, surf on the net, watch movies, eat or even read a book. These non-driving related activities might usurp the driver enough that he or she misses information essential for driving.

Therefore, a medium level of activation, possibly with some variation, should be the goal for road design, and obviously also tunnel design.

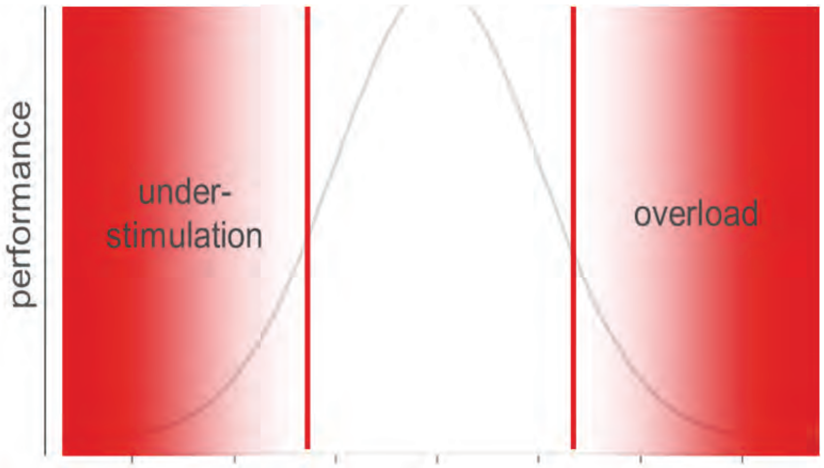


Figure 1 Illustration of a distribution of workload and the risks of overload and under-stimulation.

2.2.1 Quantifying complexity in traffic

Both for research purposes and for real world applications it would be very useful if an objective scaling of traffic situations existed with respect to the demand they place on road users. Although there have been several attempts at categorising traffic situations (e.g. Fastenmeier, 1995), there is not really a good standard yet. Recently a new approach was developed at UMTRI (Schweitzer & Green, 2007). With this method short film clips of traffic scenes are compared to two “anchor scenes”, which were given the demand values “2” and “6” on an open scale. The clips stem from the ACAS-FOT study conducted in the USA at UMTRI (Ervin et al., 2005a, 2005b; Green et al., 2007). On each film a motorway with three lanes was visible. In the case of demand “2” the traffic volume was low, corresponding to “Level of Service A” according to US standards (TRB, 2000), which means that traffic flows at or above the posted speed limit, and all road users have complete mobility between the lanes (Figure 2). The driver occupied the right lane. In the case of demand “6” the traffic density was higher (Level of Service E, meaning that the traffic flow is irregular and ususally below the posted speed limit with rapidly varying speed changes), and the driver occupied the left lane (Figure 3). “Demand” is used instead of “workload”, due to the fact that a certain level of objectivity should be achieved. The same demand level can still lead to different workload levels in different drivers.

Figure 2 Three still pictures from the anchor film clip corresponding to demand rating "2", with kind permission of Paul Green at UMTRI.

Figure 3 Three still pictures from the anchor film clip corresponding to demand rating "6", with kind permission of Paul Green at UMTRI.

The participants were free to study and watch the anchor films as they felt necessary. They were then presented with other traffic scenes, three at a time, which they had to rank in comparison to the anchor clips.

The purpose of the anchor clips was to introduce a level of objectivity, but still have the judgements made by humans out of an overall impression, instead of exclusively counting lanes and objects and inferring a complexity level from that. Rather, with access to both the ratings and the physical features in the scene, a matching can be made between the judgements given by the participants and features that might possibly influence their judgements.

The results obtained by UMTRI showed that a regression of a number of situational and event related features observed and measured in the traffic scenario on average demand ratings predicted 87% of the variance in the ratings. Generally it was found that maxima and minima of different values were better predictors of demand than the mean of the same values. For example, the acceleration of the lead vehicle influenced the demand ratings, especially when the minimum acceleration of the lead vehicle in a certain scene was considered. Lower values in minimum lead vehicle acceleration led to lower demand ratings. For braking, higher demand ratings were found for stronger lead vehicle braking.

Lower gaps led to higher demand ratings, especially when looking at the minimum and mean gaps within a scene. Similarly, lower time headways were strongly correlated to higher demand ratings ($r < -0.70$). For a full list of all variables influencing the ratings the reader is referred to the original literature (Schweitzer & Green, 2007).

A conclusion is that the road geometry and the behaviour of the surrounding road users both influence demand ratings, and that it is important not to look solely at mean values when calculating performance indicators, but to consider minima, maxima and distribution values, too.

It was decided to choose the method for the current study to evaluate the impact of the factors under investigation on the demand ratings made by the participants. In order to get a better picture, and to put the judgements made by the participants in the present study in relation to both the UMTRI rankings and to real Swedish scenes, the participants in the current study not only judged the tunnels while driving in the simulator. Additionally they rated video scenes in almost the same setting as was presented by Schweitzer and Green (2007) before driving the simulator.

Five of the presented scenes stem from the UMTRI study for a direct comparison between Swedish and American ratings. They do not contain any tunnels. Seven scenes stem from recordings on a Swedish motorway with two lanes in each direction. No tunnels were present here either, but different weather conditions occurred. Six scenes stem from the driving simulator. They were recorded in the six different tunnel types which were investigated in the study (see below). This way, the following comparisons should be possible:

- Ratings of Swedish and American participants on the same scenes filmed in the USA.
- Ratings of Swedish participants of American and Swedish motorways.
- Ratings of Swedish drivers obtained while watching video in comparison to ratings obtained while driving the simulator.

Even though the former two are of interest for validation purposes, only the last comparison will be analysed in the present study.

2.2.2 Secondary task

Drivers often engage in secondary tasks, some studies show that this is the case at least once in up to 70% of a randomised sample of 5- or 6-second-clips (Ervin, et al., 2005a; Green, et al., 2007; Klauer, Dingus, Neale, Sudweeks, & Ramsey, 2006). Modern tunnels often offer telephone and internet connection, and radio broadcasting is possible, too. Often, modern tunnels are designed in a way to promote safety and comfort, as they are brighter and can have wider lanes and/or an emergency lane. Therefore, driving in those tunnels is not as demanding and scary as in a number of older and badly lit tunnels. Therefore it is not unlikely that drivers will become bored and counteract this by engaging in secondary tasks. In those situations the risk that important developments in the traffic scenario are missed increases. It is possible that lighting levels play a role for the conspicuity of risky events when the driver is distracted. Therefore, in the present study the drivers encounter each tunnel design twice, once while they drive normally, and once while they perform a secondary task.

Instead of having the drivers perform a natural secondary task like talking on the telephone or changing a radio station, a standardised secondary task was chosen. The advantage of that is that performance on different aspects of the task can be measured easily, and that all drivers are equally unfamiliar with this task. Also, the extent of the demand on visual attention can be estimated beforehand due to results presented in the literature (Östlund et al., 2004). The disadvantage is, of course, that the ecological validity is low, but to counteract this the participant is informed in the situation description what the task is meant to represent in real life.

The artificial secondary task that was chosen is a modification of the S-IVIS task developed in the EU project HASTE. The participant is presented with a 4 x 4 square of arrows, which point either downward, sideways or upward. The participant is required to respond as fast as possible whether an arrow pointing upward exists in the current square or not. The response is given by pressing either “yes” or “no” on the touchscreen on which the task is presented. In the original HASTE task the squares could be of different sizes (from 4 x 4 to 6 x 6), and the arrows could either point in only one direction, plus possibly upwards, or in several directions. For the current study only 4 x 4 squares with arrows in all directions were used. The reason for this is that the response times found in previous studies corresponded to values which are considered as critical for glancing away from the road in one go, while still being of a realistic duration for a single glance. When no target arrow was present the mean response time for correct answers was almost 2.5 s, while it was almost 1.5 s when a target arrow was present.

It was important for reasons of comparison that the participants dealt with the secondary task in the same location. Therefore, it was an advantage that the HASTE S-IVIS task is system paced, meaning that it starts on its own and the driver has to react, which can include ignoring the task. In this sense it corresponds to an incoming phone call. The task is both visual and cognitive, like many of the secondary tasks executed in vehicles. Its difficulty level can be adjusted to suit the research question at hand, which was done here by only selecting two types of the many possible square pattern types.

2.2.3 The driver

How easy or difficult it is to manage certain traffic situations does not only depend on the infrastructure, the surrounding traffic and the vehicle, but also on the driver and his or her capabilities and characteristics. This includes the driver’s willingness and capability in performing secondary tasks while driving, as described above, but also the driver's experience with driving in general and with certain situations.

In the current study novice drivers and drivers with a very small annual mileage were excluded, but otherwise the drivers were meant to vary in experience levels. There was no a priori control of the driven mileage or for how long the drivers have held their licence, but this information was considered in the analysis.

2.3 Performance indicators

In order to be able to make a differentiated judgement of the drivers' performance in the different tunnels, a host of performance indicators (PI) was computed from the logged data. Data were logged from different sensors, namely from the driving simulator itself, from the secondary task described above, and from an eye tracker, which was installed in the simulator. Additionally, the participants' demand ratings of the traffic scene and his or her answers to the questionnaires were logged. Therefore, both the so-called driving behaviour, that is, how the vehicle moves in relation to the road, the driver behaviour, that is, what the drivers do inside of the car, and the drivers' attitudes and opinions could be assessed.

2.3.1 Driving behaviour

Driving behaviour is often classified into different levels, for example by Rasmussen (1983) into skill-based, rule-based and knowledge based behaviour. To summarise briefly, skill-based behaviour is often automatized and highly integrated behaviour. In driving, lane tracking and distance keeping can usually be subsumed under skill-based behaviour. Rule-based behaviour is goal-oriented, and it is performed according to stored rules, which are retrieved from memory, or which "pop up" from memory quite efforlessly in the respective situation. In driving, overtaking manoeuvres or the navigation of crossroads can be classified as rule-based behaviour. Finally, knowledge-based behaviour is relied upon in unfamiliar situations, where active problem solving is needed.

In the current study skill-based and rule-based behaviour were required of the participants, where the rule-based skills were demanded during the overtaking event, in which the driver had to judge whether to overtake or not. When it comes to PI, there is a difference between those PI that are based on skill-based behaviour and those that are derived from rule-based behaviour. The former can normally be acquired in most driving situations, as they have to do with how the vehicle moves laterally and longitudinally, both in relation to the road and in relation to other road users. The latter are often bound to a certain event. Gap acceptance behaviour can only be measured in situations, in which the driver actually has to make judgements related to gaps, either while overtaking or while crossing traffic in other directions. It has to be kept in mind that some skill-based PI can be influenced markedly by the behaviour of other road users, which is why it is necessary to be aware of others' presence and behaviour.

For the present study, the skill-level based PI were collected both during the event and in a situation in which the own vehicle was driving freely (Table 2). The PI assessing rule-based behaviour were only collected during the overtaking event, as they were directly related to this event.

Table 2 Driving behaviour related performance indicators (PI) on the skill-based level.

PI	Description/Equation
mean speed	The average speed over a certain time or distance. The PI indicates how fast a driver proceeds on average.
standard deviation of speed	The standard deviation of speed over a certain time or distance. This PI indicates how variable the vehicle speed is around its mean value.
mean lateral position	This PI indicates where in the lane the driver positions the car on average over time or distance.
SDLP (standard deviation of lateral position)	The standard deviation around the mean lateral position of the vehicle over time or distance. This PI indicates how much a vehicle sways laterally around it's intended line.
per cent speeding	The percentage of time spent speeding, that is, driving faster than 3 km/h above the posted speed limit.
speeding index	This index combines per cent speeding and how high the speed violation is. It was used by Hjälmdahl, Dukic and Pettersson (2009) and is based on the Power Model developed by Nilsson (2004) and computed according to the following equation: $$\frac{\int_{s0}^{s1}\left(\left(\frac{v(s)}{v_t + x}\right)^3 - 1\right)ds}{s_{tot}}$$ with v = the vehicle speed, v_t = the posted speed limit, x = an extra addition allowing for some fluctuation around the speed limit, here 3 km/h were chosen, as this corresponds to the error margin employed by the police, and s_{tot} = the total distance. The more above the speed limit the driver is, the faster the speeding index increases.

For the rule-based level different possible scenarios were identified in relation to the overtaking manoeuvre present in the study. They pertain to the driver's ability to judge the situation and to act in accordance with both traffic safety and efficiency. The scenarios can be identified by the usage of the turn indicators, the execution of a completed or aborted lane change manoeuvre, including not changing lanes at all, and the usage of the brakes. For each of these possible outcomes a number of PI can be computed. They include the distance of the own vehicle (X) to the lead and following vehicle while switching on the turn indicators, while changing lanes, etc., the brake reaction time, the TTC for the vehicle pairs X-B and X-C, and so on.

2.3.2 Driver behaviour

The analyses of driver behaviour were focused on gaze direction related performance indicators. Amongst other variables gaze direction and eyelid closure were logged with 60 Hz. The attention monitoring algorithm AttenD was run in real time and was used as a base for gaze direction related PI. The AttenD value indicates how visually attentive a driver currently is. It delivers a value between 0 (inattentive) and 2 (fully attentive). The value is computed based on actual gaze direction in combination with the recent glance history. For a full description of the algorithm see Kircher and Ahlstrom (2009).

From these variables the driver behaviour related PI were computed. A summary can be found in Table 3, together with short comments and the equation used, where applicable.

Table 3 Driver behaviour related performance indicators (PI).

PI	Description/Equation
Number of off-road glances > 2 s	The number of single glances away from the field relevant for driving of a duration of more than 2 s is established. Off-road glances of this duration have been shown to be linked to increased crash risk (Klauer, et al., 2006), therefore an increase of such glances indicates a risk. The glances were computed by using the output of the AttenD algorithm.
percentage of glances away from the field relevant for driving (FRD)	The percentage of glances away from the FRD is based on the AttenD algorithm. The algorithm works such that it either increases its buffer value or remains stable at the maximum value 2 when the driver looks into the FRD, whose definition depends on whether eye tracking or only head tracking is available. Roughly speaking it corresponds to the intersection of a circle of 90 degrees forward with the windscreen of the vehicle. Values above 1.8 indicate a fully attentive driver, while a buffer at zero indicates a distracted driver who has depleted his or her attention account.
per cent AttenD empty	The percentage of time during which the AttenD buffer equals zero. This indicates for how long the driver was distracted during the measurement period.
per cent AttenD full	The percentage of time during which the AttenD buffer was full, that is, above 1.8. This indicates for how long during the measurement period the driver was fully attentive.

Another performance indicator, which can be classified as belonging to driver behaviour, was the time need to complete the whole trip. This variable was only used for a performance comparison between drivers.

2.3.3 Secondary task performance

For the secondary task three PI were computed (Table 4). They together are able to indicate a larger picture of the strategy chosen. Even though there obviously are interindividual differences, it should be possible to see whether a driver rather sacrifices accuracy for being fast or the other way round.

Table 4 Secondary task performance related PI.

PI	Description/Equation
reaction time	The reaction time is the time from when the stimulus was first shown on the screen until the driver released the touch screen after indicating an answer.
per cent correct of all answered	The percentage of correct answers of all answers given.
per cent answered of all stimuli	The percentage of how many stimuli were answered, of all stimuli given, regardless of whether the answer was right or wrong.

2.3.4 Subjective impressions

The UMTRI demand scale as described above was used to rate the experienced demand of a traffic situation. Additionally, the participants answered a questionnaire. Amongst other things they ranked the different tunnels according to safety and according to comfort.

2.4 Preparations

The illumination range in reality differs in several orders of magnitude from what can be rendered in a simulator. Also, in reality an external light source, like the sun or artificial light in tunnels illuminates objects in the real world, while in the simulator the scene is projected on a white screen. In order to obtain scenario that at least yields relative validity, the procedure described below was followed. The goal was to produce luminance levels on the simulator screen which are comparable to luminance levels measured in reality. The focus was on the luminance of the road surface.

The luminance level of the road surface in the simulator should correspond to high, medium and low levels as measured in real tunnels. For real tunnels the luminance of the road surface can be computed by multiplying the illuminance on the road surface with the luminance coefficient (Qd) of the road surface. In the simulator those values do not exist in a comparable manner. Here the luminance of the road surface has to be modelled by using a corresponding level on the grey scale. The following procedure was employed in order to arrive at values in the simulator setting that should be as close to reality as possible:

On the 13th of October 2010 the illuminance was measured in eight different tunnels in Stockholm. At the same occasion pictures were taken in the tunnels, and for some of the tunnels the luminance of the road surface was measured directly. The measurements were made while driving in normal traffic. The measurement vehicle was placed in the right most lane in case of multiple lanes, and speed was reduced in order to obtain a headway of at least 50 m to the vehicle ahead. This was done to minimise a possible interference of vehicle lights with the measurements. Where traffic volumes were high yellow flashlights were switched on to warn traffic approaching from behind of the reduced speed. It was ascertained that the flashlights did not disturb the measurements.

The passenger in the measurement vehicle held a luxmeter (Konica Minolta T-10) out of the side window, reaching down in order to get as close to the road surface as possible. The estimated distance of the lux meter to the road surface was 60–80 cm. The luxmeter was held at a distance of approximately 20 cm from the door of the measurement vehicle, which was white. Due to the position in which the lamps were mounted under the tunnel roof it is unlikely that the car obstructed the angle of measurement. On a distance of several hundred metres the illuminance levels were read continuously, and a mean value was estimated.

Depending on the length of the tunnel photographs of the interior of the tunnel were taken either on the same passage or on a following passage, some of which were made in the opposite direction (see Figure 4). Photographs were taken using two different procedures. At first a standard exposure was chosen, which was kept constant across all tunnels. The aperture was at f/2.8, the shutter speed was 1/100 s, and the ISO setting was at 400. Then an exposure was made where ISO and aperture remained as before, but the shutter speed was varied according to the camera's integrated exposure meter. The metering was made with the matrix measurement setting, which considers the complete sensor surface and compares the measurement to a standard library. The camera equipment used consists of a Canon 5D Mark II body with a Canon 50 mm f/1.4 lens attached. A monopod was used for stabilisation. The photographs were taken in RAW format with the highest available resolution. Where traffic allowed the pictures were taken with the vehicle standing, otherwise they were taken in moving traffic.

