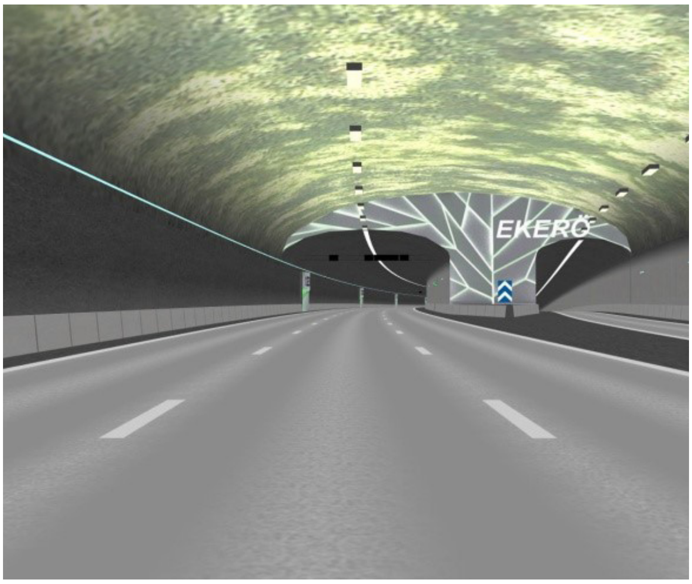
ViP publication 2014-3

# Stockholm Bypass Tunnel Merging Traffic Study

## Technical Report




Authors

Christopher Patten, VTI

Selina Mårdh, VTI

Ruggero Ceci, STA



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Virtual Prototyping and Assessment by Simulation

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# Preface

The reported study has been done in collaboration between the Swedish Transport Administration (STA) and the Swedish National Road and Transport Research Institute (VTI) in the project *Development of the Stockholm bypass Tunnel Model – Extension of surface road network and tunnel ramps for tests of safety features and future traffic scenarios* within the competence centre *Virtual Prototyping and Assessment by Simulation* (ViP; www.vipsimulation.se).

The project was financed by ViP, i.e. by Vinnova (the Swedish Governmental Agency for Innovation Systems) and the ViP partners.

The main focus of the study was to investigate the pattern of merging of traffic onto the main Stockholm bypass (Förbifart Stockholm, or FS) tunnel when the gap sizes between vehicles in the main tunnel were relatively small. It is important that the reader is aware that these small gap sizes are not intended to represent mean values that allude to total traffic intensity. Moreover, our ambition has been to create a virtual tunnel as accurately as possible. The tunnel has, however, not yet been built and some details are subject to changes, e.g. lighting details and the materials on the side walls.

The authors would like to thank the Swedish Transport Administration (STA; Trafikverket in Swedish) who have among other things supplied the tunnel blueprints that were necessary to create a virtual FS tunnel and the STA specialists Mr Henric Modig and Mr Hans Ek who participated in the planning of this study. The authors would also like to thank the Research Engineers Mats Lidström and Jonas Andersson Hultgren at the Swedish National Road and Transport Research Institute (VTI) for their simulator expertise and the Administrator Kristina Kindgren and the Research Assistant Gunilla Sörensen at VTI for their assistance. We would also like to thank the test participants for their participation.

The authors of this study were Dr Christopher Patten who specialises in engineering psychology, human machine interface (HMI) and human factors; Dr Selina Mårdh who specialises in HMI, driver behaviour and effects of surrounding landscape on behaviour; and Dr Ruggero Ceci (project manager) who specialises in HMI, psychometric scales and driver behaviour.

Borlänge, March 2014

*Christopher Patten*

## Quality review

A review seminar was carried out on 18th of December 2013 where Professor Claes Tingvall, Swedish Transport Administration and Professor Emeritus Ola Svenson, University of Stockholm reviewed and commented on the report. Dr Christopher Patten has made alterations to the final manuscript of the report. The ViP Director Dr Lena Nilsson examined and approved the report for publication on 25 June 2014.

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## Abbreviations

| | |
|---|---|
| AADT | Annual Average Daily Traffic (ÅDT in Swedish) |
| ANOVA | Analysis of Variance |
| CR10 | Category Ratio 10 scale (used for subjective ratings) |
| FS | Förbifart Stockholm (Stockholm bypass) |
| ITS | Intelligent Transportation System |
| LCD | Liquid Crystal Display |
| MCS | Motorway Control Systems |
| SD | Standard Deviation (of mean) |
| SEK | Swedish Kronor |
| SPSS | Statistical Package for the Social Sciences |
| STA | Swedish Transport Administration |
| THW | Time Headway |
| T-LOC | Traffic Locus of Control |
| VGU | Swedish design guide for road infrastructure (Vägar och Gators Utformning). |
| VINNOVA | the Swedish Governmental Agency for Innovation Systems |
| ViP | Virtual Prototyping and Assessment by Simulation |

## Definitions and concepts

| | |
|---|---|
| Entry-ramp | An entry-ramp is the ramp plus the merging zone. |
| Entry-ramp tunnel | The entry-ramp tunnel is the section of the entry-ramp that is in a tunnel. |
| Exit-ramp | The exit-ramp is the merging zone plus the ramp leaving the motorway. |
| Exit-ramp tunnel | The exit-ramp tunnel is the section of the exit-ramp that is in a tunnel. |
| Merge-completion | Merge-completion is when the merging manoeuvre has been completed. Merging is completed when the outer edge of the vehicle's front, right-hand tyre passes the lane marking between the entry-ramp and the motorway. |
| Merging zone | The merging zone comprises the observation, the adjustment and the completion section of the entry-ramp just before it joins the motorway. |
| Point of merge-completion | The point of merge-completion is the position of the vehicle in the merging zone/motorway when merging has been completed. |
| Ramp | The ramp is a section of road that starts from an auxiliary road and leads on to the motorway. In this study the ramp is also partially in an auxiliary tunnel. |

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# Stockholm Bypass Tunnel – Merging Traffic Study
# Technical Report

by Christopher Patten[1], Selina Mårdh[1] and Ruggero Ceci[2]

[1] the Swedish National Road and Transport Research Institute (VTI)
[2] the Swedish Transport Administration (STA)

## Executive summary

The Stockholm bypass (Förbifart Stockholm, or FS, in Swedish) project is a new road project that will create a bypass of central Stockholm. The entire project includes motorways, bridges and two tunnels; one of which will be 16.5 km. The Stockholm bypass is the largest infrastructure project in Sweden to date. A high level of road traffic safety is always important and when the road is in a tunnel, and especially in a long tunnel, maintaining the highest possible level of safety is paramount. The present report describes a simulator study on the merging of traffic from entry-ramps into the main tunnel. The entry-ramps in the Stockholm bypass tunnel are planned to let traffic merge into the main tunnel from five specified locations (excluding the main southbound and northbound entrances).

The present study focused upon the specific situation of driving down the entry-ramps and entering (merging) into the main tunnel with a special emphasis on measures of safety and driver performance. A group of 21 test drivers, 11 males and 10 females, participated in the study. They were instructed to drive a series of test scenarios in a 3D-model of the Stockholm bypass tunnel in the VTI driving simulator III. There was simulated traffic in the main tunnel to improve the realism for the drivers merging from the entry-ramp tunnel into the main tunnel. The gap sizes between vehicles in the main tunnel were relatively small, two gap sizes were used (1.5 s and 2.5 s). The gap sizes are not intended to represent mean values that allude to total traffic intensity. They are, however, gap sizes that road users will observe on a daily basis when using the E4 motorway through Stockholm. This fact is the rationale for using relatively small gap sizes because they reflect real-life traffic situations. The study design was a within-subject design where all test drivers drove all the four included tunnel conditions. Driving performance (speed, time headway, vehicle position, and distance to tunnel wall) and the test drivers' experiences of the driving task (CR10 ratings of four dimensions) were measured.

The main results of the study suggest that the merging zones were too short for some of the drivers to merge comfortably and safely. The merging zones are found at the point where the entry-ramp tunnels merge with the main motorway tunnel and comprise an observation section, an adjustment section and a completion (/taper) section. The distance-to-wall measure (a measure that gauges how much of the entry-ramp remains at the time of merge-completion) for the Vinsta ramp (0.5 km) with heavy traffic is particularly concerning from a road traffic safety perspective because more than 25 % of the drivers completed the merging manoeuvre with less than two seconds of time headway remaining before the end of the completion section.

In order to establish the causes and to seek and verify possible solutions to the safety concerns arising from this study, a number of areas need to be explored. Would for

instance, lengthening the merging zone at Vinsta improve the safety of that entry-ramp? What are the characteristics of an entry-ramp into a motorway tunnel that gives provision for safe and well-working merging? On the other hand, what causes unsafe merging performance? Could it be other aspects apart from the actual length of the merging zones? Moreover, only two of the five entry-ramps have been assessed in this study. What is the status of the remaining entry-ramps from a safety perspective? It is also important to investigate the effects of heavy traffic (buses and trucks) on interaction with other road users and merging.

# 1 Introduction

The Stockholm bypass (Förbifart Stockholm, or FS, in Swedish) is a road project that will create a new bypass of central Stockholm, Sweden. The entire bypass project includes motorways, bridges and two tunnels; one of which will be 16.5 km. The FS is the largest road infrastructure project in Sweden to date. The planning of the project includes the choice of the exact route, the road geometry and also the interior design of the 16.5 km tunnel, including the aesthetics of all aspects of the tunnel. The FS project is expected to replace the Essingeleden section of the E4 motorway through Stockholm. Essingeleden has an annual average daily traffic (AADT) of approximately 160 000 vehicles (in 4 lanes) which is also the expected traffic volume for the Stockholm bypass tunnel. Maintaining high levels of road traffic safety is always important and when the road is in a tunnel, and especially in a long tunnel, maintaining the highest possible level of safety is paramount (Patten & Mårdh, 2012).

Some of the research questions related to other studies planned in the FS project have addressed the interaction between vehicle and infrastructure technology (e.g. ITS systems) and human behaviour from a human machine interaction (HMI) perspective as well as safety critical aspects of road and tunnel traffic situations. Some typical issues that need attention are the signal and sign systems of the new infrastructure systems that should be designed for optimal use. Traffic messages and road signs for orientation and way-finding purposes should be tested and evaluated for best HMI practice on roads and in in-vehicle systems. Speed adaptation and regulations in tunnel and surface traffic, merging zones in tunnel entry-ramps as well as merging behaviour in general in different parts of the infrastructure system (both in tunnel and in freeway intersections) should also be considered.

The present report describes a simulator study on the merging of traffic from entry-ramps into the main tunnel. The entry-ramps in the Stockholm bypass tunnel are planned to let traffic in to the tunnel from five specified locations. The present study focuses on two of the locations with connections at Lovö and Vinsta. These two entry-ramp tunnels are fairly long (0.5 and 1.5 km), curvy and with a relatively steep descent (max 5 %). It can be argued that this may lead to difficulties in judging and maintain speed and distances between vehicles. In order to merge safely, drivers entering the motorway in the main tunnel are required to judge speed and gap size between vehicles and with timing place their vehicle in a gap without undue hindrance to other road users. This may be especially problematic for larger trucks with heavy load and for those drivers wishing to eco-drive (e.g. in-gear coasting for better fuel-economy). Also, the specific situations arising when vehicles attempt to enter the main tunnel are considered to induce a risk for incidents and collisions in the tunnel. Earlier studies have suggested that drivers' ability to gauge speed can be affected by visual design concepts (Manser & Hancock, 2007). Other forms of driver behaviour, such as eye-glance behaviour, and mental workload, have also been suggested as being affected by the lighting colours and patterns of the tunnel walls as well as the strength of the lighting (Kircher & Ahlström, 2012; Kircher & Lundkvist, 2011; Patten, Ceci, Engström, & Anund, in press). Driving experience has been suggested as having an effect on driving performance where e.g. the workload from driving per se is more demanding or greater for a less experienced driver than for an experienced driver (cf. Patten, Kircher, Östlund, Nilsson, & Svenson, 2006). Driving in tunnels is unlikely to improve performance and may even exacerbate the mentioned effects when the driving task becomes more demanding (Rudin-Brown, Young, Patten, Lenné, & Ceci, 2013).

A recent simulator study with a dissimilar design investigated traffic scenarios in a model of the Stockholm bypass tunnel (Young, Ceci, Patten, & Lenné, submitted). The test drivers in this study did not merge themselves but drove on the motorway in the main tunnel. The drivers did experience other traffic entering the motorway from the entry-ramps and compared tunnel and motorway driving. The results suggested that when sight lines were not restricted on the motorway, drivers reduced speed during a first merge event only. For the tunnel and motorway conditions, with restricted sight lines, there were no significant differences in mean speed across merge segments (Young et al., submitted) suggesting that unrestricted sight lines facilitated a reduction in mean speeds on the main route when encountering merging traffic from entry-ramps.

Locus of control refers to the extent to which individuals believe that they can control events that affect them such as in the case of driving and the resultant driver behaviour and accidents. Locus of control often divide humans into two main groups, *internals* and *externals*. Internals tend to believe that events in their life/driving stem primarily from their own actions whereas externals are more likely to rely on the actions of other people/drivers (Özkan & Lajunen, 2005). Speed and speeding behaviour can be used to study the effects of a traffic locus of control (T-LOC) (Wallén Warner, Özkan, & Lajunen, 2010). T-LOC would usually require large data sets as used by Wallén Warner et al. (2010), but the study reported here has a limited sample size (21 test drivers) and is not conducive for correct T-LOC analysis. In our study driver experience will be tested as an alternative means of deriving different driving styles or strategies when merging, but not as an alternative to T-LOC. Driver experience has been shown to have an effect on cognitive workload where inexperienced drivers carry a heavier cognitive workload for primary tasks (driving) than experienced drivers (Patten et al., 2006).

The present study focused upon the specific situation of driving down the entry-ramps and entering (merging) into the main tunnel. Three research questions were formulated and are listed in the following:

**Research question 1:** Is there a difference in the subjective and/or objective measures between the two different entry-ramp tunnels (Lovö, 1.5 km and Vinsta, 0.5 km)?

**Research question 2:** Is driver performance when merging affected by the drivers' experience when entering the main tunnel from the entry-ramp?

**Research question 3:** Does traffic intensity and its subsequent effect on the gap size between vehicles influence the frequency and character of hazardous situations such as late merging?

# 2 Method

## 2.1 Participants

Twenty-two participants were recruited from the VTI participant database. They were required to have had previous experience of simulator driving, an annual mileage of ≥ 5 000 km and having held a car driving licence for ≥ 5 years. Twenty-one participants, 11 males and 10 females, completed the study. Their mean age was 39 years (SD 4.01) with a range between 32 and 46 years. One female participant missed the scheduled appointment at the simulator due to illness. The participants received 300 SEK in compensation.

Table 1 shows a breakdown of the participants by experience (expressed in annual mileage) and gender to illustrate the relatively even dispersion of annual mileage between men and women.