Tunnel name	*Picture*
Eugeniatunnel	
Fredhällstunnel	

Löttingetunnel

Törnskogstunnel

Söderleden

Clearly visible ”striping” produced by the lighting armatures.

Södra Länken

Muskötunneln

Häggvikstunneln

Very short and straight tunnel where the exit is already visible at the entrance.

Figure 4 Photographs of eight tunnels in Stockholm, converted to black and white.

In some of the tunnels the luminance of the road surface was measured using a Minolta LS-110 luminance meter. The angle of measurement was 0.33 degrees. A comparative measurement through the windshield and with the meter held outside of the side window showed that there were no distinguishable differences between the measurements. Therefore, measurements were made through the windshield only. The luminance meter was directed at the road surface approximately 10 m ahead of the measurement vehicle. The registered values were read continuously over a distance of 100–200 m, and an average value was estimated.

All measured values for the eight tunnels are reported in Table 5. It is also reported in which driving direction the pictures were taken. As the measurements were made while driving, and because some of the tunnels were rather short, not all measurements could be made for all tunnels. However, for each tunnel at least one measurement of illuminance was made in at least one direction, and pictures was taken in at least one direction for each tunnel.

Table 5 Presentation of measurement values for measurements made in tunnels in Stockholm. Illuminance was measured with a hand-held luxmeter, which was held outside the side window of the measurement vehicle approximately 60–80 cm above the road surface. The values in the table are not corrected for this.

Tunnel	**direction**	**average lx value (tunnel location)**	**road surface cd/m²**	**photo-graphed**
Fredhällstunnel	N	270		
	S	300		x
Eugeniatunnel	N	1,700 (beginning) 500 (later)		
	S		8–10	x
	N	1,500 (beginning) 300 (later)		
Häggvikstunnel	E	1,000 (beginning) 500 (middle) 100 (end)		
290 m (580 m single tunnel) 100 W HPS Armature Schreder 2 lanes	W			x
	E	1,000 (beginning) 300 (middle) 100 (end)		
	W		10	
Törnskogtunnel	E	50–70		
2.1 km (4.2 km single tunnel) 70 + 100 W HPS Armature Schreder 2 lane	W			x
	E	50–70		
	W		4	
Löttingetunnel	E	70		
1.1 km 70 W HPS Armature Industria 1 lane	W	50–60		x
Söderleden	S	30–40 (darkest parts) 150 (middle, exit ramp)		x
Södra Länken	W	50		x
4.8 km (16 km single tunnel) 2 x 2 x 36 W fluorescent lamp (ultimate longlife) Armature Industria 3 lanes	E			x
Muskötunnel	E	50	3	x
one lane	W			x

For luminance comparisons of the photographs taken in real tunnels and the tunnels that were simulated for use in the study the pictures with situation adapted exposure were used, however, they were manipulated somewhat. In order to remove colour differences of the light, which could possibly confound the experienced brightness values the pictures were converted to black and white by transforming the colour scales to a grey scale. Certain adjustments in exposure and contrast were made in order to adapt the visual impression of the pictures to what was experienced in reality. The pictures were post-processed in Adobe Lightroom 3.2.

The pictures were then exported to jpg-format (colour space sRGB) and projected on the middle channel of the driving simulator, that is, onto the middle part of the driving scene as viewed by the driver. Here the luminance value of the road surface was measured with the help of a luminance meter.

Finally, the simulated tunnels were measured in the simulator with the help of the same luminance meter, and the contrasts between different surfaces could be compared (Table 6 and Figure 6). In order to get an idea of the range in luminance that can be achieved in the simulator, the tunnels were measured at ambient light levels from 0.2 to 1.0 (step size 0.1) as adjusted via the graphics system of the simulator. For each ambient light level measurements were made in eight different spots (Figure 5).

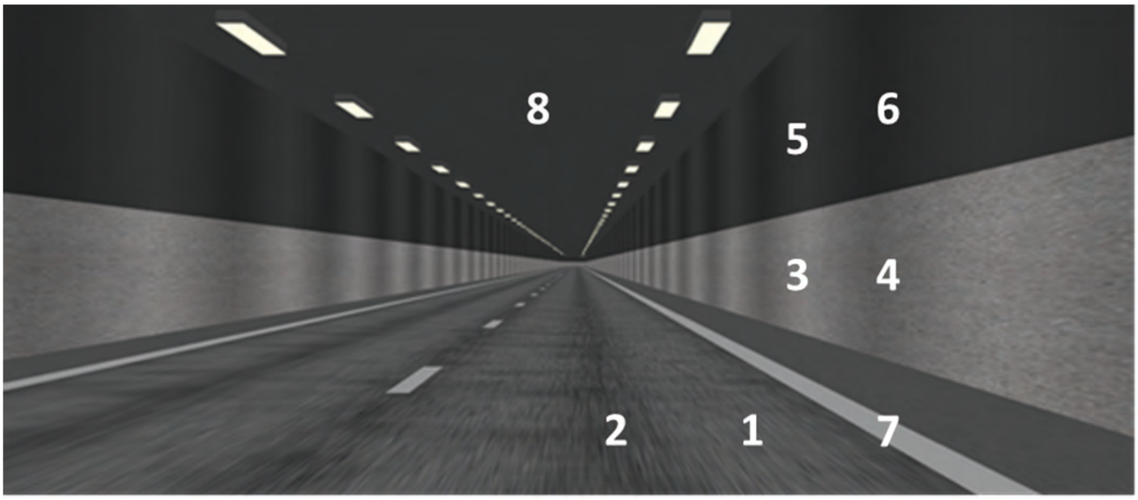


Figure 5 A simulator tunnel with light walls. The numbers indicate where the luminance measurements were taken (cf. Table 6).

Systematic luminance measurements of different ambient light levels show that the percentage of ambient light varies in an approximately linear fashion with the measured luminance level. Only for the highest ambient light levels the measured luminance increases slightly less. The ambition was to find ambient light levels that varied markedly while still providing realistic luminance levels and an acceptable graphical rendering.

Based on the values presented in Table 6 and Figure 6 three ambient light levels were selected for the study. An ambient light level of 0.3 provided just enough contrast to enable drivers to see the environment in the tunnel. An ambient light level of 1.0 was the highest possible, and was therefore used as the brightest condition. Visual inspection in combination with the measurements led to the selection of the ambient light level of 0.6 for the middle condition.

Table 6 Luminance measurements for different features of the simulated tunnel (see Figure 5). The levels marked with green were chosen for the study.

	1	2	3	4	5	6	7	8
percent ambient light	road surface, light section	road surface, dark section	lower part of the wall, light section	lower part of the wall, dark section	upper part of the wall, light section	upper part of the wall, dark section	road marking	roof
0.2	0.98	0.77	1.03	0.91	0.68	0.63	1.06	0.76
0.3	1.1	0.94	1.27	1.06	0.8	0.75	1.4	0.83
0.4	1.27	1.12	1.5	1.29	0.84	0.79	1.8	0.95
0.5	1.44	1.26	1.94	1.55	0.94	0.85	2.21	1.07
0.6	1.69	1.35	2.23	1.79	0.98	1.04	2.69	1.16
0.7	1.95	1.61	2.65	2.11	1.19	1.06	3.25	1.3
0.8	2.19	1.79	3.01	2.34	1.29	1.12	3.77	1.42
0.9	2.32	1.9	3.15	2.41	1.33	1.13	4.21	1.43
1	2.52	1.97	3.37	2.52	1.37	1.17	4.44	1.46

Figure 6 shows the measurements obtained for the simulated tunnels in a graphical fashion, the values stem from Table 6.

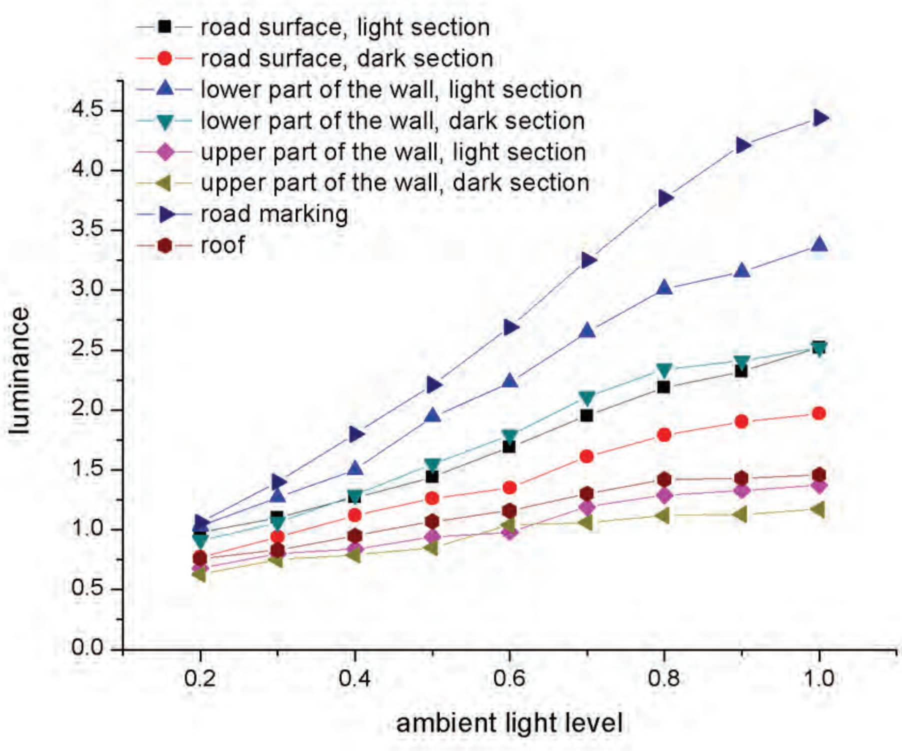


Figure 6 The luminance of different ambient light levels as measured on the projection screen of the simulator (see also Table 6).

The highest value obtained for the light section of the road surface of the brightest simulated tunnel was 2.52 cd/m^2. This can be contrasted with the values measured in reality. For the bright tunnels Häggvikstunnel and Eugeniatunnel values up to 10 cd/m^2 were obtained. The darkest tunnel, Muskötunnel, exhibited a road surface brightness of 3 cd/m^2. This implies that an absolute comparison between the real and the simulated conditions is impossible. Therefore comparisons were made between luminance levels of the simulated tunnels and the photographs of the real tunnels, which were projected on the simulator screen with the same projectors that are used for the simulated tunnels.

In Table 7 the three selected ambient light conditions are compared to the luminance values measured for photographs of the real tunnels on the simulator screen. The values for the darkest condition, which lies at an ambient light level of 0.3, are comparable to what was measured for the Muskötunnel, except for the light track on the road surface and the road markings. The luminance levels for the brightest condition lie in the same order of magnitude as for the brightest tunnels as rendered on the simulator screen. A comparison to the luminance levels measured on location for the road surface in some tunnels shows, however, that it is not possible to achieve completely realistic levels with the projectors used in the simulator (compare Table 7).

Table 7 Luminance measurements made in the simulator with projections of both simulated (upper three rows) and photographed real tunnels on the middle screen. The values for the simulated tunnels with dark walls are the same as for the light walls, except that no light section exists on the lower part of the wall.

	road surface, light track	road surface, dark track	wall, lower half, light stripe	wall, lower half, dark stripe	wall, upper half, light stripe	wall, upper half, dark stripe	road marking	roof
dark	1.1	0.94	1.27	1.06	0.8	0.75	1.4	0.83
medium	1.69	1.35	2.23	1.79	0.98	1.04	2.69	1.16
bright	2.52	1.97	3.37	2.52	1.37	1.17	4.44	1.46
Fred.	3.4	1.66	--	1.5	1.92	--	6.55	0.74
Eug.	3.43	2.93	1.92	1.77	0.89	0.86	5.37	0.87
Törn.	4.43	3.33	2	1.4	1.29	0.69	8.43	0.68
Lött.	2.41	2.3	1.42	--	--	0.8	6.52	0.64
Söd.	2.07	1.29	--	--	1.31	0.65	2.36	0.59
Musk.	2.11	1.25	--	--	0.94	0.64	3.6	0.58

3 Method

A full factorial 2x2x3 within subject design was used for the present study. Each participant drove through twelve tunnels. Each tunnel had either dark or light walls, each tunnel had one of three different levels of illumination. Each of these six tunnels was driven twice, once with a secondary task present, and once without. The tunnel numbers and the corresponding levels of the different factors can be found in Table 8.

Table 8 Tunnel numbers and corresponding factor levels.

number	tunnel design (T)	light intensity (Li)	attention (A)
1	dark walls (1)	dark (1)	distracted (1)
2			attentive (2)
3		medium (2)	distracted (1)
4			attentive (2)
5		light (3)	distracted (1)
6			attentive (2)
7	light walls (2)	dark (1)	distracted (1)
8			attentive (2)
9		medium (2)	distracted (1)
10			attentive (2)
11		light (3)	distracted (1)
12			attentive (2)

3.1 Apparatus

In this section the apparatus including the experimental factors are described in detail.

3.1.1 Driving simulator

The experiment was conducted in the VTI Driving Simulator III, an advanced moving base simulator. A Saab 9-3 cabin was mounted on the motion platform. The moving base is used to generate forces felt by the driver while driving. It can be divided into 3 separate parts: a large linear motion, tilt motion and a vibration table. The linear drive has world leading performance, it can achieve the highest acceleration of all simulators in the world. Linear motion was used in the lateral direction in the present study. The tilt motion is used in the roll and pitch direction to simulate long term accelerations such as driving in a curve or longitudinal acceleration and deceleration. The vibration table provides additional capabilities to generate road roughness for higher frequencies. While the tilt motion tilts both the cabin and the graphics projection screen, the vibration table moves the cabin relative to the projection screen.

The visual system consists of 3 DLP projectors providing a 120 degrees forward field of view and 3 LCD displays for the rear view mirrors. The projectors have a resolution of 1280x1024 pixels.

The sound system consists of five speakers, two speakers close to the windshield in the dashboard, one speaker in each of the front doors, and one rear speaker. These speakers are controlled by a separate computer which can play sound in any of the five speakers. This computer dedicated to the control of the sound interacts with its environment through the network. Detailed performance specifications are provided in Table 9.

Table 9 Performance specifications of the VTI Simulator III.

System	**type of movement**	**max values**
Cabin	Pitch angle	- 9 degrees to + 14 degrees
	Roll angle	± 24 degrees
External linear motion	Maximum amplitude	± 3.75 m
	Maximum speed	± 4.0 m/s
	Maximum acceleration	± 0.8 g
Vibration table	Vertical movement	± 6.0 cm
	Longitudinal movement	±6.0 cm
	Roll angle	± 6 degrees
	Pitch angle	± 3 degrees

3.1.2 Road

The trial started with a training section, which consisted of a six kilometer long segment of open motorway without tunnel. After the training section the experimental run began. Here the road was made up of 2 km long sections of motorway without tunnel and 4 km long sections of motorway in a tunnel. These two sections alternated, starting and ending with an open motorway section. During the course of the experiment each subject drove along 13 open motorway sections and 12 tunnel sections as indicated in Table 10. The order of the tunnel sections was randomised with certain restrictions. The same lighting levels were only allowed to occur twice in consecutive order, the same wall colour was not allowed to occur more than three times in consecutive order, and the same secondary task condition was not allowed to occur more than three times in consecutive order.

Table 10 Route design. The order in which the tunnel segments appear was randomised considering certain preconditions. MW = motorway; T_x = tunnel design ($x \in \{1; 2\}$); Li_y = light (intensity of illumination; $y \in \{1; 2; 3\}$); A_z = induced attention level ($z \in \{1; 2\}$).

training	MW *13*	$T_xLi_yA_z$ *{1-12}*	MV *14*	$T_xLi_yA_z$ *{1-12}*	MW *15*	$T_xLi_yA_z$ *{1-12}*	MW *16*	$T_xLi_yA_z$ *{1-12}*
6 km	2 km	4 km	2 km	4 km	2 km	4 km	2 km	4 km

The road had two lanes in each direction, and a shoulder on the outer side. Outside of the tunnels there was a narrow green median between the two directions, but no physical barrier. Each driving direction had its own tunnel. The road was 10 m wide altogether, the lane width was 3.5 m, and the shoulders were 1.5 m wide each.

The open motorway was completely straight, while the first 400 m of the tunnel section consisted of a left curve with radius 2000 m, and the last 400 m of the tunnel section consisted of a right curve with the same radius (Figure 7).

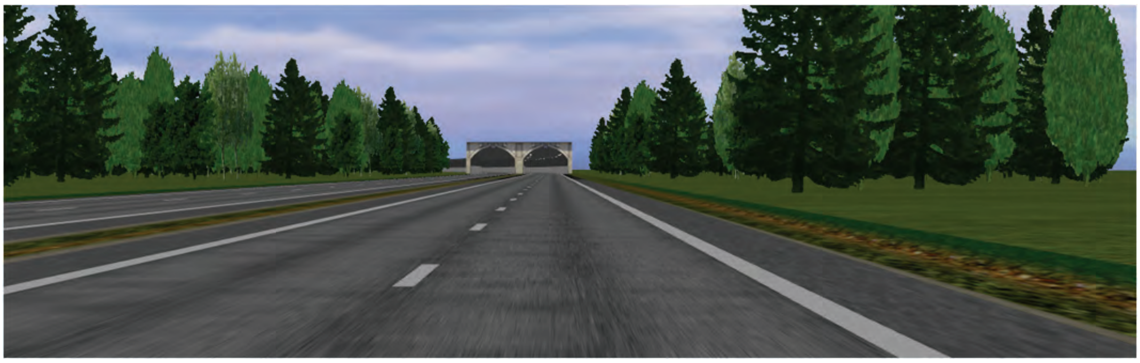


Figure 7 The end of one open motorway segment, with a tunnel coming up.

3.1.3 Tunnel design

Tunnel design was varied on two levels. The walls of a tunnel could either be dark or light. In case of light walls, the light part went from road surface level up to 2 meters above road surface level. In all cases the walls were rendered with a slight pattern, simulating the reflections of the lamps mounted under the tunnel roof (Figure 8).