*Table 1: Distribution of the 21 participants by gender and annual mileage.*

| | | **Gender** | | |
|---|---|---|---|---|
| | | Male | Female | Total |
| **Annual mileage** | < 15 000 km | 4 | 4 | 8 |
| | > 15 000 km | 7 | 6 | 13 |
| Total | | 11 | 10 | 21 |

## 2.2 Apparatus

The study was performed in VTI's driving simulator III in Linköping using the car set-up pictured in Figure 1. The simulator comprises a real car cabin including all of the controls of a real car. An automatic transmission configuration was used in this study. The car is mounted on a full motion-based platform. The visual experience is created using six projectors with a forward field of view of 120 degrees. There are also three rearward facing LCD screens to simulate rear-view mirrors. The simulator was programmed to have a modest acceleration; 0-100 km/h in 13 s. (VTI, 2014 www.vti.se).

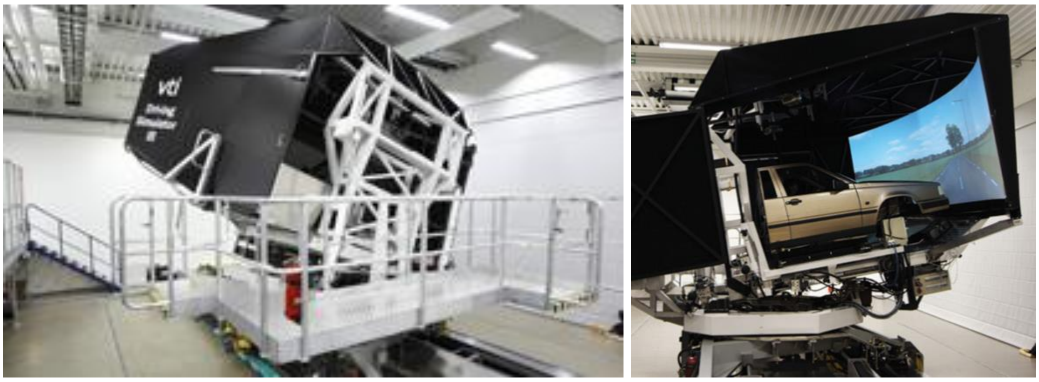

*Figure 1: Simulator III at VTI in Linköping, Sweden.*

## 2.3 Test scenario

A motorway tunnel replicated based on the blueprints of the Stockholm bypass tunnel was created in the advanced driving simulator III at VTI. The blueprints were provided by the Swedish Transport Administration (Trafikverket, 2011) and were, at the time, the most current blueprints available. The simulated tunnel included all of the original road topography, including curvature, gradient, length and breadth. It also included the planned surface texture of the walls, road signage, emergency exits and other road furniture such as extraction fans and standard lighting fixtures. The simulated main tunnel comprised a three-lane motorway. The exact details of the tunnel may change during the lifetime of the scheduled tunnel construction over the next ten or so years' time.

There were two entry-ramp tunnels, the 'long' tunnel ramp (Lovö) was 1.5 km and the 'short' tunnel ramp (Vinsta) was 0.5 km. At the end of the entry-ramp tunnels there were merging zones according to the illustration in Figure 2. The merging zones start with an observation section, then an adjustment section and finish with a completion section where the entry-ramp is joined to the right-hand motorway lane in the main tunnel. The merging zones had different dimensions, the details of which are described below. There was traffic in all three motorway lanes (less in the left-hand lane). The simulated traffic was programmed to brake if necessary to accommodate merging, but only when the own (simulator-) vehicle had completely entered the lane.

The simulation of the Stockholm bypass north bound tunnel included:

- Entry-ramps at Lovö and Vinsta
- Exit-ramps, Vinsta exit-ramp at both Vinsta and Lovö
- Merging zones of an entry-ramp comprising three sections in accordance with the Swedish VGU guidelines (Trafikverket, 2012):
  - Observation section (observationssträcka in Swedish)
  - Adjustment section (anpassningssträcka in Swedish)
  - Completion (taper) section (avslutningssträcka in Swedish)

The entry-ramp at Lovö had a long entry-ramp tunnel (1.5 km) and a merging zone of the following design (Trafikverket, 2011):

- Observation section = 100 m
- Adjustment section = 125 m
- Completion (taper) section = 100 m
- Summa = 325 m

The entry-ramp at Vinsta had a short entry-ramp tunnel (0.5 km) and a merging zone of the following design (Trafikverket, 2011):

- Observation section = 150 m
- Adjustment section = 80 m
- Completion (taper) section = 100 m
- Summa = 330 m

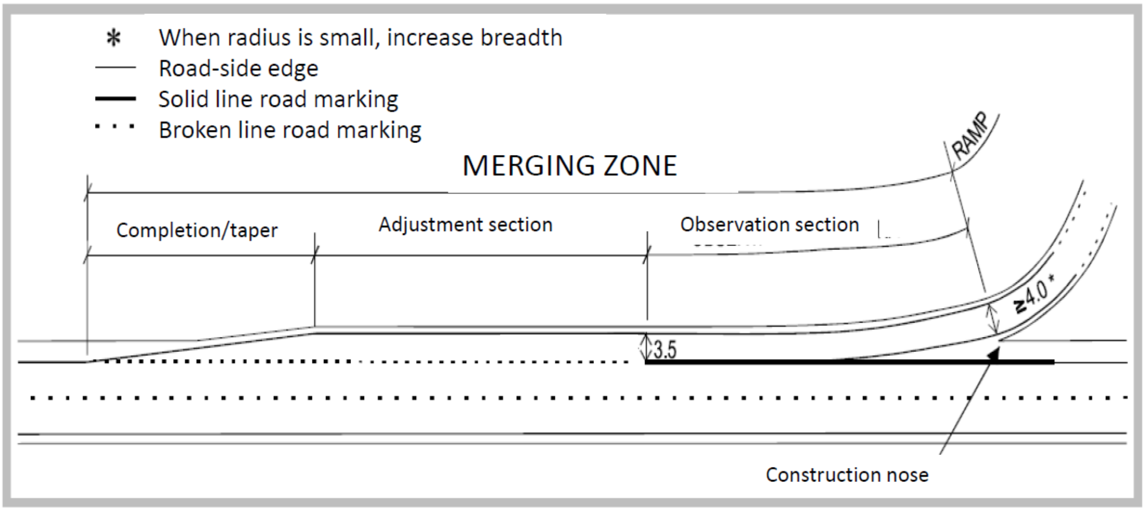


*Figure 2: Standard definition of a Swedish motorway ramp with its 3 merging zone sections, from VGU (Trafikverket, 2012). Note: Traffic is going from right to left.*

Traffic of two different intensities was simulated in the tunnel; medium traffic (2.5 s gap size between vehicles) and dense traffic (1.5 s gap size between vehicles). The simulated traffic in the main tunnel comprised a limited number of vehicles passing the entry-ramp at the time of merging.

The speed limit in the main tunnel was 80 km/h, which was also the speed of the simulated traffic in the main tunnel. In the entry-ramp tunnels the speed limit was 60 km/h.

### 2.3.1 Rationale for the choice of gap size

In this study gap size between vehicles refers to the time headway (THW) or distance in time (seconds) between vehicles. Gap size can also be an indirect indicator of total traffic volume, however, in this study the main interest was on the distances between vehicles and not on mean traffic volume per se.

Essingeleden is currently the most congested section of the E4 motorway running through central Stockholm and it is that stretch the Stockholm bypass project will replace. Essingeleden has a peak hour traffic volume of approximately 1600 to 1800 vehicles per hour in each lane, which corresponds to a mean time gap between vehicles of 2.0 to 2.25 seconds. The annual average daily traffic (AADT) for Essingeleden is approximately 160 000 vehicle (in 4 lanes), which is also the expected traffic volume for the Stockholm bypass tunnel.

The main focus of the gap size choice is not to reflect mean values but rather to focus on the outer ends of the distribution (e.g. the upper or lower quartile). Road users in Stockholm will, on a daily basis, observe these relatively small gap sizes because they reflect real-life traffic situations. This is corroborated by an observational study by Olstam, Carlsson and Yahya (2013) where, in real traffic conditions with free-flowing peak hour traffic, correspondingly small gap sizes (time headways) at ≥ 80 km/h were common and frequently occurring. Therefore, to reflect real traffic situations, gap sizes in this study were set to 1.5 s and 2.5 s between vehicles. A time gap of 1.5 s at a speed of 80 km/h equates to a distance gap of 33.3 m and a 2.5 s time gap at the same speed equates to a distance gap of 55.5 m between vehicles.

## 2.4 Experimental design

The study had a 2 (gap size) x 2 (entry-ramp) x 2 (driver experience) design with gap size and entry-ramp as within-subject variables and with driver experience (annual mileage) as between-group variable (two groups). Thus, all participants drove all four experimental conditions, the four combinations of the two gap sizes and the two entry-ramps. The order was balanced for entry-ramp (ramp length) and gap size. All participants drove the route through the tunnel in the same direction, from south to north.

### 2.4.1 Independent variables

Gap size: two levels, 1.5 s and 2.5 s

Entry-ramp: two levels, long (at Lovö) and short (at Vinsta)

Driver experience: two levels, annual mileage < 15 000 km and > 15 000 km

## 2.5 Dependent variables - measures

### 2.5.1 Driving performance measures

The following dependent variables were used (se Figure 3):

- Distance-to-wall (m).
- Position-between-vehicles at the point of merging (%).
- Time headway (THW)
  - between the simulator vehicle and the forward vehicle (s),THW-forward
  - between the simulator vehicle and the rearward vehicle (s), THW-behind
- Mean speed (m/s)
  - prior to merging (at the construction nose)
  - at the point of merging
  - merge + 25 m

The *distance-to-wall* variable was calculated by measuring the distance from the front of the simulator vehicle to the final point on the entry-ramp (the joining of the right-hand ramp lane marking and the right-hand motorway lane marking), see Figure 3. The measurement was taken at the point of merge-completion, i.e. when the front right outside edge of the simulator vehicle had fully entered the first (right-hand) motorway lane. The distance was measured in metres (m). It should be noted that the last forty metres or so of the entry-ramps are tapered to the extent that there is no longer enough room for a car's breadth.

The *position-between-vehicles* variable at the exact point of merge completion was calculated using the measurement window described in Figure 3. The unit used was a decimal notation. A decimal notation can also be expressed as a percentage to improve comprehension, i.e. 100 % (or 1.00) is a collision with the vehicle in front, 50 % (or 0.50) is exactly in the middle between the vehicles in front of and behind the simulator vehicle and 0 % (or 0.00) is a collision with the vehicle behind. This dependent variable conveys a similar result to the time headway measures described below but in terms of relative position instead of time-distances.

*Time headway* between the participant's (/simulator) vehicle and the vehicle in front (THW-forward) was calculated. THW is a distance measure in time between two vehicles and as the THW expression implies it is usually to the vehicle in front. In this study THW between the simulator vehicle and the rearward vehicle (THW-behind) was also calculated at the same time as the THW-forward, to provide a corresponding time measure to the vehicle behind the simulator vehicle. The time-distance from the simulator vehicle to the vehicle in front (THW-forward) and from the vehicle behind to the simulator vehicle (THW-behind) was calculated in seconds.

*The mean speed* variable was calculated at three different points; 1) prior to merging which was at the construction nose, 2) at the point of merging using the measurement window described in Figure 3 and 3) from the point of merge-completion + 25 m. The mean speed variable was calculated in metres per second (m/s).

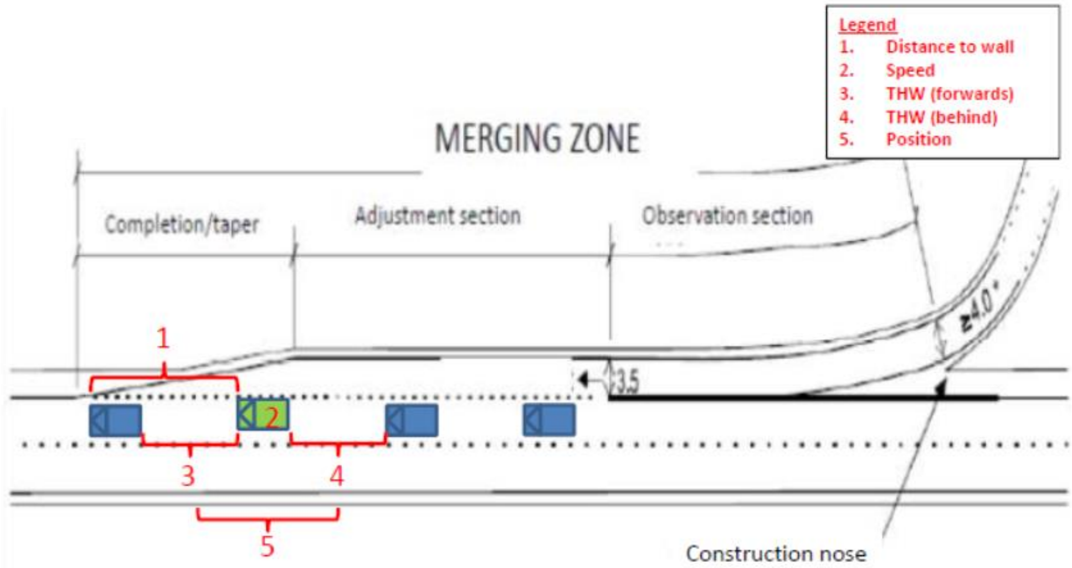


*Figure 3: The measurement window for driving performance dependent variables.*

### 2.5.2 Subjective measures

Three questionnaires were administrated, pre-experimental, peri-experimental and post-experimental.

**Pre-experimental questionnaire**

The pre-experimental questionnaire contained background questions including age, gender, driving experience, simulator experience and motion sickness.

**Peri-experimental questionnaire - CR10 rating scale**

The Category Ratio scale 10 (CR10), developed by Borg (1982) and Borg and Borg (2008), was used for the participants' self-rating of the following CR10 dimensions:

- Mental demand
- Time pressure
- Frustration and
- Perceived level of risk

The scale ranges from 0 to >11 and an important feature of the scale is the verbal anchors associated with each rating. Figure 4 illustrates the relationship between the rating scores and the verbal anchors that provide more depth to the numbers.

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

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

*Figure 4: The CR10 scale (Borg, 1982; Borg & Borg, 2008).*

The CR10 scale was administered directly after each of the four completed experimental conditions. Hence, after merging into the main tunnel from an entry-ramp, the participants were asked to stop the vehicle some distance into the main tunnel and rate the four CR10 dimensions. The participants remained seated in the simulator vehicle while rating and were also provided with the CR10 scale on a sheet of paper resting on the passenger seat. The verbal anchors were provided in Swedish (Swedish participants). The CR10 ratings were measured directly after exiting the different experimental conditions in order to reduce the likelihood of confusion and memory loss regarding the different conditions. The following four questions were read aloud on the loudspeaker from the simulator control room by the test leader, who also recorded the answers, and rated by the participants:

- How *mentally demanding* did you experience the merging manoeuvre in the tunnel?
- How *temporally demanding (time pressure)* did you experience the merging manoeuvre in the tunnel?
- How *frustrating* did you experience the merging manoeuvre in the tunnel?
- How *risky* did you experience the merging manoeuvre in the tunnel?