3.1.4 Light intensity

The factor “light intensity” was varied on three levels. They corresponded to the full ambient light level, the ambient light level x 0.6 and the ambient light level x 0.3 (Figure 8). The procedure for how these lighting levels were decided upon is described in more detail in Section 2.4 on page 22.

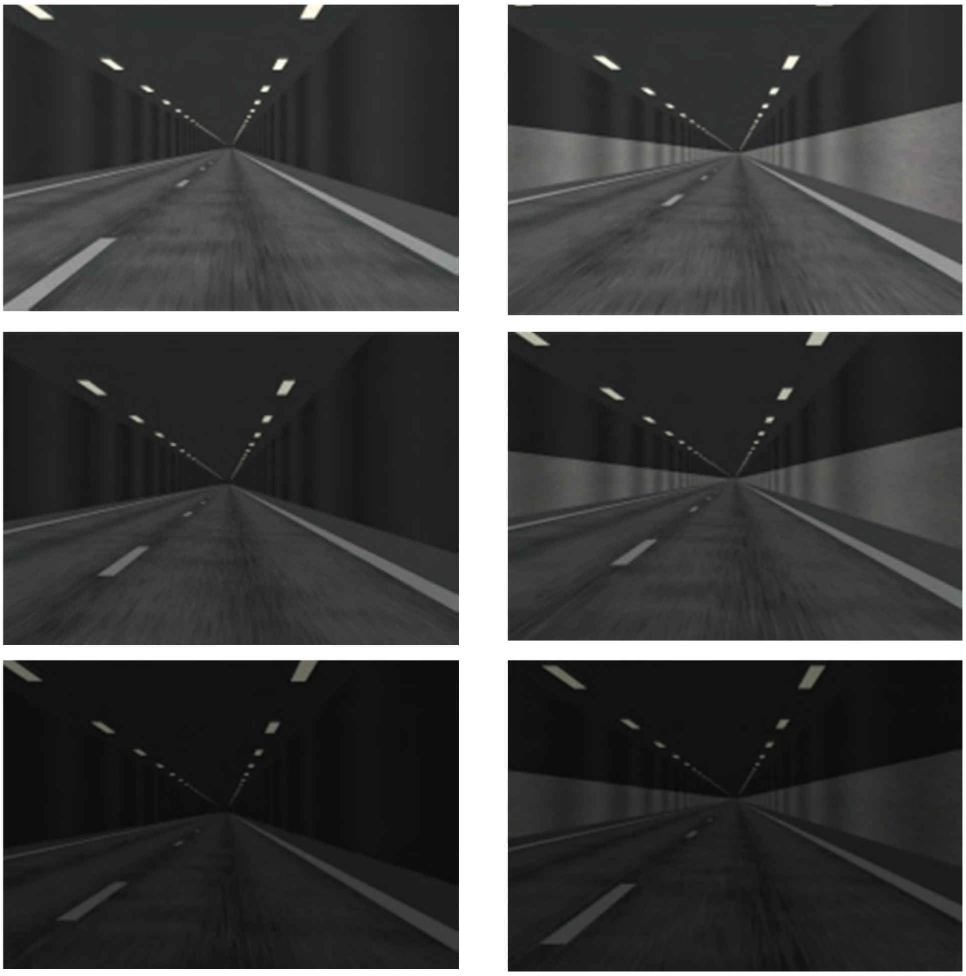


Figure 8 The factor ”tunnel design” was varied on two levels (columns), the factor “light intensity” was varied on three levels (rows). Each of the tunnels was driven twice, once under secondary task load and once without secondary task.

In the simulated tunnels the manipulation of the ambient light level entailed that everything visible in the image turned correspondingly darker. This includes simulated light sources, like the head and rear lights of other vehicles and the lamps mounted under the tunnel roof. In reality it is likely that the light walls would reflect some light onto the road surface, making it brighter than in the same light intensity condition, but with dark walls. These interactions were not entered into the simulation in order to keep the retroreflection of the road surface constant within each light intensity factor level.

In order to simulate the transitional phase in the tunnel entry and exit where natural light and tunnel illumination mix, the ambient light level was reduced in a linear fashion starting at the tunnel entrance and reaching its final level 180 m into the tunnel. The light was increased again in a similar fashion, starting 180 m before the tunnel ended and ending with the tunnel exit.

3.1.5 Other traffic

Some other traffic was present, partly to force the driver into planned interactions with other road users, as in the event described below, and partly to make the driving scenario more realistic. All other vehicles were silver-grey Volvos. Vehicle make and colour were kept constant in order to avoid confounding effects of colour and conspicuity, which could influence the driver behaviour in tunnels of different lighting and design, as the contrast to the background could differ.

Except for the event, there were three vehicles far ahead of the vehicle driven by the participant, which were visible on the entire open motorway section, and which disappeared from view after they had entered the tunnel entrance. There were also some vehicles far behind the participant's vehicle, their headlights were visible in the rear view mirror. Their speed was steered based on the participant's speed, such that interactions with them were impossible. All vehicles had their head and tail lights turned on.

3.1.6 Event

In each tunnel the same traffic event occurred (Figure 9). A short while after entering the tunnel, two vehicles (Vehicle A and Vehicle B) became visible in front of the own vehicle, driving behind each other with a distance of 60 m from front to front. They were steered in such a way that the own vehicle approached them more and more. Another vehicle (Vehicle C) came up from behind, driving in the passing lane. It was coupled to the own vehicle's speed in such a way that it would lie side by side with the own vehicle 1,800 m into the tunnel. After having passed the own vehicle it would accelerate and drive off with a speed 1.6 times as high as the own vehicle's speed.

When the own vehicle had approached the first of the two lead vehicles (Vehicle A) to a distance headway of 185 m, Vehicle A braked slightly, illuminating the brake lights. When the distance headway from the own vehicle to Vehicle A reached 170 m, the brake lights of Vehicle A were turned off, and Vehicle B started to brake. When the own vehicle had encroached to 150 m from Vehicle A, the brake lights of Vehicle B were turned off. During this process the participant had to decide whether to brake, too, and remain behind the two lead vehicles until the overtaking Vehicle C had passed, or whether to change lanes and overtake the two lead vehicles before Vehicle C had passed. In any case Vehicle C then accelerated and disappeared from view in the second curve of the tunnel. If the driver would not even overtake Vehicles A and B after Vehicle C had overtaken, the two vehicles would eventually switch on their warning lights and slow down to a stop.

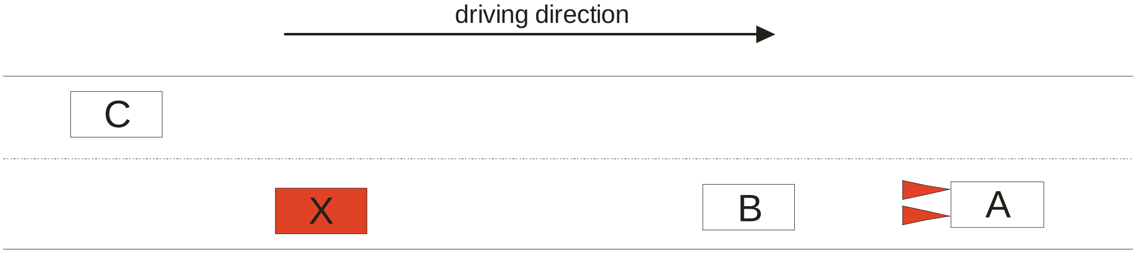


Figure 9 Schematic overview of the event. Vehicle X is the own vehicle driven by the participant. When Vehicle A and then Vehicle B brake, the participant has to decide whether to overtake before or after Vehicle C has passed.

3.1.7 Secondary task

In half of the tunnel passages the participants were put under additional workload, which was accomplished by letting them perform an adaptation of the arrow task developed in HASTE (Östlund, et al., 2004). This loading task occurred twice per tunnel. The first occurrence was during the event, from 1,000 m into the tunnel to 1,900 m into the tunnel, while the overtaking Vehicle C was approaching from behind, until the decision window to overtake before or after Vehicle C had passed. The second time the task occurred when the participant drove freely, between 2,900 m into the tunnel and 3,700 m into the tunnel. In both cases the road was completely straight.

Basically, the participants had to determine whether in a matrix of arrows there was an arrow pointing upward or not. For the present study only matrices showing arrows pointing in three (non-target) or four (target) directions were included (Figure 10). In the HASTE study those two conditions led to "reaction" times of 1.5 s, when a target arrow was present, respectively 2.3 s when no target arrow was present. These reaction times were obtained in a setting in which this was the primary task, without any driving involved. The reaction times correspond to off-road glance durations, which have been shown to be relatively dangerous (Klauer, et al., 2006). In the present study the participants could dispose of their glances as they wished, they were not required to use a single glance in order to make the assessment of whether the target was present or not. When no answer was given after five seconds the trial was scored as "unanswered", and the next matrix was presented. For each trial it was scored whether the answer was correct or not, and how long it took to complete the trial.

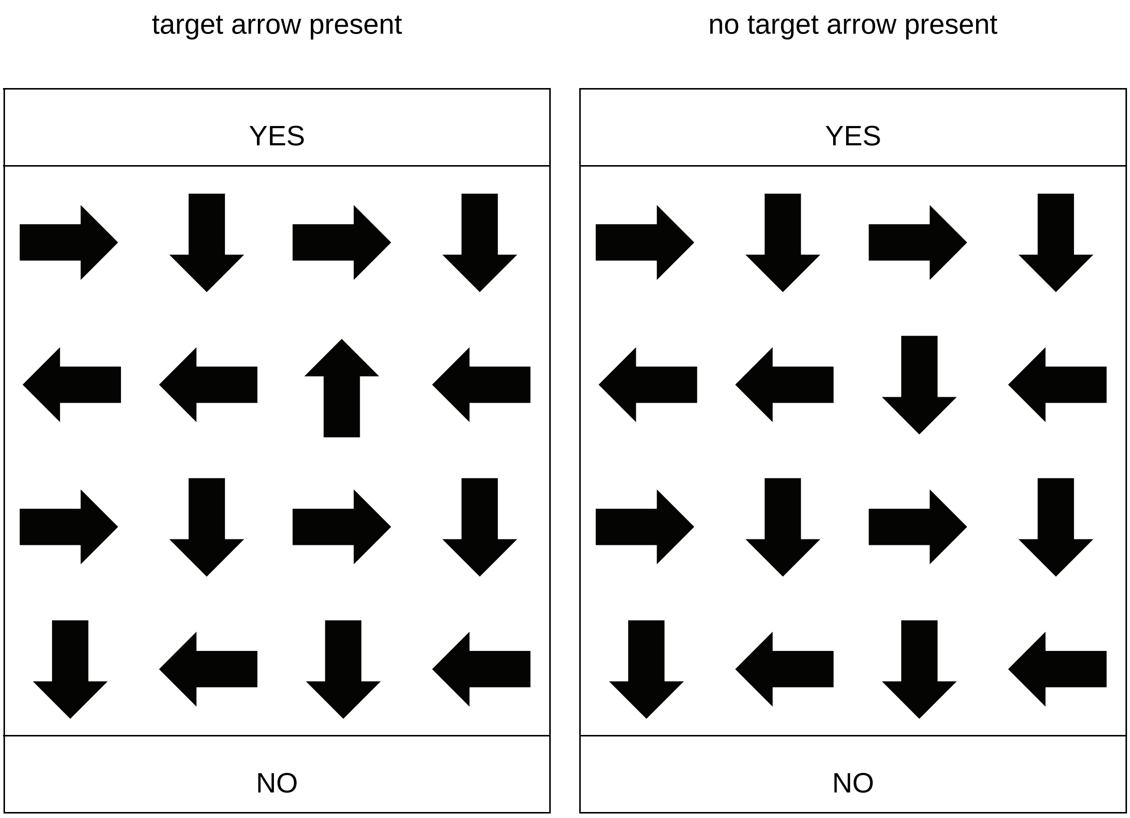


Figure 10 Two examples of the arrow task matrix, on the left hand side with a target arrow present, on the right hand side without target arrow present.

3.1.8 Demand rating

The participants rated the demand of traffic scenarios both in the laboratory, while watching films of traffic scenarios recorded from the driver's point of view, and while actually driving in the simulator. The complexity rating method was kept as similar as possible to the method introduced by Schweitzer and Green (2007), but certain adjustments were made for the situation at hand.

As in the Schweitzer and Green study, the participants were shown two film clips of 15 s duration, which were shown in repeat mode in parallel. These anchor films were exactly the same as those used in the study reported by Schweitzer and Green (2007).

In the Schweitzer and Green (2007) study, the clips to be rated were shown three at a time, always with an inherent order from lower to higher complexity. In the present study, however, only one film at a time was shown. This had several reasons. Firstly, no additional guidance should be given to the participants, as would be the case with several pre-ordered clips. Secondly, during the simulator session the participants were to rate the current traffic scene, with only one scene present at a time. Also, the number of clips was much lower as compared to the Schweitzer and Green study, which did not necessitate a compressed rating scheme for time saving reasons.

Just as in the Schweitzer and Green study, in the laboratory situation the participants were asked to indicate for each clip whether they could imagine to a) manually dial a number on a cell phone, b) manually tune the radio or c) enter a navigation destination in the current situation. When the participants drove the simulator, they only rated the demand of the scene.

For the demand ratings the participants were told to base their estimates on the anchor clips representing demand levels "2" and "6" as described above. The anchor clips were shown continuously, for the ratings outside of the simulator on the same screen as the clip to be rated, and for the simulator setting on a laptop positioned on the passenger seat. Schweitzer and Green instructed their participants that the scale ranged from 1 to 10, whereas in the present study no specific end points were given. Participants were free to use fractions, no requirements were made to stick to integers. Outside of the simulator, the participants made their ratings on a paper sheet prepared for the purpose, while during driving the rating was given verbally. The judgements as to whether the participants would engage in the three different secondary tasks described above were also made on the paper sheet on a continuous scale reaching from "absolutely" to "absolutely not", which was recoded into 0 to 100. It should be noted that the participants were advised particularly to only rate the traffic scene in relation to the anchor scenes, regardless of the workload put on them through secondary tasks and the like.
In addition to the three training clips each participant rated five clips from the ACAS-FOT study, which were also used by Schweitzer and Green, seven clips from Swedish motorways, and six clips from the driving simulator. Further technical specifications are given in Table 11.

Table 11 Specifications of the films shown to the participants for ratings according to the UMTRI demand scale.

	ACAS-FOT	Swedish Motorway	Simulator
frequency of frames	5ps	12.5 fps	25 fps
playback speed	2x	1x	1x
colour	black and white	black and white	colour
number of films	5 (1 for training)	7 (1 for training)	6 (1 for training)

In the simulator the participants rated the demand twice in each tunnel, the first time in the end of the overtaking event, 2,100 m into the tunnel, and the second time 3,800 m into the tunnel. This implies that for those occasions in which the secondary task was active, the demand was rated soon after the secondary task was completed.

Additionally each participant rated the demand of the driving scenario in three positions 1,000 m into the open motorway – once on the first motorway, before the first tunnel was entered, once on the 7th motorway, halfway through the experimental drive, and once on the 13th and last motorway, when all tunnels had been passed. The ratings were initiated by a sound played in the simulator cabin, and the participant said the answer aloud, such that it could be heard by the experimenter.

3.2 Participants

Participants were recruited from a volunteer database. The inclusion criteria are presented in Table 12.

Table 12 Inclusion criteria for the participants.

Inclusion criterion	**Motivation**
26–65 years of age	no absolute beginners, and no drivers of older age
possession of a valid driver's licence	used to driving a car
annual mileage > 5,000 km	relatively experienced driver
no glasses while driving	avoid eye tracking problems due to reflections and frame of glasses hiding eyes

Of the 30 participants originally booked ten cancelled their participation on relatively short notice due to illness or other reasons. This led to a slight loosening of the inclusion criteria, as new participants had to be found quickly. Finally, altogether 28 drivers participated in the study, 10 women and 18 men. The mean age was 41.3 years, with a standard deviation of 7.6 years. Their driving experience ranged from below 5,000 km yearly (3 participants) over 5,000–10,000 km yearly (4 participants) and 10,000–20,000 km yearly (12 participants) to above 20,000 km yearly (9 participants), that is, 75% of the participants drove a relatively high mileage.

Most participants did not have much experience with driving in tunnels. Of the 28 drivers 20 stated that they drove through tunnels a few times per year at most. Six participants drove through tunnels at least once a month, one reported to drive through tunnels at least once a week, and the remaining participant used tunnels on a daily basis.

None of the participants indicated more than a slight anxiety while driving in tunnels – 18 stated that they were not afraid at all, while 10 participants said that they felt a slight anxiety, but used tunnels anyway.

3.3 Procedure

Each participant received an e-mail confirming the appointment for participation in the study. The instructions were attached, allowing the participant to read through them at home for preparation.

The participants arrived at the reception of VTI and were met by one of three experimenters. They were led to a laboratory room, where they could read through the instructions, ask questions and then were asked to sign the informed consent form.

While still in the laboratory, the participants first practiced rating the demand of the surrounding traffic with three different films, one from the ACAS-FOT study, one from a Swedish motorway, and one from the simulator setting. Then they went on to rate several motorway scenes, both from the US study, from a Swedish motorway, and from the simulator setting. One clip at a time was rated, while the anchor clips ran in continuous mode and were visible all the time. When the participant had completed rating both the demand and the likelyhood of executing the secondary task in a corresponding real world situation the experimenter started the next film clip. The order in which the clips were presented was randomised considering the criterion that not more than three films from the same background (US, Swedish motorway, simulator) could be shown in sequence.

When the film rating was finished, the participants got a chance to read an instruction for the arrow task and to practice it on the same computer on which the films were shown. When the participant felt comfortable with the task, he or she was guided to the simulator hall. There the participant first read the following scenario description, which should give him or her a setting to which the simulator drive should be related:

> You are on a business trip in a part of the country that you are not familiar with. An old friend of yours whom you haven't seen in a long time lives about two hours away. You have taken one day off to meet up with your friend, and you have decided to see each other in the middle, such that both of you have about one hour to drive. The road that you have to take is 74 km long, and you have never driven it before. You only know that there are quite a number of tunnels along the way. You have checked thoroughly how you have to drive, and you are sure that you are going to find your way. The weather is fine, the road surface is dry, and you are alone in the car. You and your friend decided to meet at 13.00. The speed limit on the road is 90 km/h, and when you set out you have 50 minutes left in order to arrive on time. There is a clock in the car. On the trip recorder you see how far you have come.