**Post-experimental questionnaire**

The post-experimental questionnaire comprised fifteen questions about the participants' experiences of driving in the simulated tunnel. The questionnaire was completed in the post-experimental phase, i.e. after the participant had exited the simulator. The questions were answered using a seven-point Likert scale where 1 represented "strongly disagree" and 7 represented "strongly agree". The participants were asked to indicate the number on the seven-point scale that, for each of the questionnaire statements, most accurately reflected their experience.

The questions covered the following aspects of tunnel driving and the driving scenarios:

- The entry-ramp tunnel
- The merging zones
- Merging (per se)
- The signposting (statutory speed sign)

In the questionnaire, screen captures from the simulator were used to remind the participants of the specific location in the tunnel that the different topics were related to.

A traffic locus of control (T-LOC) questionnaire was also administered despite not formally qualifying due to the small sample size (Özkan & Lajunen, 2005).

## 2.6 Procedure

The study procedure started when the participants arrived at VTI in Linköping, whereupon written instructions were given. The participants were informed that their participation was completely voluntary and that they could withdraw at any time. Informed consent forms were signed by each of the participants before commencing with the experiment. The participants completed a background questionnaire and were calibrated on the CR10 rating scale. Before entering the driving simulator they were informed about the driving session with the different experimental (tunnel) conditions.

The participants were informed that the drive would start with a training stretch followed by driving the entry-ramp tunnels into the main tunnel. They were told that after each entry-ramp they would stop in the main tunnel and rate their experiences on the CR10 scale. It was explained to the participants that they after the rating should continue driving, i.e. going further in the main tunnel, exiting at the first exit-ramp and then re-entering through the next entry-ramp. The participants were instructed to drive "as they normally would under similar circumstances in real traffic" and observe traffic rules and regulations. The speed limit was 80 km/h in the main tunnel and 60 km/h in the entry-ramp tunnels. Other instructions given were:

- No overtaking (stay in the right-hand lane when in the main tunnel)
- Use wing mirrors for rearward observations
- No vehicles would enter the blind spot

Once in the simulator the participants familiarised themselves with the basic vehicle controls. The driving started with a familiarisation drive on a surface ("open") road after which the driving scenario continued with a low speed surface road section whereupon the participants entered the first entry-ramp tunnel.

After each of the four tunnel conditions, the participants had to stop in the tunnel to answer/rate the four CR10 questions. After the rating they continued to drive, thus entering a new entry-ramp condition. After the final tunnel condition, the participants got out of the simulator and answered a post-questionnaire and a T-LOC questionnaire.

The whole procedure took approximately 1.5 hours.

## 2.7 Data analyses

The statistical analyses used were ANOVA repeated measures and t-tests (SPSS version 17.0). Effect sizes (Eta squared) were classified according to Cohen (1988).

The point of merge-completion has been defined as the moment in time when the front-right outside wheel edge of the simulator vehicle has exactly passed over the lane marking between the entry-ramp and the lane which the vehicle is merging. The point of merging was used as a freeze-frame moment in time (or window), in which the main measurements were taken; these can be seen in Figure 3. In Figure 3 the participant's (/simulator) vehicle is indicated by the green car's position and five measures are illustrated by numbers, where 1 is the distance-to-wall measure, 2 is the mean speed at the point of merging, 3 is the THW-forward, 4 is the THW-behind and 5 is the position-between-vehicles measure. The distance-to-wall variable is more precisely a measurement of the distance from the right-hand front edge of the simulator vehicle to the end of the taper section of the merging zone when the merging manoeuvre has been completed.

Four participants had rear-ended collisions, one participant in the experimental condition with long entry-ramp and 1.5 s gap size and three participants in the experimental condition with short entry-ramp and 1.5 s gap size. THW-forward, THW-behind and position-between-vehicles data for these four participants were removed because of complications with zero values in the simulator data.

Outliers (i.e. $\geq 3$ z-scores from the mean) were excluded from analyses.

The significance level used in the statistical analyses was $\alpha = .05$ ($p < .05$). Analyses that are not significant are labelled with an "n.s." suffix. Interaction effects were calculated for all analyses but only reported in the Results section when there were significant or near-significant effects.

# 3 Results

## 3.1 Distance-to-wall

The distance-to-wall variable was analysed with a 2 x 2 x 2 repeated measures ANOVA. The within-subject independent variables were entry-ramp tunnel length (1.5 km and 0.5 km) and gap size (1.5 s and 2.5 s) and the between-subject independent variable was annual mileage (two groups; < 15 000 km and > 15 000 km). The analysis showed significant main effects of ramp length ($F(1, 19) = 50.735$, $p < .001$, Eta squared = .73 large effect size) and gap size ($F(1, 19) = 5.376$, $p < .05$, Eta squared = .22 large effect size), but not of annual mileage ($F(1, 19) = 3.435$, $p = .08$ n.s.).

In Figure 5 the distance-to-wall variable at the time of merge-completion is illustrated for the four tunnel conditions in a box plot diagram. The long ramp is at Lovö and the short ramp is at Vinsta. Two reference (broken) lines are included; one at 22.2 m and the other at 44.4 m, representing 1 respective 2 seconds of travel with a velocity of 80 km/h (or 22.2 m/s).

It should be noted that the analysis of variance (ANOVA) analyses the mean values, while the box plots in Figure 5 indicate the median values as well as the quartile distributions for the distance-to-wall variable.

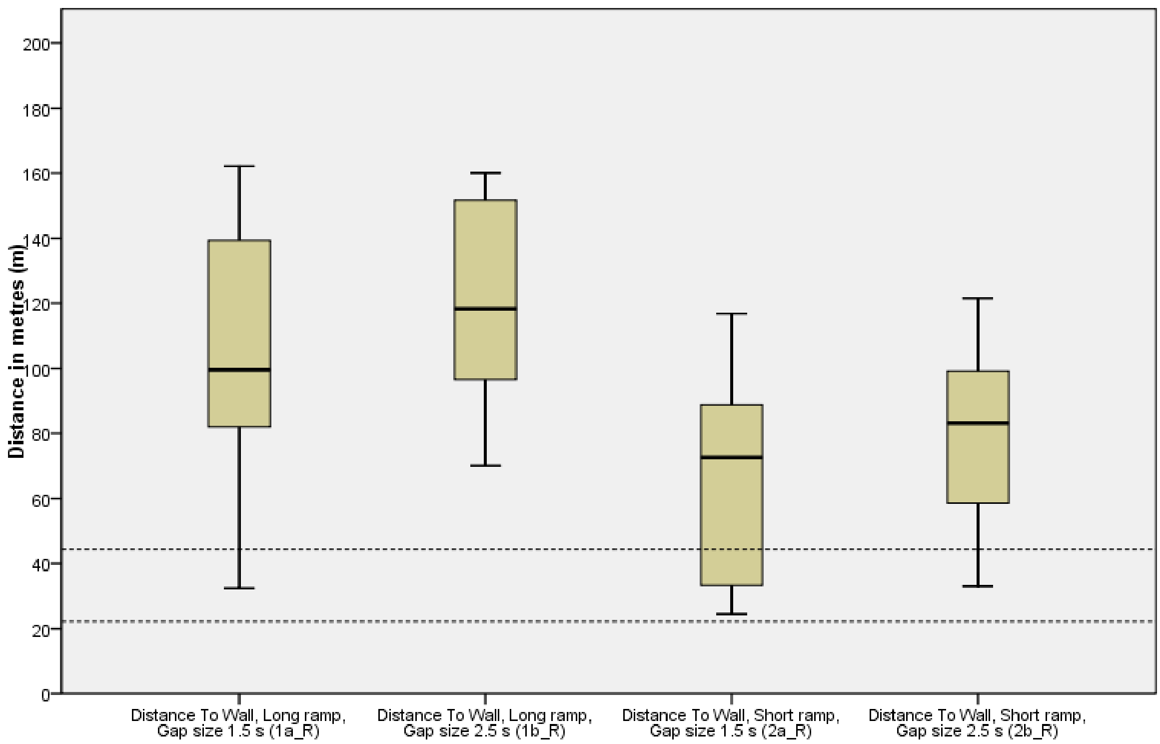


*Figure 5: Distance-to-wall variable (m) at the time of merge-completion, divided by entry-ramp tunnel length and gap size. Boxplot diagram with median values and quartile distributions. Broken lines indicate 22.2 m and 44.4 m, i.e. 1 and 2 seconds of travel with 80 km/h, respectively.*