However, your colleagues at work have encountered a problem, and they need your help to solve it. Several times during your trip they send pictures to your tablet computer which you have in the car, and you are meant to make a judgement of some kind. It is important for your company to solve the problem today. The arrow task which you just practiced is meant to represent this. Please try to put yourself mentally into this situation and drive as you would give those preconditions.

In addition, the participants were informed that the one who performed best on a weighted combination of driving performance, secondary task performance and arriving on time would win 2,000 SEK before tax in addition to the payment received for participation.

Then the participant entered the simulator, and the experimenter explained all necessary safety routines. Next, the profile for the eye tracker was generated, while the participant was asked to drive along a 6 km long training route. After the training the simulator came to a halt, and the participant got a last chance to ask questions before the trial.

The experimental trial then started, and the participant drove along the 74 km long track, which lasted approximately 50 minutes. The experimenter noted down the demand ratings uttered by the participant.

When the simulated drive stopped, the participant was asked to fill in a web-based questionnaire, which included demographical questions as well as questions directly related to the experimental drive, and more general questions on tunnels. In addition, the participant was asked to rank the different tunnels according to safety and comfort based on screenshots from the simulator. The experimenter remained in the vicinity to be able to help out with the questionnaire.

Finally, the participant received a reimbursement of 300 SEK before tax.

3.4 Analysis

The analyses were done with a repeated measures GLM, as the design was completely within subjects. The factors analysed within the GLM were attention, tunnel design and illumination. Each participant drove both through the event situation and a non-event free vehicle situation. This factor was added into the analysis as two different measures, because not all dependent variables were meaningful to be analysed in both event and non-event situations, and the intention was to still keep analyses as equal as possible across the dependent factors.

For some analyses the factor inattention was not present, for example when comparing lab results to simulator results. In these situations the analysis was conducted in an analogous way, except that the factor in question was omitted.

For analyses of possible changes over time, which were conducted on open motorway data, a repeated measures GLM was used.

More detailed information about the performance indicators used in the analyses are included in the results section, in order to keep the descriptions in local proximity to the analyses made.

The analyses were made at a significance level of $\alpha = 0.05$, but for the overview tables presented below, significance levels of $\alpha = 0.01$ and $\alpha = 0.10$ are also indicated to give a more complete picture.

4 Results

First the results over time are presented for some key PI. Then the results based on the three factors investigated are shown. For comparability sections of 500 m length were used in the analyses.

4.1 Performance over time

Performance over time was analysed in order to investigate whether the participants changed their behaviour systematically over time. Data from the open motorway sections were used for these analyses, as these road sections were equal in design throughout the trip. Analyses were made for both driving performance indicators and demand ratings, as they were collected on all open motorway sections. The arrow task was not performed on the open motorway, therefore no secondary task performance assessments could be made for performance over time.

4.1.1 Driving behaviour

Three driving performance indicators were analysed for the road segment in between 1,300 and 1,800 m on each open motorway section. It was assumed that the drivers would have adjusted their behaviour to open motorway driving by then, after having come out of the different tunnel types. A section of 500 m was used, as this corresponds approximately to what is required as minimum input for certain performance indicators (Kircher & Ahlstrom, 2010).

The mean speed over all participants increased significantly over time ($F = 8.8$, $p < .05$), from 89 km/h on the first motorway segment to 97 km/h on the 12th and 96 km/h on the 13th motorway segment (Figure 11).

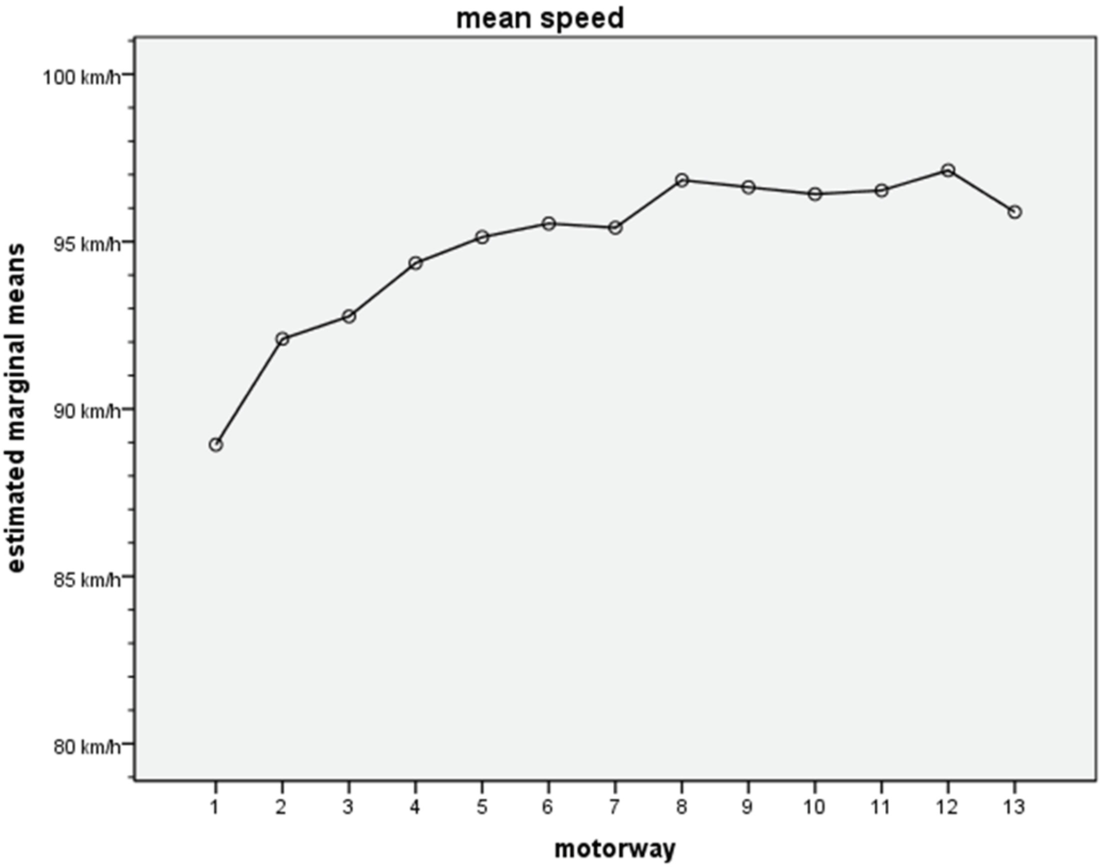


Figure 11 Mean speed across participants per motorway segment for the distance between 1,300 m and 1,800 m on each segment.

The standard deviation of speed did not change significantly over time and fluctuated between 2.2 and 2.9 km/h across the different sections ($F = 1.0$).

The drivers positioned the vehicle on average 81 cm from the left lane boundary and 92 cm from the right lane boundary. There was a trend for a change over time ($F = 2.3$, $p < .10$), but the variation was not a systematic offset over time, but rather that the most extreme mean lateral positions were assumed on the earlier motorways, while the mean lateral position stabilised more towards the end of the trip (Figure 12).

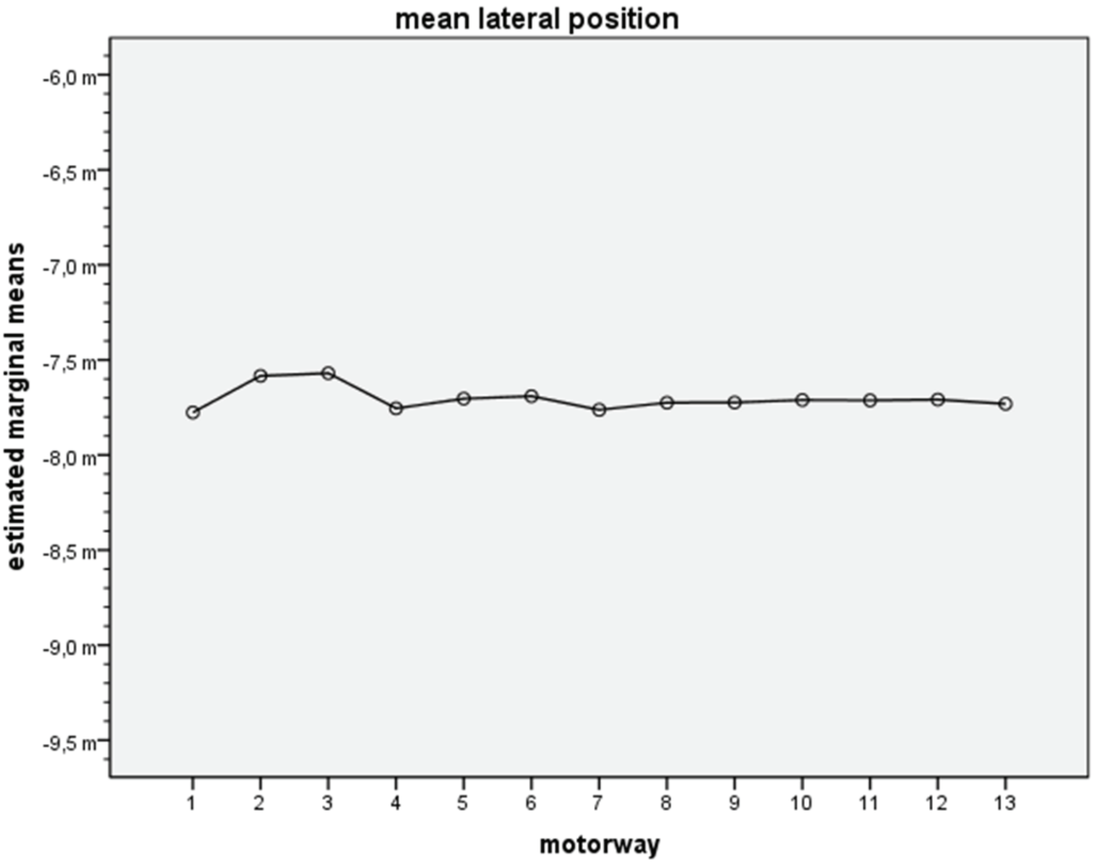


Figure 12 Mean lateral position across participants per motorway segment for the distance between 1,300 m and 1,800 m on each segment.

The SDLP changed significantly over time ($F = 3.6$, $p < .05$). Whereas the mean speed increased more or less steadily over time, the pattern was different for SDLP. On the second and third section comparatively high mean values were observed, while the remaining values were quite similar to each other. A detailed analysis showed that four individuals were responsible for the SDLP increase on these segments, and when they were excluded, the SDLP values remained stable over time for the remaining drivers.

4.1.2 Demand ratings

Demand ratings were made on three of the 13 open motorway sections. The first rating was made in the middle of the first section, the second rating was made in the middle of the seventh section, and the last rating was made in the middle of the last section. A repeated measures analysis showed that the participants did not change their in demand ratings over time with respect to the open motorway section ($F = .19$, $p > .05$). The average demand rating of the open motorway section was 1.5 (± 1.3). Means and standard deviations for the separate sections are presented in Table 13.

Table 13 Means and standard deviations for the demand ratings on the open motorway sections.

	first section	middle section	last section
mean	0.9	1.9	1.6
standard deviation	1.4	1.2	1.2

4.2 Performance per factor

In this section it will be considered how the factors tunnel design, light intensity and attention influenced the performance indicators computed for driving behaviour, driver behaviour, secondary task performance and experienced situational demand. A combined view of the performance regarding these different aspects will lead to a judgement whether and how these factors may influence traffic safety.

Where possible, both the behaviour in close proximity to the event and the behaviour while driving as free vehicle were investigated. The exact placement of the event depended on the driver's speed, therefore the data analysed stem from slightly different positions. For each participant data from a distance of 500 m were considered both for the event and the free driving analysis. For the event the data collection ended either at distance 1,900 m, or when the vehicle started to overtake, whichever occurred first. As the tunnel in the area in question was completely straight, the exact sampling location should not have influenced the PI values. Data collection started 500 m before that. For the free vehicle situation the data analysis was done for 3,200 m to 3,700 m.

The samples were taken from where the drivers performed the secondary task in half of the tunnels, both during the event and in the no-event situation.

4.2.1 Driving behaviour

In order to assess driving behaviour on the skill-based level, the performance indicators mean speed, standard deviation of speed and SDLP were analysed. A summary of the significant effects can be found in Table 14.

*Table 14 Overview of the significant main effects and interaction effects for the driving behaviour related PI under investigation (** equals $p < .01$; * equals $p < .05$; (*) equals $p < .10$).*

Event	**tunnel**	**light**	**attention**	**tunnel * light**	**tunnel * attention**	**light * attention**
mean speed	(*)		**			
sd speed				(*)		*
mean lat pos						
SDLP			*			
per cent speeding				(*)		
speeding index			*			

No Event	tunnel	light	attention	tunnel * light	tunnel * attention	light * attention
mean speed	(*)		**			
sd speed			**			
mean lat pos		*				
SDLP			**		**	
per cent speeding						
speeding index			**			

Mean speed

For the event situation no significant interaction effects on mean speed between the factors tunnel design, light intensity and attention could be found. There was a trend for a main effect of tunnel design, with the participants driving slightly faster in tunnels with dark walls (80.4 km/h) than in tunnels with light walls (79.3 km/h; $F = 3.4$, $p < .10$). Another main effect for the factor attention could be found for the event situation, with the participants driving almost 4 km/h faster on average when they were attentive (81.5 km/h) than when they were distracted (78.3 km/h; $F = 7.3$, $p < .05$). The estimated marginal means for mean speed are presented in Figure 13.

For the situation in which the subject vehicle was driving freely, average speeds were more than 10 km/h higher than in the event situation. The effects found for the free vehicle situation were very similar to those found for the event situation. A trend to faster mean speeds was found for dark walls (91.6 km/h) as compared to light walls (90.7 km/h; $F = 3.5$, $p < .10$). A bigger main effect was found for attention, with the drivers going faster when attentive (93.5 km/h) than when distracted (88.9 km/h; $F = 12.1$, $p < .05$). When assessing the mean speed it is also important to look at the standard deviation of speed, which can give an indication whether the driven speed was aimed for or not.

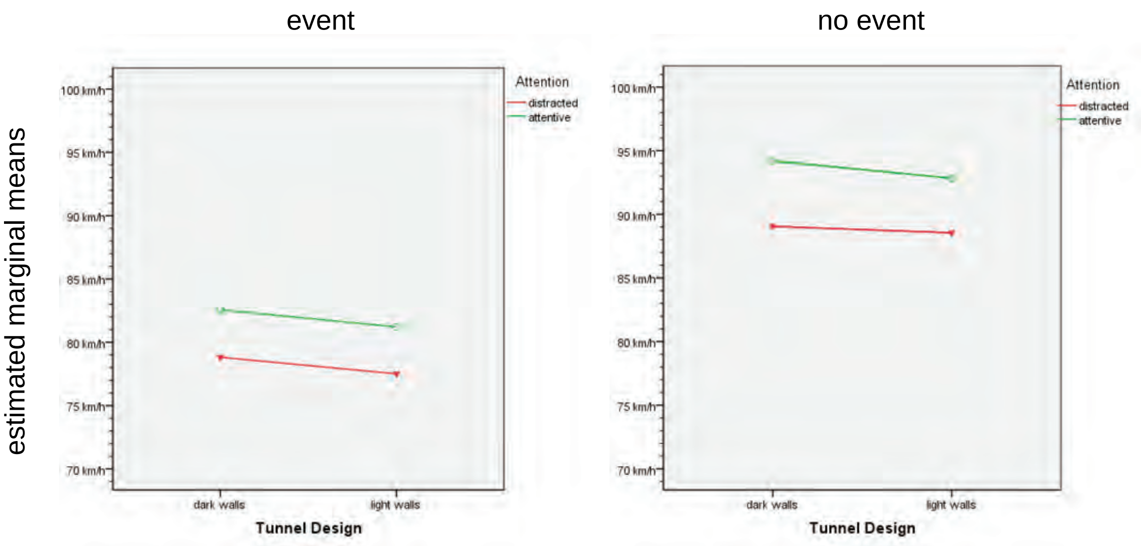


Figure 13 Estimated marginal means for mean speed depending on tunnel design and attention state.

Standard deviation of speed

At least in free vehicle situations the standard deviation of speed gives an indication how well the driver succeeds in keeping the target speed. This requires that the speed is not influenced too much by gradients or, obviously, a cruise control system.

In a car following situation the standard deviation of speed can be more dependent on the behaviour of the lead vehicle. In such a situation it can be more meaningful to consider the standard deviation of the time headway to the lead vehicle as a longitudinal control performance indicator, provided that the following vehicle has been in the following situation over some time.

In the study at hand the own vehicle approached the lead vehicle steadily, and the lead vehicle speed was coupled to the own vehicle's speed under certain circumstances, therefore an assessment of time headway variance is not meaningful in that situation.

In the non-event situation the standard deviation of speed varied only with attention. When attentive, the standard deviation of speed lay at 2.5 km/h, while it was 3.5 km/h for the tunnels in which the driver completed the secondary task ($F = 17.0$; $p < .05$).

Mean lateral position

In the present study the participants were meant to drive in the right hand lane when the lateral position was assessed. During the event-situation this was ascertained by analysing the distance of 500 m that occurred immediately before a lane change to the left for overtaking, if a lane change occurred at all. During the non-event situation it turned out that some participants had not completely finished their overtaking manoeuvre, which resulted in their drifting back into the right lane slowly, primarily during the first phase of the analysed distance. This behaviour influenced the lateral position data, but it was not possible to choose another road segment further down the tunnel for analyses, as it was necessary that the arrow task be executed in the same location.

On average the participants kept a distance of 83 cm to the left lane boundary and 90 cm to the right lane boundary in the event condition, while the distances were 67 cm to the left and 1.06 m to the right in the non-event condition. The lane was 3.5 m wide, and the vehicle width was 1.77 m.

The left most average placement was found for Tunnel 09 without event, that is, the tunnel with light walls and medium illumination, when the participants were distracted. The distance to the left lane boundary was 62 cm, and to the right 1.11 m. The right most average placement was measured for Tunnel 07, the tunnel with light walls and the lowest illumination, while the participants were distracted, during the event. The distance to the left lane boundary was 89 cm, and 84 cm to the right boundary. This was the only tunnel where the average placement was slightly further to the right than to the left within the lane. For all other tunnels the average placement was further to the left than to the right within the lane.

During the event none of the investigated factors influenced the average lateral placement in the tunnel.

When driving freely, the illumination had a significant effect on lateral position ($F = 3.4$, $p < .05$), but the displacement was small. In the darkest condition the participants drove on average 63 cm away from the left boundary, in the medium condition 66 cm away from the left boundary, and in the darkest condition they placed the vehicle 68 cm away from the left boundary.

SDLP

The standard deviation of lateral position, which indicates how much a driver sways around the own average lateral position.

During the event situation attention significantly influenced SDLP ($F = 36.6$, $p < .05$). Higher values occurred for distracted driving (0.17 m) than for attentive driving (0.12 m), indicating that the participants swayed more around their mean lateral position when visually distracted. No other factors significantly influenced SDLP.

During the no-event situation, again, there was a main effect for attention, where SDLP values were significantly higher for the tunnels in which the driver was distracted (0.2 m) than for tunnels in which the driver was attentive (0.14 m; $F = 21.3$, $p < .05$).

Additionally, there was an interaction effect between tunnel design and attention ($F = 11.4$, $p < .05$). While the SDLP was higher during distraction no matter the tunnel design, the difference was much more pronounced for tunnels with light walls. Drivers swayed the most when distracted and the walls were light, while they swayed the least when not distracted and the walls were light. The SDLP values for dark tunnel walls lie in between and are only slightly higher for distracted than for attentive driving (Figure 14).

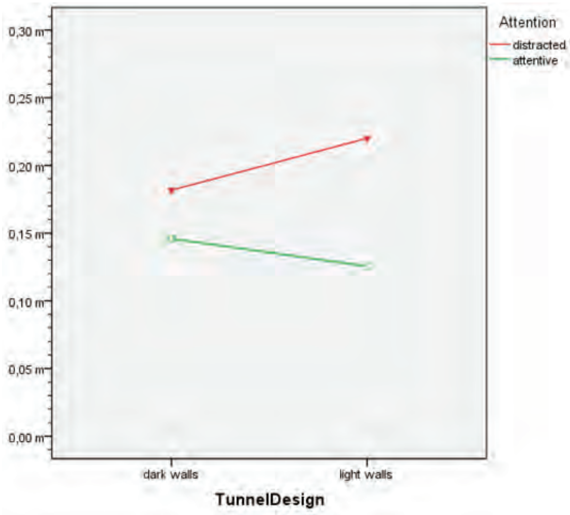


Figure 14 Interaction between tunnel design and attention for the no-event situation.

Per cent speeding

Speeding is illegal, and keeping to the posted speed limits should be conducive to traffic safety. Therefore, it is interesting to know which percentage of the trip was spent speeding. Speeding in this context is a speed above 93 km/h. A 3 km margin to the posted speed limit was granted, as the same is done for speed controls by the police. During the event the participants speeded for 10% of the time on the 500 m that were analysed. During the 500 m that were analysed for free driving, the participants spent on average 34.9% speeding. This is a significant difference ($F = 23.7$. $p < .05$).

No significant influence of any of the three investigated factors on the percentage of time spent speeding could be found, except for a trend that the participants speeded slightly more (14% of the time) in the tunnel with dark walls in the medium lighting condition. This lack of significant differences in per cent speeding is interesting, considering that mean speed varied with several of the factors investigated. These differences, however, do not seem to influence the percentage of time spent above the speed limit.

Speeding Index

The speeding index incorporates both the frequency with which the driver speeds and the magnitude of the violation. Values below zero indicate that the speed was below the speed limit for more than approximately half of the time.

Both during the event and when driving freely the speeding index lay below zero on average. However, during the event the index was significantly lower (speeding index = -0.32; $F = 98.4$, $p < .05$) than while driving freely (speeding index = -0.03).

During the event attention had a significant influence on the speeding index ($F = 4.6$, $p < .05$). As already indicated by other performance indicators the participants drove at slightly higher speeds when attentive (speeding index = -.29) than when distracted (speeding index = -.36). The same effect was found during the non-event situation ($F = 9.1$, $p < .05$), except that the values were slightly higher, with a speeding index of 0.04 for attentive and of -0.09 for distracted driving.

Tactical behaviour

It was planned to analyse the drivers' tactical behaviour with respect to overtaking, but it turned out that the lead vehicles were overtaken only 11 times of 336 possible times before the vehicle from behind had passed the participant's vehicle. These 11 overtaking manoeuvres stem from only four different participants. How the overtaking manoeuvres were distributed across the different tunnel types can be seen in Table 15.

Table 15 Distribution of the overtaking manoeuvres across the different tunnel types.

	attentive	
	light	dark
bright	2	2
medium	1	1
dark	1	

	distracted	
	light	dark
bright	1	1
medium	1	
dark	1	

More overtaking manoeuvres occurred in tunnels with light walls, under bright lighting conditions, and when the driver was attentive, but there were overtakings in the other conditions, too. It had been planned to analyse different details of the manoeuvres, but they were too few and came from too few participants to allow a more detailed analysis.

4.2.2 Driver Behaviour

Eye glance behaviour was analysed, in order to assess how visually demanding the different tunnel types were with different illuminations. The eye tracker did not work reliably for all participants. Data from six participants had to be excluded due to quality problems. The analyses under this headline are therefore based on the data from 22 participants.

The AttenD algorithm was used as a basis for the results presented here. That is, glance duration and the percentage of glances away from the field relevant for driving (FRD) were calculated based on the output from the algorithm. This implies that both eye tracking and head tracking can be the source of glance duration values, and it implies that the data were filtered and treated according to the rules on which the AttenD algorithm output is based (Kircher & Ahlstrom, 2009).

An overview of the significant effects for driver behaviour related performance indicators is presented in Table 16.

*Table 16 Overview of the significant main effects and interaction effects for the driver behaviour related PI under investigation (** equals p < .01; * equals p < .05; (*) equals p < .10).*

Event	tunnel	light	attention	tunnel * light	tunnel * attention	light * attention
# of 2 s glances			*		*	
% away fr FRD			(*)			
% AttenD empty						
% AttenD full			*			

No Event	tunnel	light	attention	tunnel * light	tunnel * attention	light * attention
# of 2 s glances	*		*			
% away fr FRD	*		*	(*)		
% AttenD empty						
% AttenD full	*		**			

Number of 2 s glances

Single glances away from the forward road of a duration of more than 2 s are considered dangerous and related to an increased crash risk (Klauer, et al., 2006). The number of single more than 2 s long glances away from the field relevant for driving (FRD) was on average smaller than 1 for the two 500 m long situations for which data were analysed.

In the event situation there was a significant effect for the factor attention, which showed that drivers had more very long glances away from the FRD when they were distracted with the arrow task (0.8 glances on average) than when fully attentive (0.4 glances on average; $F = 6.2$; $p < .05$).

Additionally, there was a significant interaction of the factor attention with tunnel design ($F = 4.5$, $p < .05$). The number of very long glances was largest for distracted drivers in dark tunnels (0.8) and smallest for attentive drivers in dark tunnels (0.35).

Also in the situation without any event, drivers had significantly more very long glances away from the FRD when distracted (0.75 glances on average) than when attentive (0.4 glances on average; $F = 5.5$; $p < .05$).

Additionally, in the free vehicle situation very long glances were more frequent for dark walls (0.7) than for light walls (0.45; $F = 6.5$, $p < .05$). No interaction effect was found, and the illumination level did not influence the glance duration in any of the two situa-tions.

Per cent away from FRD

It was also investigated which percentage of the glances was directed away from the FRD. This is a more long-term assessment of the driver's attention level, as it reflects the behaviour over a longer period of time. In this case a distance of 500 m was considered, which corresponds to 20 s in case of a speed of 90 km/h.

During the event none of the investigated factors had a significant effect on the percentage of glances directed away from the FRD.

During the non-event situation the influence of the different factors was rather complex. The factor attention had a significant effect on the percentage of glances away from the FRD ($F = 6.2$, $p < .05$), with 15% of the glances directed away from the FRD without arrow task and 26% of the glances directed away from the FRD while distracted by the arrow task. In addition to this main effect a trend for an interaction was found between the tunnel design and the illumination ($F = 3.2$, $p < .1$). While the drivers looked away from the FRD 25% of the time when the walls were dark and the illumination was on the darkest level, they looked away only 18% of the time when the walls were light, but the illumination on the darkest level. For all other combinations of lighting and tunnel design the glances away from the FRD made up approximately 19–21% of all glances. A significant main effect for tunnel design was found ($F = 6.4$, $p < .05$), but as can be seen in Figure 15, the effect actually comes from the difference in the condition with the darkest illumination.

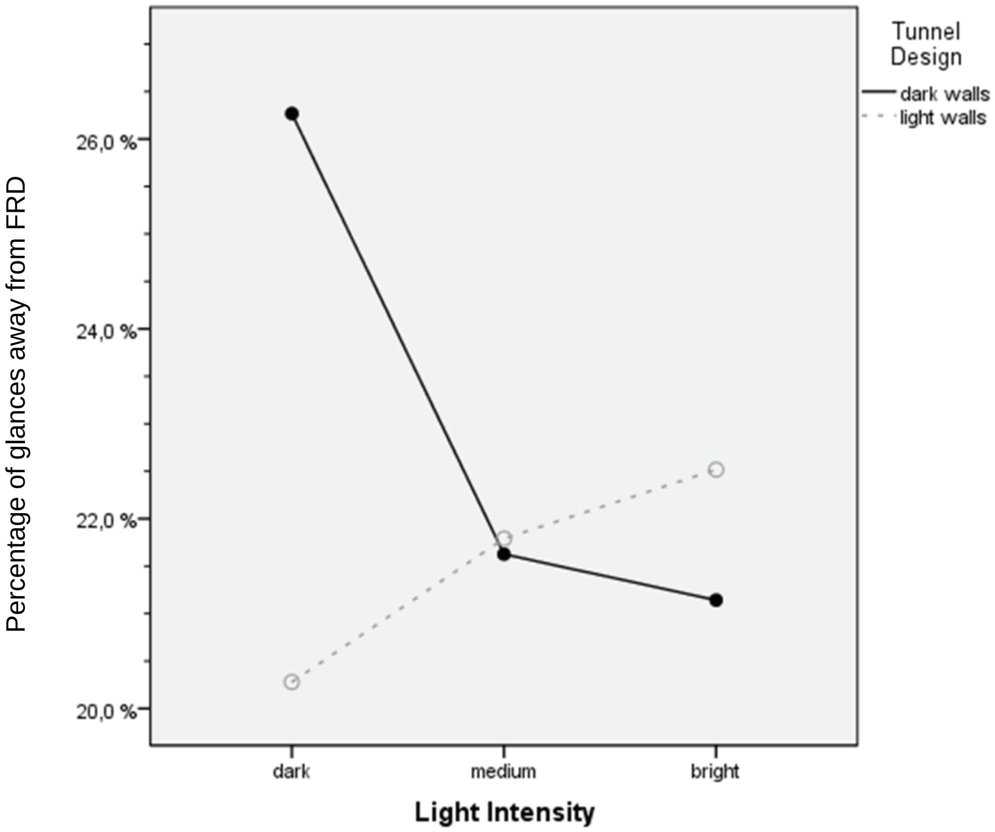


Figure 15 Illustration of the relationship between light intensity and tunnel design in the non-event situation with respect to the percentage of glances directed away from the FRD.

Percentage AttenD empty

The AttenD algorithm continuously indicates the attentional status of the driver. When the algorithm output reaches zero, the driver is considered to be distracted. It was investigated whether the different factors under assessment in this experiment had an influence on the percentage of time during which the AttenD algorithm equalled zero.

On average the algorithm equalled zero for about 10% of the time. No significant differences were found for any of the factors under investigation.

Percentage AttenD full

Furthermore, it can be investigated which percentage of the time the AttenD buffer equals 1.8 or more. As described above, it can assume values between zero and two. A driver is considered to be fully attentive when the values are at 1.8 or higher, as normal eye blinks should be allowed, which have a duration of 0.1 to 0.2 s.

During the event situation the factor attention had a significant influence on the percentage of time during which the drivers were attentive according to the AttenD algorithm ($F = 5.5$, $p < .05$). When not distracted by the arrow task, the drivers had a full buffer for 71% of the time, while they had a full buffer for 60% of the time when executing the arrow task.

During the non-event situation the same effect was found ($F = 13.1$, $p < .05$). When distracted, the drivers had a full buffer for 61% of the time, but when attentive, the buffer was full for 80% of the time. This was also significantly different from the event-situation ($F = 7.5$, $p < .05$). During the non-event situation, the tunnel design also influenced the percentage of time with full buffer ($F = 5.5$, $p < .05$). When the walls were dark, the participants had a full buffer for 69% of the time, while the buffer was full for 73% of the time when the walls were light (Figure 16).

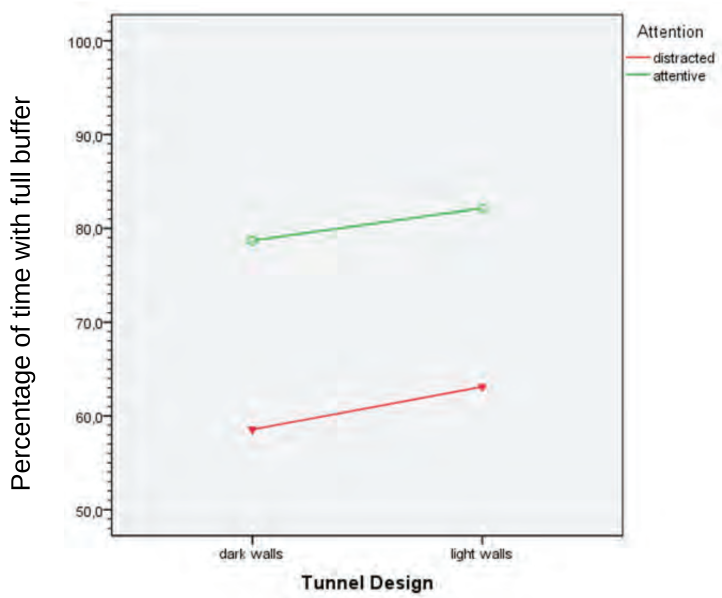


Figure 16 Visualisation of the effects of attention and tunnel design on the percentage during which the buffer was full in the non-event situation.

4.2.3 Secondary task performance

For secondary task performance only the factors tunnel design and illumination could be investigated, as the secondary task in itself represented the factor attention. Several performance indicators were chosen to assess how well the participants did on the arrow task.

For one participant the secondary task performance was accidentally not logged, therefore the data presented here stem from 27 participants.

For all performance indicators considered there were no significant differences between the event situation and the non-event situation. That indicates that approximately the same number of tasks was solved, the same percentage of answers was correct, and reaction times were equal in both cases.

Answer time

The average reaction time was investigated, regardless of whether the answer given was correct or not. Only occasions in which no answer at all was given were excluded. No significant effects of tunnel design or illumination could be found on the overall reaction time, neither during the event or while driving as a free vehicle.

Average answer times lay at about 2.8 seconds on average, no differentiation was made between stimuli with or stimuli without target.

Per cent correct answers

The same was true for the number of correct answers. For all answered stimuli it was computed whether the answer was correct, which could either be an upward arrow identified correctly or no target, which was rejected correctly. A wrong answer, on the other hand, represented either a false alarm, that is, confirming an upward arrow when there was none, or a miss, that is, rejecting a target arrow.

Of all answered stimuli, 86% were answered correctly during the event and 87% were answered correctly while driving freely. The lowest percentage of correct answers was found for the tunnel with dark walls and the lowest illumination during the event (84.6%), while the highest percentage of correct answers was found for the tunnel with dark walls, but the brightest illumination, during the event (91.2%), there was no significant difference, however.

Per cent answered

The percentage of answered stimuli varied between 82.8% for the brightest tunnel with dark walls during the event, which is the same tunnel that scored the highest correct rates, and 96.8% for the brightest tunnel with light walls in the no-event situation. However, also for this performance indicator no significant differences between the different factors could be found, except for a trend for a higher answer rate for tunnels with dark walls (86%) than tunnels with light walls (82%; $F = 3.5$, $p < .1$). It can be stated that the participants showed a great interest to deal with and answer the secondary task in all tunnel conditions.

To summarise, it can be said that the performance on the secondary task was relatively equal throughout the different conditions, both in terms of quantity, that is, how many stimuli the drivers responded to, and qualitatively, that is, how many of the answers were correct. The relatively high correctness rates indicate that the participants actually made an effort while answering, instead of pressing the buttons randomly.

4.2.4 Demand ratings

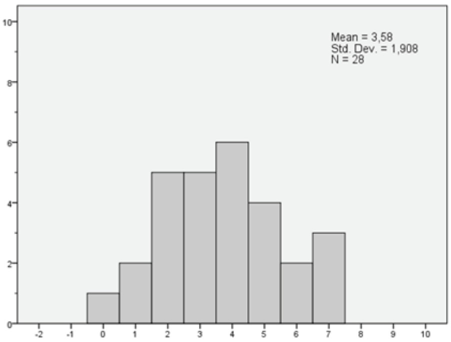
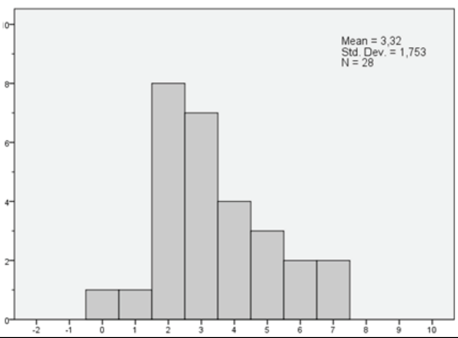
Demand ratings were collected in the laboratory and in the simulator. The results from both sites, and a comparison for those scenarios that were rated at both sites are presented here.