The mean and standard deviation (SD) values for the distance-to-wall variable are reported below.

The long ramp with the 1.5 s gap size for participants with annual mileage < 15 000 km had a mean distance-to-wall of 91.56 m (SD = 47.37). The long ramp with the 1.5 s gap size for participants with annual mileage > 15 000 km had a mean distance-to-wall of 115.18 m (SD = 31.4). The mean distance-to-wall for the long ramp with the 1.5 s gap size was 106.2 m (SD = 38.93).

The long ramp with the 2.5 s gap size for participants with annual mileage < 15 000 km had a mean distance-to-wall of 101.07 m (SD = 25.8). The long ramp with the 2.5 s gap size for participants with annual mileage > 15 000 km had a mean distance-to-wall of 133.18 m (SD = 24.15). The mean distance-to-wall for the long ramp with the 2.5 s gap size was 120.95 m (SD = 28.95)

The short ramp with the 1.5 s gap size for participants with annual mileage < 15 000 km had a mean distance-to-wall of 60.15 m (SD = 28.66). The short ramp with the 1.5 s gap size for participants with annual mileage > 15 000 km had a mean distance-to-wall of 67.23 m (SD = 29.72). The mean distance-to-wall for the short ramp with the 1.5 s gap size was 64.54 m (SD = 28.81).

The short ramp with the 2.5 s gap size for participants with annual mileage < 15 000 km had a mean distance-to-wall of 75.27 m (SD = 30.64). The short ramp with the 2.5 s gap size for participants with annual mileage > 15 000 km had a mean distance-to-wall of 80.57 m (SD = 29.17). The mean distance-to-wall for the short ramp with the 2.5 s gap size was 78.55 m (SD = 29.09).

## 3.2 Position-between-vehicles at merging

The position-between-vehicles (decimal notation) variable was analysed with a 2 x 2 x 2 repeated measures ANOVA. The within-subject independent variables were entry-ramp tunnel length (1.5 km and 0.5 km) and gap size (1.5 s and 2.5 s) and the between-subject independent variable was annual mileage (two groups; < 15 000 km and > 15 000 km). The analysis showed a significant main effect of gap size (F (1, 18) = 16.01, p < .001, Eta squared = .47 large effect size), but neither of ramp length (F (1, 18) = 1.401, p = .25 n.s.) nor of annual mileage (F (1, 18) = .118, p = .74 n.s.).

In Figure 6 the position-between-vehicles variable at merging is shown as a decimal notation for the four tunnel conditions. The decimal notation can also be expressed as a percentage where; 100 % (or 1.00) means a collision with the vehicle in front; 50 % (or 0.50) means a position exactly in the middle between the vehicles in front and behind; and 0 % (or 0.00) means a collision with the vehicle behind.

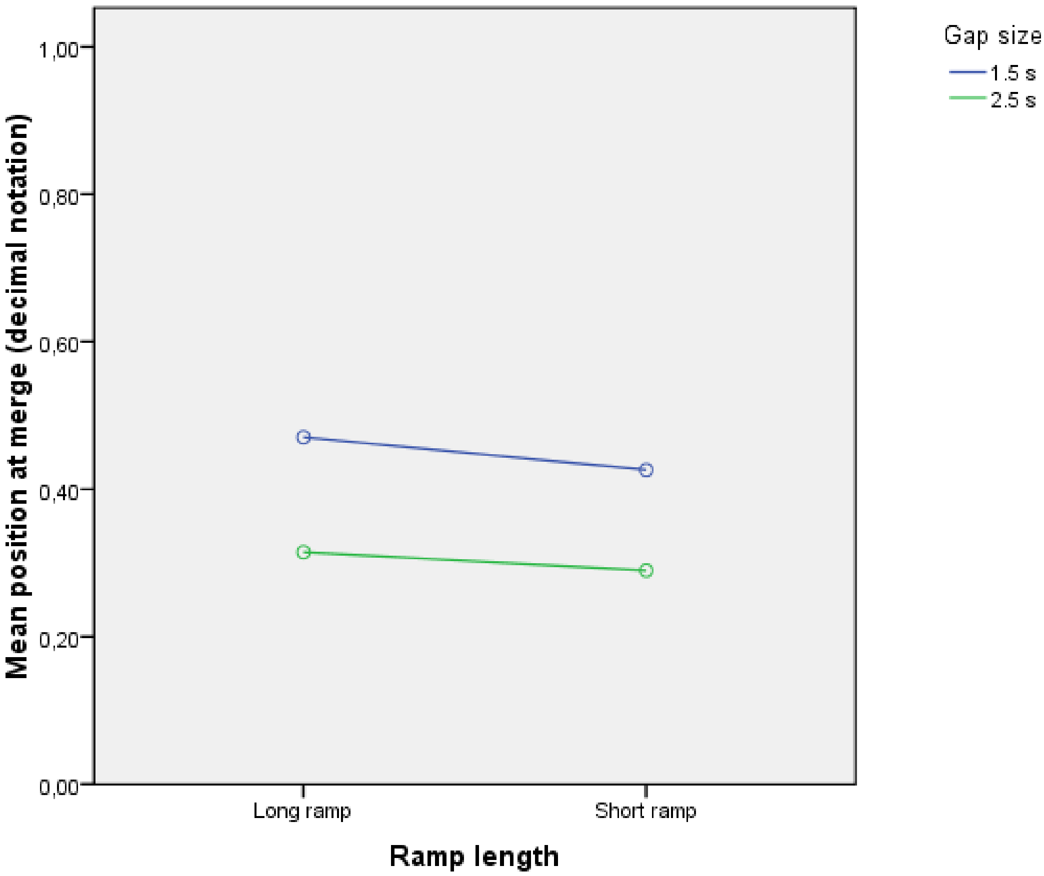


*Figure 6: The mean position-between-vehicles (decimal notation) at merging, divided by entry-ramp tunnel length and gap size.*

The mean and standard deviation (SD) values for the position-between-vehicles variable are reported below.

The long ramp with the 1.5 s gap size had a mean position-between-vehicles of .47 (SD = .23). The long ramp with the 2.5 s gap size had a mean position-between-vehicles of .31 (SD = .09).

The short ramp with the 1.5 s gap size had a mean position-between-vehicles of .42 (SD = .23). The short ramp with the 2.5 s gap size had a mean position-between-vehicles of .29 (SD =.13).

## 3.3 Time headway at merging

The time headway (THW) measures THW-behind and THW-forward are intertwined. Both measures were extracted at the point of merge-completion.