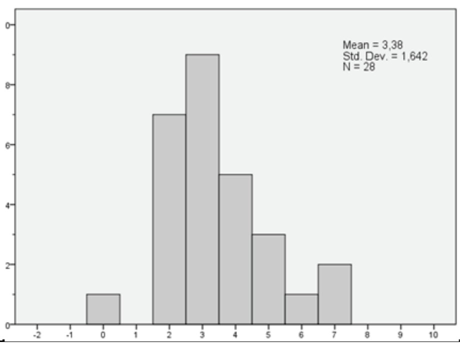
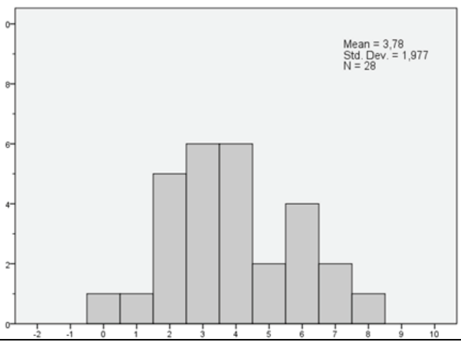
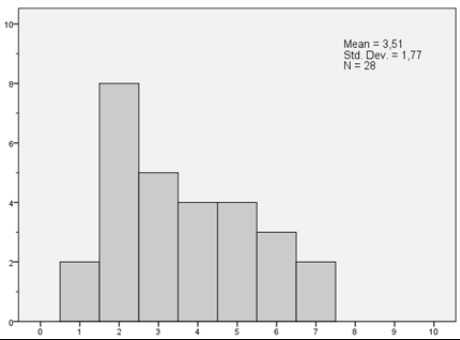
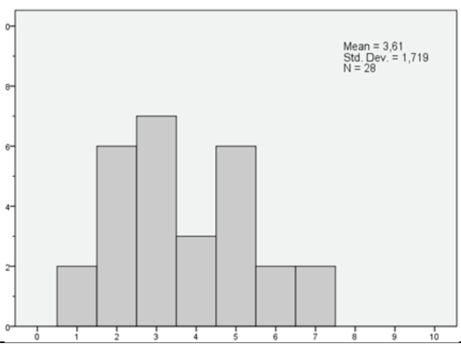
Lab

Before the participants entered the simulator they rated both recordings of the simulator scenarios and other traffic scenarios, which were presented on a computer screen. Here the results for the ratings of the recordings from the simulator are presented. The simulator films corresponded approximately to the position where the participants rated the demand while driving, too. On the films, however, the “own vehicle” overtook the two lead vehicles, while most participants chose not to overtake while driving.

The ratings differed between the participants with demand value ranges of 4 to 8 points. For some of the scenes the ratings were very widespread, while they were more homogenuous in other cases. In Table 17 histograms of the demand ratings and the mean, the median, the mode, the range and the minimum and maximum values given are shown for the lab ratings of the films recorded in the simulator. For comparison, the demand ratings from the event situation in the simulator are included, too. Only the values for non-distracted driving are shown. The rank of each tunnel based on the mean ratings is provided both for the laboratory and for the simulator.

Table 17 Histograms of the lab ratings based on the films recorded in the driving simulator, and further distribution values. For comparison the simulator values for non-distracted driving are included as well. In case of multiple modes, all are given.

	Histogram of the ratings	Further distribution values		
			Lab	**Sim**
Simulator 1 (T_2Li_1) 		Mean	3.58	3.18
		Median	3.5	3.25
		Mode	3	3, 4
		Range	7	6
		Min	0	0
		Max	7	6
		Rank	*4*	*4*
Simulator 2 (T_2Li_2) 		Mean	3.32	3.03
		Median	3.0	3
		Mode	2	3
		Range	7	6
		Min	0	0
		Max	7	6
		Rank	*1*	*2*

Simulator 3 (T_2Li_3) 		Mean Median Mode Range Min Max *Rank*	3.38 3.0 3 7 0 7 *2*	3.03 3 2 6 0 6 *1*
Simulator 4 (T_1Li_1) 		Mean Median Mode Range Min Max *Rank*	3.78 3.5 2, 3, 4, 6 8 0 8 *6*	3.32 3 3 8 0 8 *6*
Simulator 5 (T_1Li_2) 		Mean Median Mode Range Min Max *Rank*	3.51 3.0 2 6.5 0.5 7 *3*	3.18 3 3 7 0 7 *4*
Simulator 6 (T_1Li_3) 		Mean Median Mode Range Min Max *Rank*	3.61 3.0 2, 5 6 1 7 *5*	3.12 3.25 4 6 0 6 *3*

The median values for the simulator ratings were quite similar, and several participants commented that they could not see a difference in demand between the recordings from the simulator. Between participants, however, the ratings varied markedly.

For comparison, the same distribution values are provided for films recorded on a Swedish motorway (Table 18) and for films recorded on an US American motorway (Table 19). These ratings are not analysed any further within the scope of the present report, however.

Table 18 Distribution values for the ratings given for films recorded on a Swedish motorway. In case of multiple modes, all are given.

	Sweden 1	Sweden 2	Sweden 3	Sweden 4	Sweden 5	Sweden 6	Sweden 7
Median	3.00	4.00	3.00	4.00	3.25	5.00	3.75
Mode	1 & 3	3	3	4	2, 3 & 4	5	4
Range	5.00	8.00	6.00	7.50	8.00	8.00	8.00
Minimum	1.00	1.00	1.00	.50	.00	2.00	.00
Maximum	6.00	9.00	7.00	8.00	8.00	10.00	8.00

Table 19 Distribution values for the ratings given for films recorded on US American motorways.

	USA 1	USA 2	USA 3	USA 4	USA 5
Median	4.00	4.00	6.00	4.00	6.00
Mode	4	3	6	4	6
Range	4.00	6.50	6.30	6.50	5.50
Minimum	1.00	1.50	1.70	.00	2.50
Maximum	5.00	8.00	8.00	6.50	8.00

Only the factors illumination and tunnel design could be analysed with respect to the demand ratings, as the participants did not execute any secondary task while watching the films in the lab. There was a trend that the illumination influenced the ratings, with the darkest illumination receiving average ratings of 3.7, while the medium lighting level was rated at 3.4. The brightest level was rated as 3.5 on the demand scale ($F = 2.5$, $p < .10$). Ratings were consistently slightly higher on average for tunnels with dark walls than with light walls, but the difference was not significant.

Simulator

The participants rated the demand of the current situation twice while driving in the tunnels, once during the event and once while driving freely. The ratings were analysed with respect to the three factors tunnel design, illumination and attention (Figure 17). Generally ratings were higher during the event than in the non-event situation ($F = 84.0$, $p < .05$), which can also be seen in the figure.

For the ratings made during the event a significant difference in the ratings was found for the factor tunnel design, where dark walls received higher demand ratings (3.7) than light walls (3.4), indicating that dark walls were experienced as more demanding ($F = 6.8$, $p < .05$). Additionally, attention had a strong effect on the ratings, with the event situations being rated as 3.1 on average when the driver was attentive and 3.9 on average for inattentive drivers ($F = 25.9$, $p < .05$).

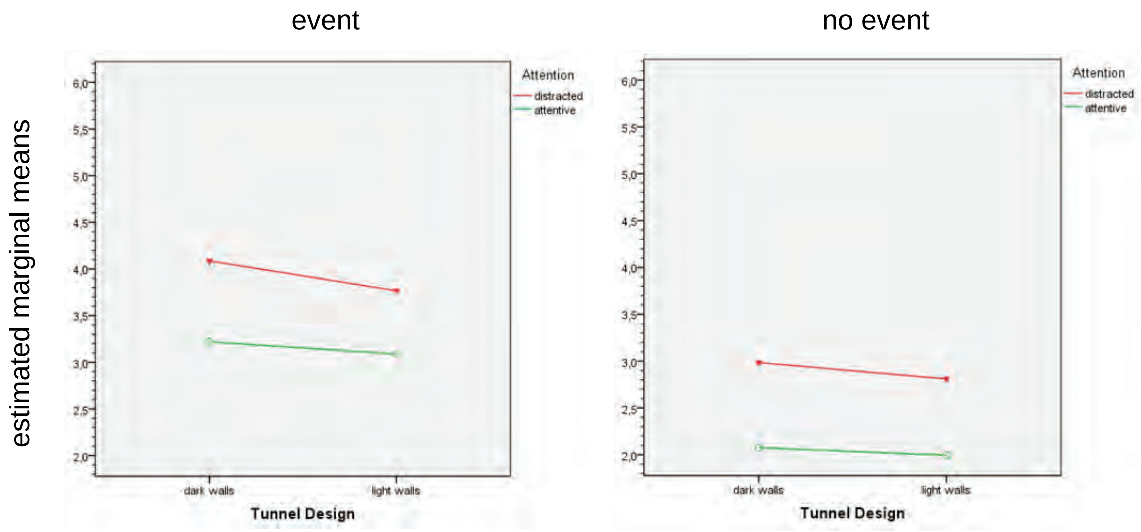


Figure 17 Demand ratings for the factors attention and tunnel design in the event and the no-event situation.

Comparison lab simulator

It is of interest to understand how the ratings in the laboratory can be related to the ratings obtained while driving in the simulator, therefore the demand ratings for tunnels corresponding to each other were compared statistically. The tunnels that were considered in the analysis were all tunnels without a secondary task, such that the factors for the analysis were tunnel design, illumination and setting, that is, whether the rating was obtained in the laboratory or in the simulator.

In Table 17 a number of distribution values are presented both for the laboratory ratings and the demand ratings from the simulator drive. On average the mean ratings and also the medians are very similar for all tunnels in both cases. The distribution within the tunnels is much larger than between. The ranges for the demand values given were very similar in both settings, as were the minimum and maximum values given for each tunnel situation. The overall rank positions for the tunnels within each setting were not exactly equal, but followed the same pattern. The ranks were based on the mean values, as too many medians were exactly the same. The difference in ranks was in some cases based on differences in the third decimal.

A repeated measures analysis showed that there were trends for all three main effects, showing that average demand ratings tended to be higher in the simulator (3.5) than in the laboratory (3.1; $F = 4.2$, $p < .10$), that average ratings for dark tunnels tended to be higher (3.4) than for light tunnels (3.2; $F = 3.3$, $p < .10$), and that ratings for the tunnels with the darkest illumination tended to be higher (3.5) than for the other two illumination levels, which lay both at 3.3 ($F = 3.3$, $p < .10$). No significant interactions were found. The ratings for the different factors are shown in Figure 18.

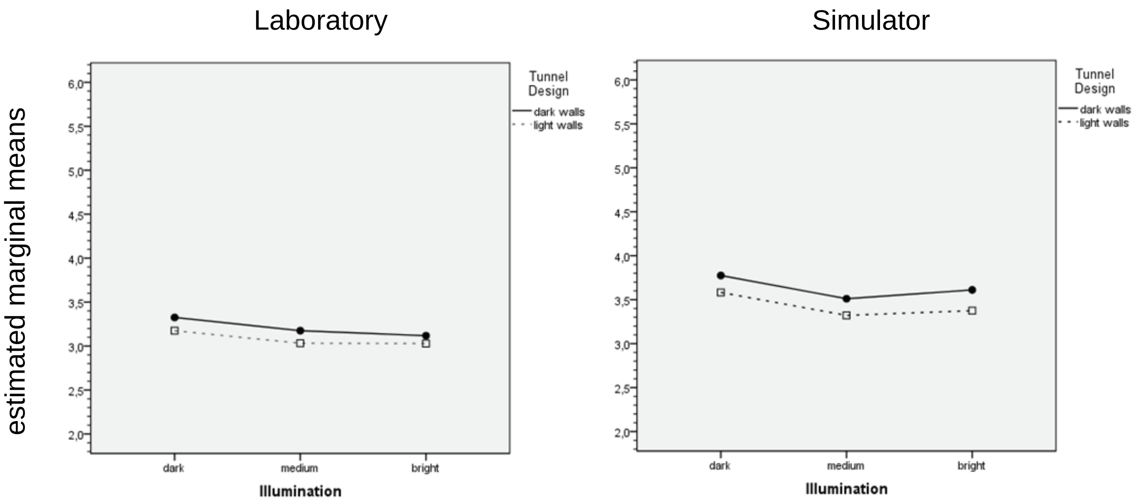


Figure 18 Comparison of demand ratings for the laboratory and the simulator for the factors tunnel design and illumination.

4.2.5 Questionnaire

As part of the questionnaire the participants were asked with a multiple choice question on which dimensions the tunnels had varied. The answer alternatives and the number of participants who said yes, there was a difference between the tunnels, versus no, there was no difference between the tunnels, are presented in Table 20. Clearly, most participants had noticed that the colour/brightness of the walls and the strength of the illumination had been varied, but not the other factors. However, there were no unanimous answers, and five participants indicated that the walls of the tunnels did not differ from each other, respectively that the illumination was not varied across the tunnels. One participant got both of these questions wrong, while the others missed only one of those questions. In addition, almost a third of all participants assumed that the road surface colour/brightness had varied, and almost a quarter of the participants thought that the tunnels had varied in length.

When the participants indicated that the illumination varied across tunnels, they were asked a follow-up question on how many levels of illumination had appeared. Seven of the 23 participants who had noticed a variation in illumination responded that they did not know the number of levels, five participants indicated that there were two levels, nine participants indicated correctly that there were three levels, and two participants thought they had noticed four levels of illumination. A further follow-up question indicated that the brightest illumination was most appreciated by all but three participants, who preferred the medium illumination level.

Another follow-up question yielded that 19 participants preferred the light walls, two preferred the dark walls, and two had no particular preference. Those five who had not noticed a difference in wall colour/brightness were not asked to answer the question.

Table 20 The number of participants who thought that the tunnels varied on a certain factor (yes) respectively did not think that the tunnels varied on a certain factor (no), per factor. The factors marked with grey are those that actually varied.

	length	colour/ brightness of wall	height of roof	colour/ brightness of road surface	strength of illumination	curvature
yes	6	23	1	8	23	2
no	22	5	27	20	5	26

The participants were also asked to rank screen shots of the six different tunnels. One ranking was made according to how safe the tunnels were judged to be, and one was made according to how comfortable they were to drive in.

Both rank orders turned out to be the same. They are displayed in Table 21, including the average rank for both ratings. For both ratings it can be seen that the standard deviation and the range of ranks was smaller for the first two ranks than for the remaining ones. The middle ranks varied the most between participants, while the worst tunnel in terms of safety and comfort found more agreement. The two highest ranks were given to tunnels with light walls, while the four highest ranks were given to the brightest four tunnels.

Table 21 Ranking of the different tunnels according to safety and comfort, based on screen shots from the simulator. The ranks from the demand ratings in the laboratory and in the simulator are included for comparison.

tunnel type	**picture**	**safety**	**comfort**	**demand**
T_2Li_3		mean rank 1.1 min – max 1 – 2 std 0.3	mean rank 1.1 min – max 1 – 3 std 0.4	lab: 2 sim: 1
T_2Li_2		mean rank 2.2 min – max 2 – 4 std 0.5	mean rank 2.2 min – max 2 – 4 std 0.5	lab: 1 sim: 2
T_1Li_3		mean rank 3.0 min – max 1 – 5 std 1.1	mean rank 3.0 min – max 1 – 6 std 0.9	lab: 5 sim: 3
T_1Li_2		mean rank 4.1 min – max 2 – 5 std 0.7	mean rank 4.0 min – max 2 – 6 std 0.8	lab: 3 sim: 4

T_2Li_1		mean rank 4.5 min – max 3 – 6 std 1.1	mean rank 4.8 min – max 3 – 6 std 1.0	lab: 4 sim: 4
T_1Li_1		mean rank 5.6 min – max 3 – 6 std 0.7	mean rank 5.6 min – max 3 – 6 std 0.7	lab: 6 sim: 6

The participants were also asked more general questions, particularly about driving in long tunnels. They were confronted with several factors and asked for their opinion on how those would influence traffic safety.

No participant could see any disadvantage with bright walls and wide shoulders. A bright road surface and very strong illumination was viewed positively by most participants. Oncoming traffic in the same tube, entry and exit ramps and very weak illumination were generally seen as detrimental to safety. “Entertainment” or activation, which was specified as colours or art was seen as slightly more negative than positive (Table 22).

Table 22 Each cell represents the number of participants assuming that a certain factor would change traffic safety in a long tunnel in a certain way.

	decreases a lot	**decreases a little**	**no change**	**increases a little**	**increases a lot**
bright walls			9	16	3
wide shoulder			2	13	13
bright road surface		2	8	17	1
oncoming traffic in same tube	16	10	1		1
exit ramps in tunnel	5	19	3	1	
entry ramps in tunnel	8	14	3	3	
very strong illumination	1	1	4	13	9
very weak illumination	15	9	1	3	
“entertainment”/activation	5	9	10	3	1

The participants were asked to compare driving in a more than 10 km long motorway tunnel with driving on an open motorway in terms of how they would be affected psychologically (Table 23). On average the participants stated that driving in a tunnel would be about the same as on an open motorway, or a little bit more difficult, fatiguing, boring and dangerous, but for almost all questions there were some other opinions, too.

Table 23 Each cell represents the number of participants for certain opinions on driving in a motorway tunnel as compared to an open motorway.

	much less	a little less	about the same	a little more	much more
more difficult	2	2	7	15	2
physically fatiguing		2	13	12	1
psychologically fatiguing		2	7	16	3
boring	2	2	7	9	8
dangerous	2	4	8	13	1

Finally, the participants were asked what they considered as important for a tunnel to be safe to drive in. The answer that was most prominent was that the tunnel should be bright, even though it was not always specified whether this brightness should stem from an increased illumination or brightly coloured walls. Wide lanes and road shoulders were mentioned as safety promoting, and a few participants stressed the importance of having one tube per traffic direction. The presence of guiding lights either to demarcate the edge between the road surface and the wall, or embedded into the wall, was desired. Two participants saw a variation in the tunnel wall design in form of for example art as particularly positive, while another participant explicitly stated that art on the walls was not desirable.

In a final question the participants were asked how they had experienced the scenario description that they had received for the simulator drive. The majority of the participants found it easy to put themselves into the described situation mentally, only four participants mentioned that they found it a little difficult. A third of the participants stated that the situation description influenced their driving at least somewhat, while the remaining participants did not think so. Most of the participants did not find the situation description helpful, however.

5 Discussion

In the discussion of the results the different aspects of the evaluation will be highlighted both separately and in combination. Both subjective impressions and the drivers' actual behaviour contribute to the final evaluation of the different tunnels investigated.

In short, the data from the present study show that tunnel walls in a light colour yield a higher traffic safety than dark walls and are more appreciated by the drivers, as long as the illumination is good enough. The illumination levels under investigation affected the behavioural results only marginally and showed basically that only very low levels of illumination are preferred the least by the participants, both with respect to safety and comfort.

5.1 Performance over time

The results show that the drivers increase their mean speed over time on average on the open motorway section. This can be due to the fact that they get used to the simulator and want to speed up, or that they check their speed less and less and happen to speed up, as it is difficult to judge one's speed in the simulator without glancing at the speedometer repeatedly.

The SDLP values were larger in the beginning, but stabilised quickly and remained at the same level over time for the motorways 4-13. This indicates that drivers had more difficulties in the beginning to keep lateral control, but that they improved over the course of the study. Similarly, the average lateral position was further to the left for the first three motorways, but was adjusted on the fourth and stable throughout the remaining motorway sections.

The demand was only judged on the first, seventh and 13th motorway in order to avoid annoying the drivers. The demand ratings did not change significantly over time, and they were rather low for the motorway section, indicating that the inter-rater reliability within the drivers was good. It is possible that the drivers remembered their earlier judgements and just repeated them, but on the other hand, each driver made twelve other ratings in between, such that it is more likely that each motorway rating was produced based on what was seen.

To sum up, certain behavioural changes could be observed over time on the open motorway. This implies that a balancing or randomising of the order of the tunnels is necessary to avoid the chronological order confounding the results. It is not necessarily true, however, that the speed in the tunnels developed in the same way, as the surrounding traffic influenced the drivers' speed during the event. The average speed in the non-event situation was somewhat lower than the mean speed on the open motorway section. It is possible that the tunnel environment has a restraining effect on speed, due to the more confined environment, the walls close by, and several other factors.

On average the drivers placed the vehicle 16 cm further to the left when inside a tunnel as compared to on the open motorway section. This could be an effect of the drivers' wanting to put as much distance between themselves and the wall as possible. Analogous behaviour has been observed in an earlier study (Törnros, 1998). Even though no comparison to an open motorway was made, it was shown that drivers held their distance to the tunnel walls, both when the closest wall was on the left or on the right side.

5.2 Secondary task performance

Secondary task performance is discussed first, as it is important to know how drivers treated the arrow task in relation to the primary driving task. This knowledge allows for a more informed interpretation of the remaining results.

The results from the secondary task performance indicate that drivers put approximately equal effort into the secondary task, independent of tunnel design. The secondary task was attended to very frequently; more than 80% of all stimuli were answered, and more than 80% of those were answered correctly. The average reaction time was almost 3 s, which indicates that drivers often had to employ more than one glance in order to determine their answer. The fact that the number of very long single glances, exceeding 2 s, was higher when the drivers were distracted by the arrow task than for normal driving indicates that the task engaged the drivers, and that they were willing to neglect driving substantially even though in a tunnel, and while in interaction with other road users.

It has to be kept in mind that participants in a research study are often very eager to please the experimenter and to perform well. Several participants had indicated before entering the simulator that they would never use their mobile phone or enter an address in the navigation system in a tunnel situation like the ones experienced, but during the experiment they still answered more than 80% of the arrow tasks. It is not clear whether this number allows any quantitative conclusions about the possible percentage with which drivers can execute secondary tasks in tunnels, but it indicates that the tunnel design and illumination levels are not expected to influence the frequency of secondary task activity vehemently.

The fact that neither the tunnel design nor the lighting levels influenced the results in the secondary task can be interpreted such that drivers did not allow extra resources for the secondary task under less demanding conditions. The drivers may always have operated at their maximum capability, which could have been determined by having them execute the secondary task without concurrent driving task. This had not been done, however, as this was not the main goal of the study. Alternatively, the drivers may have allocated enough resources to the secondary task to perform at a sufficiently good level, while still feeling able to manage the driving. The demand ratings show that drivers felt a higher demand while executing the arrow task, which can be an indication that they temporarily mobilised more efforts, or that they felt that the remaining spare capacity was reduced.

5.3 Driving behaviour

When it comes to driving performance, the factor which had the highest influence by far is the driver's attentional status. Whether the driver was distracted or not influenced the driving performance indicators more than the tunnel lighting or the colour of the walls. Therefore, in the next section the driver's attentional status in itself will be investigated more closely. Here it will be discussed how the driver's state influences parameters related to driving behaviour.

The mean speed decreased both during the event and especially while driving freely when the driver was distracted by the arrow task. In the latter case the speed was reduced by more than 4 km/h, which can either be a sign of degraded control or of compensatory behaviour. The standard deviation of speed increased during the distracted periods in comparison to the attentive periods, however. This could be a hint that drivers actually have a harder time controlling their speed. Still, some planned compensatory behaviour could be involved, as drivers might reduce their mean speed on purpose, knowing that their speed will fluctuate more, and hoping that a general speed reduction will avoid serious periods of speeding while distracted. In case that this actually was the plan for at least some drivers, it can be stated that it was crowned with some success. The speeding index, which accumulates the percentage of time spent speeding weighing in how high the overspeed actually was, was lower for distracted than for attentive drivers. However, the percentage of speeding was not influenced, which indicates that during distraction the extreme speed peaks were reduced more than the overall time spent speeding. Generally speeding was not a problem in the tunnels, though, therefore not too much weight should be put on the speed values. See also the method discussion on page 68 for speed keeping in simulators.

Especially with respect to driving in tunnels it is important to be aware of the lateral position of the vehicles. Driving too close to the wall can entail a safety risk, but in tunnels with oncoming traffic driving too close to the middle is not safe, either. The results for lateral control indicate, however, a behaviour that is comparable to what was found for speed. The average lateral placement was not influenced during the event, but the SDLP was increased, just as the standard deviation of speed was increased, indicating a degradation of control. In a situation like the one present in the event it can be discussed whether it is safer to place the vehicle further to the middle or not. A placement further to the left would increase the distance to the tunnel wall, which was quite big to begin with, however, as a road shoulder of 1.5 m breadth was present all the way through the tunnel. There was traffic in the left lane, which in most cases passed the own vehicle before the own vehicle overtook the lead vehicles. A placement further to the right would increase the distance to the other traffic, while still keeping a substantial safety distance to the tunnel walls. On average the participants drove further to the left during the non-event situation than during the event, but this is easily explainable by those participants who had not yet completed their overtaking manoeuvre when measurements in the non-event situation began.

Unfortunately the overtaking event was designed too tight, such that most drivers chose not to overtake before the vehicle approaching from behind had passed. Therefore no systematic analysis of how the factors under investigation influenced tactical driving behaviour could be made. See the methods section on page 68 for a further discussion of such an overtaking event as a method.

5.4 Driver behaviour

Several aspects of eye gaze behaviour were analysed. As mentioned, single glances of more than 2 s are dangerous (Klauer, et al., 2006). Not surprisingly, drivers showed a larger number of such very long glances when distracted by the arrow task than when not distracted. However, not only the distraction task, but also the tunnel walls had some influence on the number of very long glances away from the forward roadway. Generally, the dark tunnel walls produced more very long glances than the light tunnel walls. One possible explanation could be that the drivers used more foveal vision in order to track the road edges, as they were more difficult to see when the walls were dark. It appears unlikely that drivers put more effort into the arrow task in dark tunnels, which might lead to more long single glances. This notion is supported by the fact that they did not perform better on the arrow task when they used more long glances.

The percentage of time spent glancing at other areas than the "field relevant for driving" (FRD) follows a similar pattern. Obviously the percentage of glances outside of the FRD was higher when the drivers were distracted than when they were attentive. However, in the non-event situation the dark walls produced a higher number of glances away from the FRD, just like the number of very long glances increased for the dark walls. A closer analysis of the interaction effect with lighting showed, however, that this result only held up for the darkest illumination condition, in which it was very difficult to see a boundary between the tunnel wall and the road surface. This supports the idea that in very dark conditions drivers use foveal vision in order to locate the border between the road surface and the wall.

The reader is cautioned to consider the discussion of the eye tracker performance before putting too much weight on the results presented here, but systematic effects of eye tracker performance in conjunction with tunnel design appear unlikely, therefore it can be assumed that these results are more than pure coincidence. As mentioned, all performance indicators were computed based on the output generated by the attention monitoring algorithm AttenD. This implies that glance duration is not determined via a fixation-and-saccade algorithm, but via AttenD on the raw data. The logic behind the AttenD algorithm is to interpret the head and eye direction to draw conclusions about the driver's attentional state, and for this certain assumptions about likely eye movement behaviour is made for occasions of lost tracking. Therefore it is possible that glance direction interpretations were made, that were not actually observed.

Other performance indicators were based directly on the output provided by the AttenD algorithm. These were the percentage of time during which the AttenD output equalled zero, that is, the driver was classified as distracted, as well as the percentage of time during which the AttenD output was 1.8 s or higher, that is, the driver was classified as fully attentive. Values in between indicate a driver somewhere in between fully attentive and really distracted. Roughly speaking, drivers were distracted for about 10% of the analysed time, and they were fully attentive for around 70% of the analysed time, which leaves 20% for the middle ground. The duration of the distracted period did not change with the factors under investigation, but the duration of the attentive period did.

Both during the event and in the non-event situation the drivers showed shorter percentages of full attention when executing the arrow task, which hardly is surprising. Drivers who actually do the arrow task have to look away for a substantial amount of time. The difference in the percentage of time with a full AttenD buffer between distracted and attentive driving was smaller during the event than in the non-event situation. In both cases the buffer was at 1.8 or higher for about 60% of the time when the driver was distracted, but drivers were fully attentive for 70% of the time during the event, and 80% of the time during the non-event situation. This indicates that not only the arrow task, but also the traffic complexity draw on the driver's attentional resources, which is not surprising. It is remarkable, however, that the drivers do not seem to sacrifice further resources on the secondary task during the event. It appears like 60% of full attention is some kind of minimum for the drivers, such that they can put more effort into the secondary task during the non-event situation than during the event, where the traffic already provokes a number of off-FRD glances. On the other hand, the drivers neither solved more arrow tasks nor delivered a better hit rate during the non-event situation.

The fact that drivers are less fully attentive but not more distracted during the arrow task indicates that they still keep up some level of control. Buffer values larger than zero and below 1.8 s indicate that some glances away from the FRD were made, but that the glances back to the road in between the off-road glances were long enough to prevent the buffer from reaching zero, which, according to AttenD, indicates that a certain level of attention still is kept up, even though it is somewhat diminished.

Not only the arrow task influenced the percentage of time with full attention. In the non-event situation light walls led to somewhat higher percentages with full attention, which is related to the results discussed above. Therefore, a conclusion is that light walls help the drivers keep their gaze in the field relevant for driving, and they reduce the number of very long glances away from the FRD.

Altogether, the results indicate that drivers become less attentive when they are distracted by a secondary task, which is an expected consequence. It also seems like it is more difficult for the drivers to keep up their attention when the tunnel walls are dark, and there is an indication that very dark illumination can aggravate this. The discussion above shows that diminished attention also leads to less controlled driver behaviour. Light tunnel walls can compensate for these losses to some extent, but it is very important to consider that the driver state had the biggest influence on the performance indicators evaluated here. It is of major importance to keep driver state in mind when planning new tunnels and remodelling old ones, in order to assure that drivers will be as attentive as possible in a potentially boring and uniform environment.

5.5 Demand ratings

An important result with respect to the demand ratings is that the results from the laboratory and from the simulator were very equal both in magnitude and in distribution. There was a trend for slightly higher ratings in the simulator, which could either be an effect of being immersed in the situation and having to drive oneself, or of having access to a rear view mirror, and therefore being able to see the vehicle approaching from behind. No mirror inset or similar was available for the films shown in the laboratory, which is of disadvantage, as the complexity of a scene can be influenced by what is going on behind the vehicle in question.

Still, the mean ratings in the simulator and in the laboratory are very similar and only differ by an offset of approximately 0.4 rating points. The trends for lighting and tunnel design could be found in both test environments.

The traffic scenarios were basically equal in all tunnel situations, the only difference lay in the tunnel design and the illumination level. It appears that those two factors only had a slight impact on the ratings, as compared to changes in the traffic situation or, as seen in the demand ratings from the simulator, in driver state. It is promising that such slight differences in situation demand could be found in a similar fashion both in the simulator and in the laboratory. This is a tentative indication demand ratings probably can be made in the laboratory instead of having to use a simulator, but further comparisons with a wider range of traffic scenarios should be made. Further method-related issues will be discussed in the methods section on page 68.

Schweitzer and Green (2007) indicate that the ratings did not vary much between participants, which would allow for relatively small sample sizes. The results from the present study do not quite support these findings, as ranges for most films were about seven rating points. There was an important difference in the experimental setup between the two studies, however. Schweitzer and Green showed three films at a time, already pre-sorted according to demand as assessed by the experimenters. This method is likely to limit the distribution of answers, as the pre-sorting already gives a hint about “expected” demand values. In the current study one film at a time was shown, which makes the possible rating spectrum much wider. The participants practiced on only three films, which might have been too little. Especially during the simulator drive later it appeared that some participants had misunderstood the instructions, or their goal was to impress the experimenters, as they rated practically all scenarios with “0” or “1”. For future trials using the same method it is suggested to verbalise the decision process during the practice trials, and possibly have the experimenter make an example, reflecting about traffic density, the weather, the road type, the current manoeuvre and other aspects, which could be relevant for the demand assessment.

In the instructions for the simulator drive the participants were told to assess the traffic situation. It was not stated explicitly that they should not consider the secondary task in their ratings, but they were not either encouraged to do so. The results indicate, however, that the participants weighed in their secondary task engagement and therefore apparently rated the situation as a whole, and not only the traffic relevant features. The largest effect was found for event versus non-event, indicating that experienced demand increases vehemently when an interaction with other road users is required. The interaction in question also involved active decision making on the part of the driver, having to decide whether or not to overtake before the vehicle approaching in the fast lane. Whatever the decision turned out to be, an action was required from the driver; either a lane change or braking due to the lead vehicles’ relatively low speed.

Dark tunnel walls received slightly higher demand ratings than light tunnel walls, following the pattern that light tunnel walls had a positive impact on safety related performance indicators. It is encouraging that the objectively measured indicators find support in the subjective ratings from the drivers, as this implies a high acceptance when it comes to implementation.

5.6 Questionnaire

On the whole, the questionnaire supports the results found in the behavioural data and in the demand ratings. Bright walls and higher illumination was preferred, with a preference to the bright walls over additional illumination, as long as the illumination does not fall below a minimum level.

Most participants noticed which factors had been varied during the simulator study, and which had not. In addition, some participants had identified other factors which they thought had been varied, like for example the tunnel length, the height of the roof, or the brightness of the road surface. Unfortunately it is not possible to follow up which of the tunnels appeared to be longer or as having a brighter road surface, etc. This information could otherwise help when designing new tunnels, to make them appear as short, spacious and bright as possible.

Some participants had, according to their answers in the questionnaires, not noticed that the tunnels had varied in brightness, and that they had light respectively dark walls. The differences between the tunnels were quite considerable, which makes it hard to explain these answers. Possibly the participants were so focused on the driving, the arrow task or arriving on time that they paid little attention to the actual tunnel design.

The rankings for safety and comfort produced exactly the same order for the six tunnels used in the simulator. This indicates that feeling safe is very much related to feeling comfortable, at least when it comes to tunnel driving. The participants showed a better agreement when ranking the tunnels based on pictures shown to them than when giving demand ratings while driving. When comparing the actual ranks obtained by the different tunnels, it turns out that the picture-based ranking and the demand ranks from the simulator correspond to each other better than the picture ranks and the ranks from the demand ratings in the lab. As mentioned before, however, it needs to be kept in mind that the demand ratings were very similar to each other on average.

When talking about tunnels in general, the overall impression is that the participants agree that everything that makes a tunnel simpler also makes a tunnel safer. Bright walls, bright illumination, wide shoulders, no oncoming traffic and no entry or exit ramps are seen as safety enhancing. Most participants also consider activation in the form of colours or art as detrimental to safety. At the first glance, these answers appear reasonable, easier should usually be safer.

The question was put as multiple choice question, without giving the participants a chance to motivate their answers. Even though the question was phrased for long tunnels, it is possible that the participants considered each topic on its own and for example compared a tunnel segment without exit ramp to a tunnel segment with an exit ramp. Most participants were not very frequent tunnel users, therefore the topics of boredom and fatigue might not have played a major role when answering the questions. This assumption goes hand in hand with the answers given to the question, in which the participants compared open motorway driving to tunnel driving. For the most part the participants assumed it would be about the same as on an open motorway, or slightly more boring or fatiguing in a tunnel. It is unclear, however, whether the participants considered one single trip, possibly the first, through such a long tunnel, or whether they assumed driving there on a regular basis.

When driving in a long tunnel on a daily basis, it is very likely that boredom and fatigue play a larger role, which could have yielded different answers on the questionnaire. People are easily bored, and being in an understimulating environment for a longer period of time inevitably leads to the search for activating stimuli or entertainment. Taken to the extreme, complete sensory deprivation can lead to hallucinations already after 15 minutes (Mason & Brady, 2009). Tunnels that are completely stripped of variation and change can therefore lead to the drivers' looking for stimulation inside the car instead of outside. Eyes off road increase the potential for conflicts, however (Klauer, et al., 2006), therefore measures to keep the drivers' eyes and attention on the road could possibly be safety enhancing, even though this might appear counterintuitive at first glance.

5.7 Method

The evaluation was done with the help of driving behaviour assessed in a simulator study. The simulator used is very high-end and consists of a motion cueing system, which conveys a rather realistic feeling of movement to the driver. A predecessor of the simulator was validated for speed and lateral position (Alm, 1995; Harms, 1994), with the result that the absolute speeds measured in the simulator usually are somewhat higher than in real driving, but that the relative changes correspond to what is observed in reality. The same is true for lateral position, also here the relative changes correspond to what is found on real roads.