### 3.3.1 THW-behind

The time headway to the rearward vehicle (THW-behind) variable was analysed with a 2 x 2 x 2 repeated measures ANOVA. The within-subject independent variables were entry-ramp tunnel length (1.5 km and 0.5 km) and gap size (1.5 s and 2.5 s) and the between-subject independent variable was annual mileage (two groups; < 15 000 km and > 15 000 km). The analysis showed a significant main effect of gap size ($F(1, 16) = 355.95$, $p < .001$, Eta squared = .96 large effect size), but neither of ramp length ($F(1, 16) = 1.533$, $p = .23$ n.s.) nor of annual mileage ($F(1, 16) = .138$, $p = .72$ n.s.).

The results are shown in Figure 7. Outliers (i.e. ≥ 3 z-scores from the mean; not included in the analysis) are shown in Figure 7 with the corresponding participant numbers.

It should be noted that the analysis of variance (ANOVA) analyses the mean values, while the box plots in Figure 7 indicate the median values as well as the quartile distributions for the THW-behind.

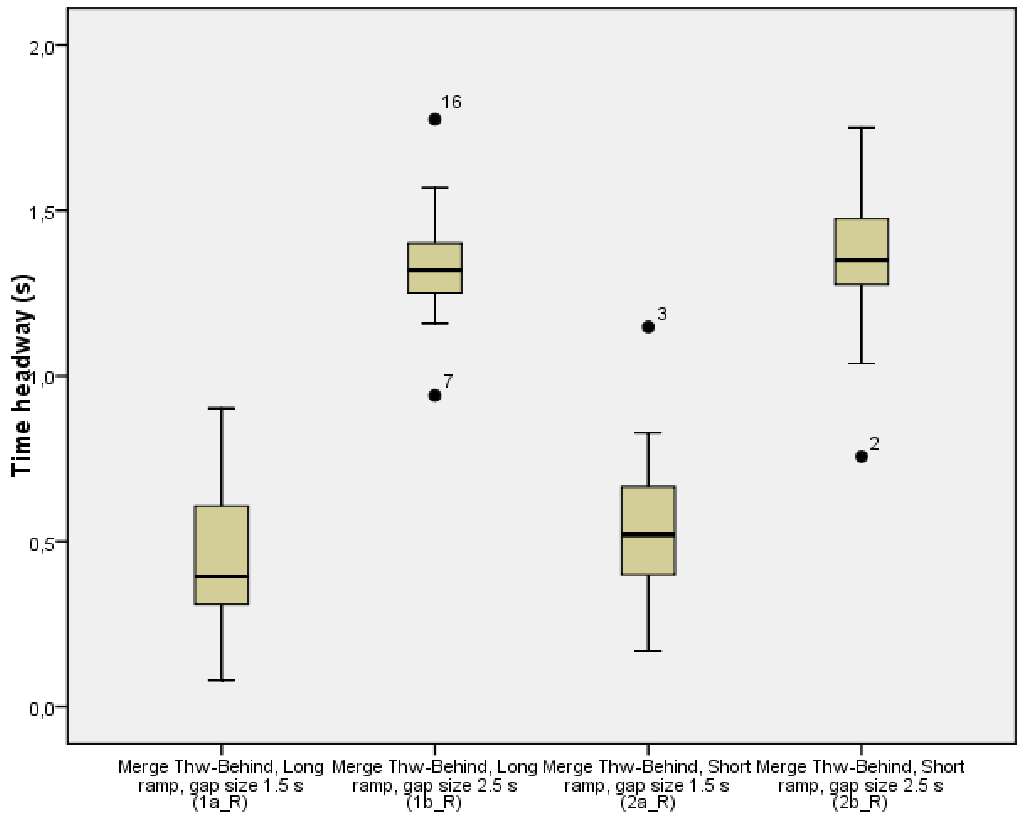


*Figure 7: The time headway to the rearward vehicle (THW-behind) (s) at merging, divided by entry-ramp tunnel length and gap size. Boxplot diagram with median values and quartile distributions.*

The mean and standard deviation (SD) values for the THW-behind variable are reported below.

The long ramp with the 1.5 s gap size had a mean THW-behind of .45 s (SD = .21).
The long ramp with the 2.5 s gap size had a mean THW-behind of 1.35 s (SD = .18).

The short ramp with the 1.5 s gap size had a mean THW-behind of.53 s (SD = .25).
The short ramp with the 2.5 s gap size had a mean THW-behind of 1.35 s (SD =.23).

### 3.3.2 THW-forward

The time headway to the vehicle in front (THW-forward) variable was analysed with a 2 x 2 x 2 repeated measures ANOVA. The within-subject independent variables were entry-ramp tunnel length (1.5 km and 0.5 km) and gap size (1.5 s and 2.5 s) and the between-subject independent variable was annual mileage (two groups; < 15 000 km and > 15 000 km). The analysis showed a significant main effect of gap size ($F (1, 15) = 4.719$, $p < .05$, Eta squared = .24 large effect size), but neither of ramp length ($F (1, 15) = .61$, $p = .81$ n.s.) nor of annual mileage ($F (1, 17) = .0$, $p = .95$ n.s.). There was also a significant interaction effect between ramp length x gap size x mileage group ($F (1, 15) = 4.568$, $p < .05$, Eta squared = .23 large effect size).

The results are shown in Figure 8. Outliers (i.e. ≥ 3 z-scores from the mean; not included in the analysis) are shown in Figure 8 with the corresponding participant numbers.

It should be noted that the analysis of variance (ANOVA) analyses the mean values, while the box plots in Figure 8 indicate the median values as well as the quartile distributions for the THW-forward variable.