5.7.1 Illumination

In the present study the subject matter of interest was how different levels of illumination affect driver behaviour. The maximum illumination intensity that can be reached by the projectors is approximately equal to the ambient light levels at dusk and dawn. This limits the absolute intensity range, such that the drivers' eyes do not need to adapt very much between simulated bright and dark conditions. In real tunnels the ambient light emitted by the lamps can be measured directly, but this is not possible in a simulator, where the lamps are not real, but projected on a screen. Therefore, in the simulator the luminance reflected from the projection screen was measured. The maximum luminance that can be obtained in the simulator is pure white, when the projectors work at full capacity. Both darker colours and dimming the projectors leads to a diminished luminance.

For those tunnels, in which the luminance of the road surface was measured while actually driving through them, luminance values of 3 to 10 cd/m^2 were obtained. The former value stems from the Muskötunnel, connecting an island to the mainland, which is experienced as a very dark tunnel. The latter values stem from inner-city tunnels, which have a rather bright illumination.

When photographs taken of these tunnels were projected on the simulator screen and the luminance of the road surface was measured, the range between those values was greatly diminished. The road surface of the Muskötunnel reached 1.25–2.11 cd/m^2, while the tunnel with the brightest road surface, the Törnskogstunnel, reached 3.33–4.43 cd/m^2. Still, the pictures actually look like they are very different in brightness.

For the simulated tunnels the luminance ranged from 2.52 cd/m^2 in the brightest tunnel on the bright sections to 0.94 cd/m^2 in the darkest tunnel on the dark section. This is a bit less both in absolute values and in range as compared to the projected images. As the eye adapts to the given conditions, it is difficult to say how much brighter a scene appears to be psychologically, from what was actually measured. There is an enormous range of illumination conditions, from bright sunlight to comparatively dark artificial illumination, in which human can see properly, because the eye adapts and controls the amount of light reaching the retina. First when certain threshold values are reached, vision becomes impeded. Full photopic vision, that is, colours are clearly perceived, occurs at luminance values above 2–3 cd/m^2. Scotopic vision, where colour perception especially in the red range is impossible, and mainly different levels of brightness in the blue-green range are perceived, occurs at luminance values below 0.001 cd/m^2. Mesopic vision, which is a combination of photopic and scotopic vision, occurs at luminance values of approximately 0.001 to 3 cd/m^2. Here, colour perception is degraded (Blake & Sekuler, 2006).

The luminance values measured in the real tunnels lay all at or above the border for mesopic vision, while the projected and simulated tunnels were in the high end of the mesopic range. In the simulation the tunnel walls were grey, and the surrounding vehicles were of grey colour to avoid any confusion that might be caused by contrasting information in colour perception.

This discussion shows that there are a number of uncertainties coupled to how the simulated brightness of the tunnels actually was experienced, and how that would translate to perception and behaviour in reality. It is hoped and assumed that the relative differences in luminance in the different conditions are big enough to let the participants experience different levels of brightness, and the diminishing contrast in the conditions with lower light should increase the impression of darkness.

Especially the results from the subjective ratings indicate that the participants were sensitive to the different lighting levels, which lends validity to the obtained results. Still, it would be beneficial for further simulator studies to conduct a validation experiment, in which lighting is controlled strictly both in the simulator and in a real tunnel setting.

5.7.2 Scenario and event

Confronting the participants with exactly the same event throughout the drive is of advantage in terms of control and comparison. In all twelve tunnels the same overtaking event occurred, which means that the participants at first did not know what to expect in terms of traffic, but would get more and more certain about what was coming up the further they drove. Here the order of the tunnels was varied to make sure that the increasing familiarity with the simulator and with the event should not have a systematic influence on the results. An alternative or additional approach could have been to introduce the event already during the training, and/or to let the participants know that the same manoeuvre would occur each time they drove through a tunnel. It was assumed that a manoeuvre like the one employed was rather frequent for motorway driving, such that the way the drivers handled the situation while encountering it for the first time in the simulator would not greatly influence their behaviour during the subsequent events.

One reason why the event was included in the study in the first place was the goal to assess how the tactical driver behaviour was influenced by the factors under investigation. Frequently, driving performance is evaluated with indicators showing how well a driver can maintain the speed, headway and lateral position of the vehicle. Apart from this pure vehicle control, it is also of interest, however, how well the driver interacts with other road users, which gives an indication of how good a picture the driver has of the situation at hand. During the event presented in the study at hand the driver was put in a situation where he or she had to decide whether to let a vehicle approaching in the left lane overtake before overtaking a slower lead vehicle, or whether it was safe and effective to change lanes and overtake before the other vehicle had passed. The former manoeuvre disturbs the participant, forcing him or her to slow down and wait, while the latter manoeuvre potentially disturbs the vehicle approaching from behind, as it could be forced to brake, depending on its speed and how much the participant would accelerate during overtaking. Both not overtaking when it would have been possible with wide margins, and overtaking in the last moment, could be seen as suboptimal strategies, which do not maximise profit for all parties involved.

It turned out that in almost all occasions the participants chose to wait and let the vehicle approaching from behind pass first, before they overtook the lead vehicle. Even though the event had been tested beforehand, it was apparently too tight for comfort for most participants. This underlines once more how important it is to run “naïve” pilots and not to rely solely on the developers for scenario assessment. If the event is to be used in future studies it is recommended to extend the distance of the approaching vehicle somewhat, and to test thoroughly with external pilots. Furthermore it might be useful to have a queue of vehicles approaching from behind, which would imply a longer waiting time behind the lead vehicle before the participant would be able to overtake. Obviously, this latter manipulation requires a lot of space to stage the event.

Even though in the present study the event did not yield the expected results, it is considered to have potential when timed properly. The possibility to obtain results that complement control level based performance indicators with indicators on the tactical level is very valuable, as breakdowns or reduced performance on the tactical level might occur before the control level is affected. Therefore it is recommended to put some effort into improving the overtaking event for future simulator studies.

5.7.3 Demand ratings

The method used here to rate the demand of a scenario as experienced by the driver is relatively new and therefore not widely discussed in the literature. Compared to rating scales like the Borg Scale, which originally was developed for physical effort (Borg, 1982), the method proposed by UMTRI (Schweitzer & Green, 2007) appeared promising and worth a try. Especially the presence of fixed anchor values linked to a certain scenario should provide guidance for the participants and normalise their ratings, which should impart some objectivity on the ratings obtained. For the present report only the demand ratings for the tunnels under examination were analysed, but ratings were obtained both for some scenarios that had been tested in the original study by Schweitzer and Green, and in addition, some Swedish motorway scenarios were rated for comparison. A future analysis of those results could shed some light on cross-cultural differences.

Most issues related to the demand rating method are discussed above, under heading 5.5 Demand ratings. Dedicated studies aiming at a systematic validation of the method would be very valuable to assess the potential of the method as a reliable on-line demand rating scale. The assessment should include comparisons between test beds, that is, real traffic versus simulator driving versus ratings based on films viewed in the laboratory, and it should include cross-cultural comparisons. A systematic variation of different aspects of the scenario, for example the number of other road users, possible interactions, the weather, the road type, but also of the driver state, like fatigue, mental load etc. would allow conclusions about which factors affect the ratings in which way, which could extend and complement the work already initiated by Schweitzer and Green (2007).

5.8 Future research

The present study can be seen as a first step in finding out what affects behaviour in a tunnel, which, in turn, affects traffic safety. There is a multitude of factors that may play a role, and different combinations can yield different results. The approach taken here was to vary three factors, two of them situated in the environment, and one situated in the driver. No variation was made in the surrounding traffic, in the road layout, or in the "decoration" of the tunnels.

Generally, when investigating traffic safety and driver comfort in tunnels it has to be kept in mind that the overall effect is often more than a sum of the parts, as there can be interactions and accumulating effects that will not be noted if only a single factor is varied. Also, safety indicators do not necessarily change linearly – the present study indicates, for example, that there seems to be a level for "enough light", and a higher illumination is not followed by a greater benefit. Then other factors come into play.

In the following further measures that have a potential to enhance traffic safety and driver comfort are presented, and it is discussed which kind of effect they may have on drivers and their behaviour. Based on these factors it is suggested to conduct simulator studies that follow up on the one presented here, and in which new factors are varied systematically. Building upon the present results and extending them would be a strong basis for informed decisions on future tunnel design.

It is recommended to take into consideration the driver's ability to handle interactions with other road users when investigating the effect of design or other measures on road safety. A better timing of an overtaking event like the one used in this study, or the development of another appropriate interaction scenario would allow conclusions about the driver's ability to judge and handle the situation.

5.8.1 Attention increasing activation

As the results clearly indicate that driver state plays an important role for the behaviour that can be observed, it appears worthwhile to plunge more deeply into the topic. Especially boredom, fatigue and resulting driver distraction are concerns that should not be taken lightly. With tunnels becoming longer and more frequent, and humans being curious by nature, it is highly recommended to study how this human feature can best be used when it comes to tunnel safety.

Generally it is safer if the drivers' gaze is directed at targets outside of the vehicle than inside of the vehicle. Therefore measures that help the driver keep his or her attention outside of the vehicle should be a natural way to enhance safety. In stimulus poor environments in which workload are low the eye looks for things that interrupt the monotony, and the driver should have mental capacity to spare. Instead of letting the eye wander inside of the car to find stimulation there, it is suggested to provide stimulation for the driver outside of the car. A suggestion would be to offer stimulation in the form of "meaningless" information, which could be presented on variable message signs (VMS). This information could include the name day of the day, the weather in major cities, or other things that are fun to read, but not necessary to know. Statistics about the current tunnel could also be included, for example the number of vehicles currently travelling through the tunnel, etc. An important difference of this type of information as compared to the architectural measures employed in for example the Lærdalstunnel in Norway is the flexibility. First of all, this type of information can be changed daily, such that daily commuters can expect something new each time they use the tunnel. Second of all, the VMS could be used for crucial information, too, if this should become necessary. How crucial information should be distinguished from meaningless information is a matter of research, but a suggestion would be colour coding.

This type of research is crucial, as its basic idea goes against the spontaneous notion that a simple and frugal environment should always be safer than an environment with distractions and activation, especially if those are not traffic related. The suggested approach would embrace the human nature and use it to its advantage, keeping the drivers' attention directed in front of the car, without a need to admonish and prohibit. Such an approach should be met with more goodwill and cooperation on the drivers' side than regulations that prohibit distracting activities inside of the vehicles, which are likely to be undercut anyway, if they are not enforced strictly.

5.8.2 Visual guidance

Further more traditional measures that should be investigated include LEDs or similar visual guidance along the tunnel walls. They could either be placed in the corner between the road surface and the wall, or a bit higher up, such that the lateral positioning is simplified. With clear visual guidance the driver does no longer need to monitor the road edges actively, because the peripheral vision can take care of that automatically and effortlessly, as is usually the case when driving on open roads. Different alternatives of visual guidance are presented in Figure 19. These examples were seen in new and modern tunnels in northern Italy.

Picture	Description
	One tube for both directions, rural road. Light walls up to a height of approximately 3 m. LEDs or similar close at the edge of the walkway (red on own side, white on other side). Not very strong illumination.
	Motorway tunnel, separate tubes. Light walls up to a height of approximately 3 m. Yellow beacons demarcating the walkway. Stronger illumination.
	One tube for both directions, rural road. Light walls up to a height of approximately 3 m. Beacons demarcating the tunnel walls, not at outer edge of walkway but rather between walkway and tunnel wall (red on own side, white on other side). Not very strong illumination.

Figure 19 Visual guidance as realised in different types of tunnels in northern Italy.

The red and white markings, both with LEDs or beacons, clearly indicate the driving direction and remind the driver that oncoming traffic can occur. In the motorway tunnel the beacons were yellow, which indicates that the traffic is unidirectional in this tube. The beacons are retroreflective and do not need electricity, while the LEDs obviously do need power. The LEDs could be placed very close to the actual edge of the lane, which is of advantage for an immediate understanding of where the vehicle can be placed. The beacons cannot be placed as close to the edge of the lane, as they are taller and might interfere with rear view mirrors.

All tunnels have very light coloured walls up to a height of approximately three metres, which made the whole appearance of the tunnel much brighter, even though this does not come across fully in the photographs. Even though the illumination did not appear that strong in the rural tunnels, the white walls made the tunnel appear bright and friendly. The motorway tunnel had a much brighter illumination, which at nighttime appeared almost too bright, especially upon exiting.

These are all factors that can be considered in further studies. It is of interest how visual guidance influences the driver's eye movements and scanning patterns, but also how it affects the positioning in the lane and the standard deviation of lateral position. In single tube tunnels, however, it should also be investigated whether a visual guidance like the beacons in Figure 19 mask the presence of oncoming traffic.

5.8.3 Architectural measures

As mentioned, in the long tunnels in Norway and China the monotony was disrupted by architectural measures. In the Lærdalstunnel this was done with the help of space and colour – three caves illuminated with blue were built to split the tunnel into four segments of equal length. In the Zhongnanshan tunnel artificial palms, grass and an artificial sky were used. As mentioned, research from Norway (Flø & Jenssen, 2007) showed that how the tunnel was decorated and coloured influenced driver behaviour to some extent, but that it also influenced experienced comfort or anxiety. Therefore it is necessary to establish that new design ideas do not create discomfort with the drivers.

Fixed decorations might become boring to daily commuters after a while, as they know what to expect. With light and projections it would be possible to create changing decorations and effects, which could, for example, reflect the weather outside.

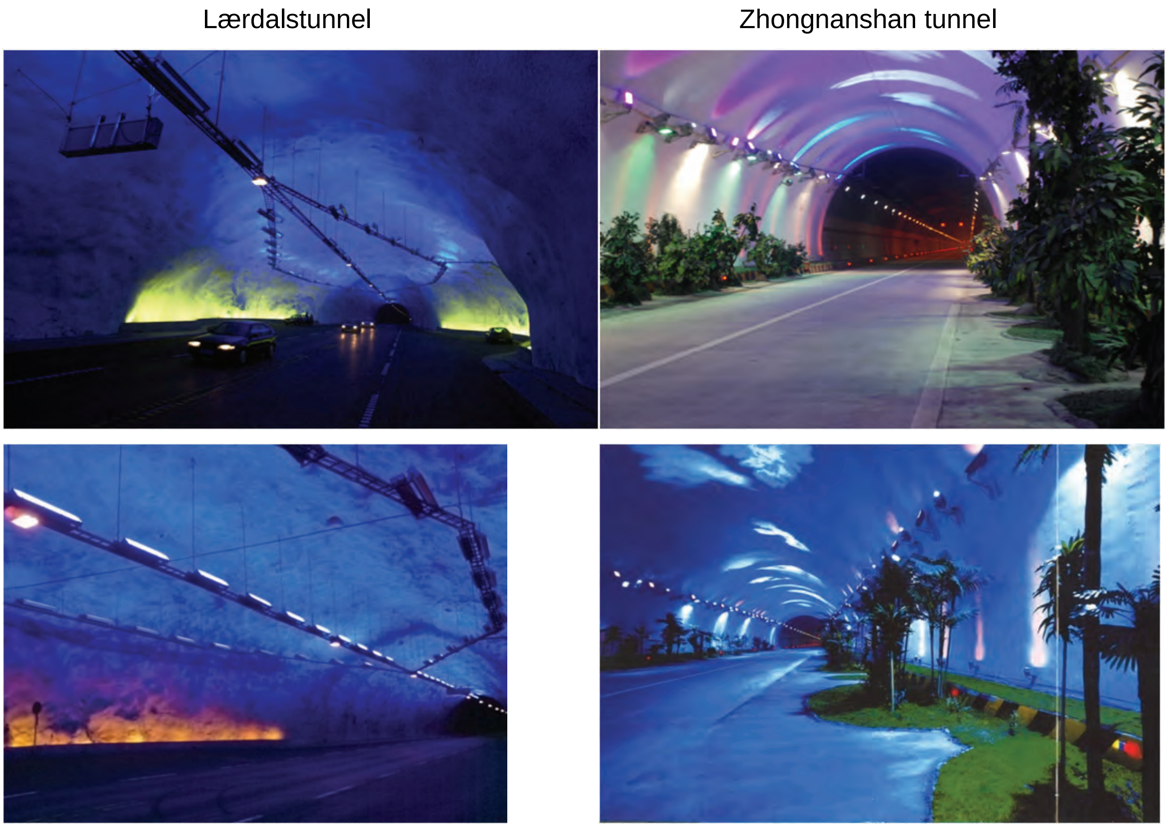


Figure 20 Examples of architectural measures to counteract monotony and fear from the Lærdalstunnel in Norway and the Zhongnanshan tunnel in China (Photo: SINTEF, with kind permission).

Except for decoration and lighting, other architectural means include how the tunnel is built. This ranges from whether to use a single or a double tube over the tunnel profile and general spaciousness to the curvature, gradient, and the presence of exits, entries, junctions or roundabouts. These features are a bigger challenge for the driver in tunnels than on open roads, as the ability to judge speed is reduced in tunnels (Flø & Jenssen, 2007). Generally, more variety will reduce monotony, but will increase the workload. The traffic volume is another factor which influences workload, and which dictates some of the architectural features to some extent.

Future studies could therefore include systematic variations of traffic volume in combination with architectural features of different sorts.

6 Conclusions

Safety and comfort as measured via behavioural performance indicators, as well as experienced safety and comfort rely on a combination of factors. As long as the illumination is sufficient, it is more important with bright walls to enhance traffic safety and driver comfort in tunnels. Absolute values for what "sufficient" is cannot be given based on the data from this simulator study, as the absolute illumination range in a simulator is smaller than in the real world by several orders of magnitude.

The factor that had the biggest influence on behaviour and experienced demand was the secondary task, which induced visual distraction from the forward roadway. Due to the design chosen for the present study it is not possible to draw conclusions about which tunnel design has the greatest potential to induce driver distraction. What can be said, however, is that given an existing external visual distraction the consequences especially related to glance behaviour are worse for tunnels with dark walls than for tunnels with bright walls.

Further studies which focus on different factors are needed. Visual guidance in the form of LEDs or other measures might help keeping the drivers' eyes on the road and simplify the lane keeping task. Special attention should be directed at the issue of monotony in longer tunnels, which become more and more widespread. Here ITS should be considered as a candidate with great potential to enhance traffic safety, and it is encouraged to investigate usages that might appear counterintuitive at first.

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