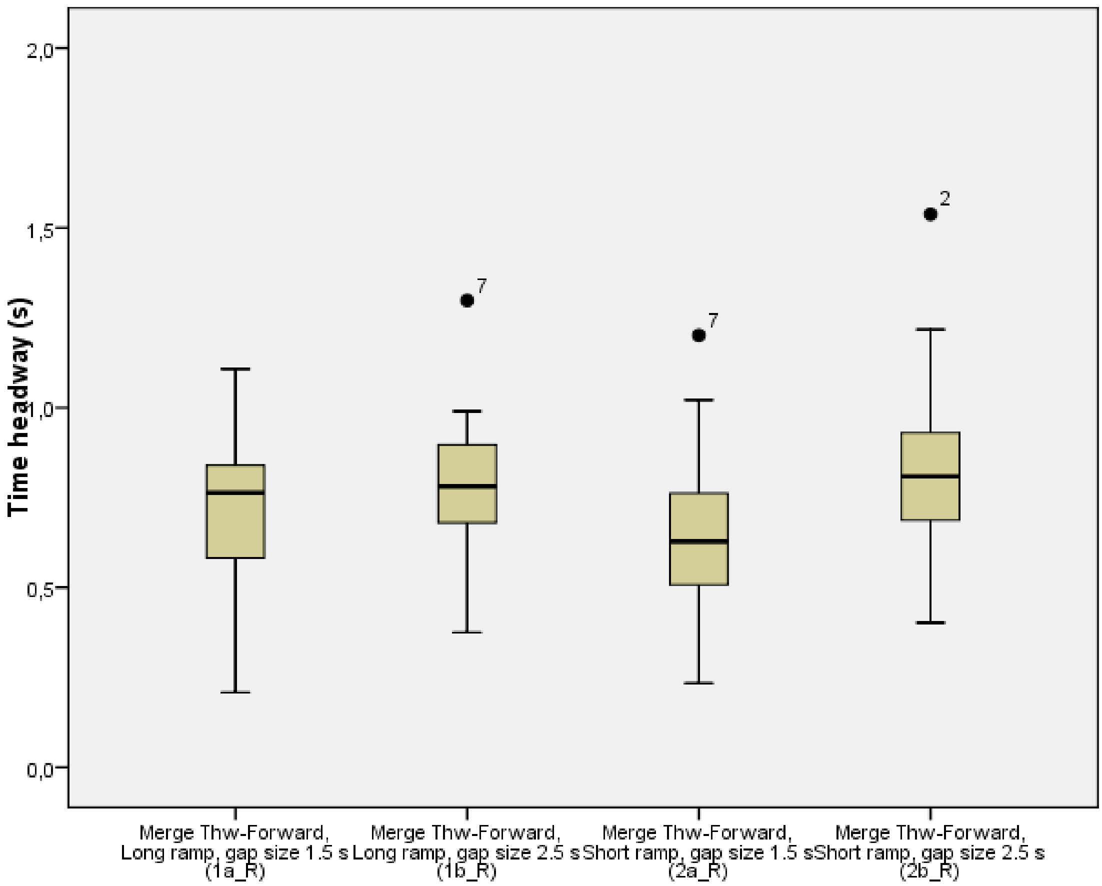


*Figure 8: The time headway to the vehicle in front (THW-forward) (s) at merging, divided by entry-ramp tunnel length and gap size. Boxplot diagram with median values and quartile distributions.*

The mean and standard deviation (SD) values for the THW-forward variable are reported below.

The long ramp with the 1.5 s gap size had a mean THW-forward of .70 s (SD = .24). The long ramp with the 2.5 s gap size had a mean THW-forward of .79 s (SD = .21).

The short ramp with the 1.5 s gap size had a mean THW-forward of .66 s (SD = .25). The short ramp with the 2.5 s gap size had a mean THW-forward of .81 s (SD =.28).

## 3.4 Speed

### 3.4.1 Speed at merging

No significant differences were found for the mean speed variable.

*Table 2: Mean speed (m/s) at merging for the four tunnel conditions, combinations of ramp length and gap size.*

| | Mean | Standard deviation | N |
|---|---|---|---|
| SpeedAtMerge long ramp 1.5 s gap size | 21.7 | .73 | 19 |
| SpeedAtMerge long ramp 2.5 s gap size | 21.6 | .93 | 19 |
| SpeedAtMerge short ramp 1.5 s gap size | 21.6 | 1.09 | 19 |
| SpeedAtMerge short ramp 2.5 s gap size | 21.2 | .94 | 19 |

### 3.4.2 Speed for three different sections of the ramp

Speed was analysed with a 3 x 2 x 2 x 2 repeated measures ANOVA. The within-subject independent variables were section-on-ramp (construction nose before merging, at merging and at merging + 25 m), entry-ramp tunnel length (1.5 km and 0.5 km) and gap size (1.5 s and 2.5 s). The between-subject independent variable was annual mileage (two groups; < 15 000 km and > 15 000 km). The analysis showed a significant main effect of section-on-ramp (F (1.215, 20.663) = 5.855, p < .05 Greenhouse-Geisser, Eta squared = .26 large effect size), but no effects of ramp length (F (1, 17) = 4.145, p = .058 n.s.), gap size (F (1, 17) = .2, p = .66 n.s.) and annual mileage group (F (1, 17) = 3.557, p = .077 n.s.).

There was a significant interaction effect between section-on-ramp and annual mileage group variables (F (2, 34) = 4.11, p < .05, Eta squared = .20 large effect size). Figure 9 illustrates the interaction, i.e. the mean speed (m/s) in different ramp sections by section-on-ramp and annual mileage group. Ramp length and gap size are aggregated in Figure 9. The speed of the traffic in the main tunnel was set at 80 km/h which is equivalent to 22.2 m/s.

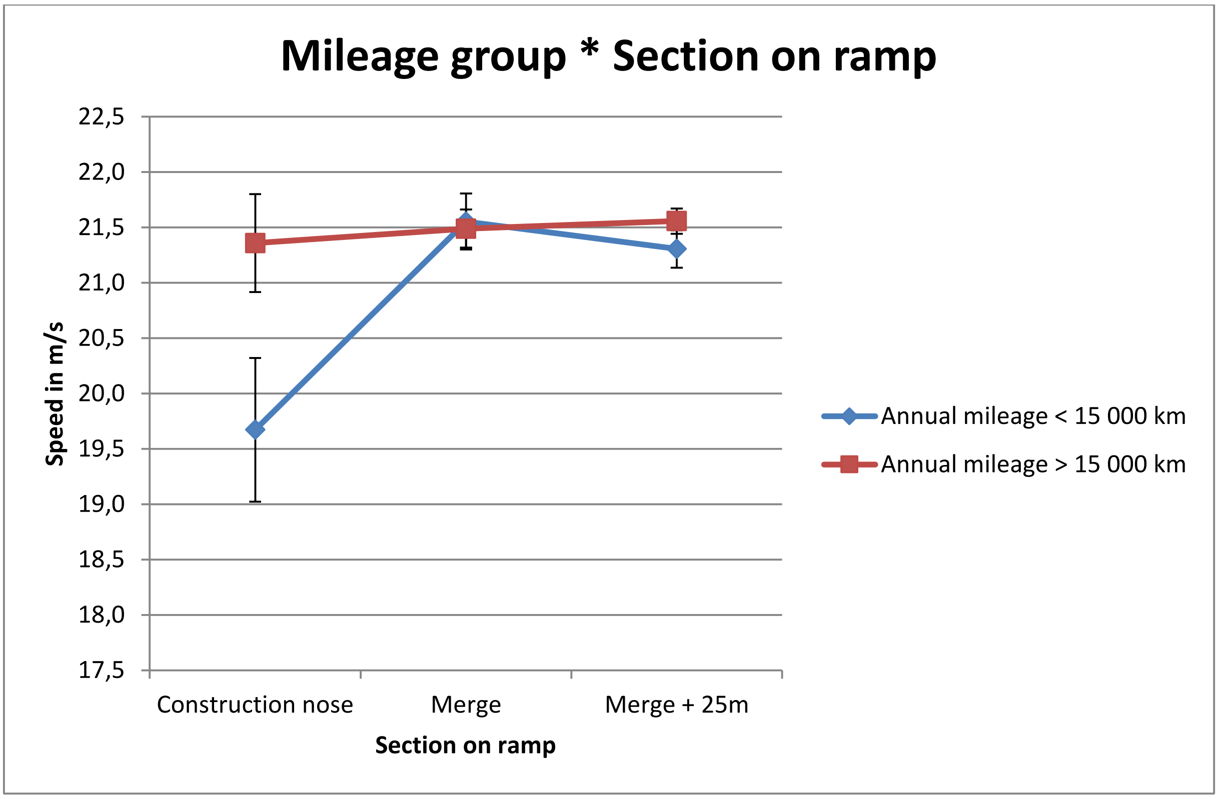


*Figure 9: Speed (m/s) in three different ramp sections by mileage group and section-on-ramp. Means ± standard error bars.*

## 3.5 Mental demand

The mental demand dependent variable (CR10 rating) was analysed with a 2 x 2 repeated measures ANOVA. The within-subject independent variables were entry-ramp tunnel length (1.5 km and 0.5 km) and gap size (1.5 s and 2.5 s). The analysis showed a significant main effect of gap size ($F (1, 20) = 27.984$, $p < .001$, Eta squared = .58 large effect size) but not of ramp length ($F (1, 20) = 1.236$, $p = .28$ n.s.). Figure 10 illustrates the results.

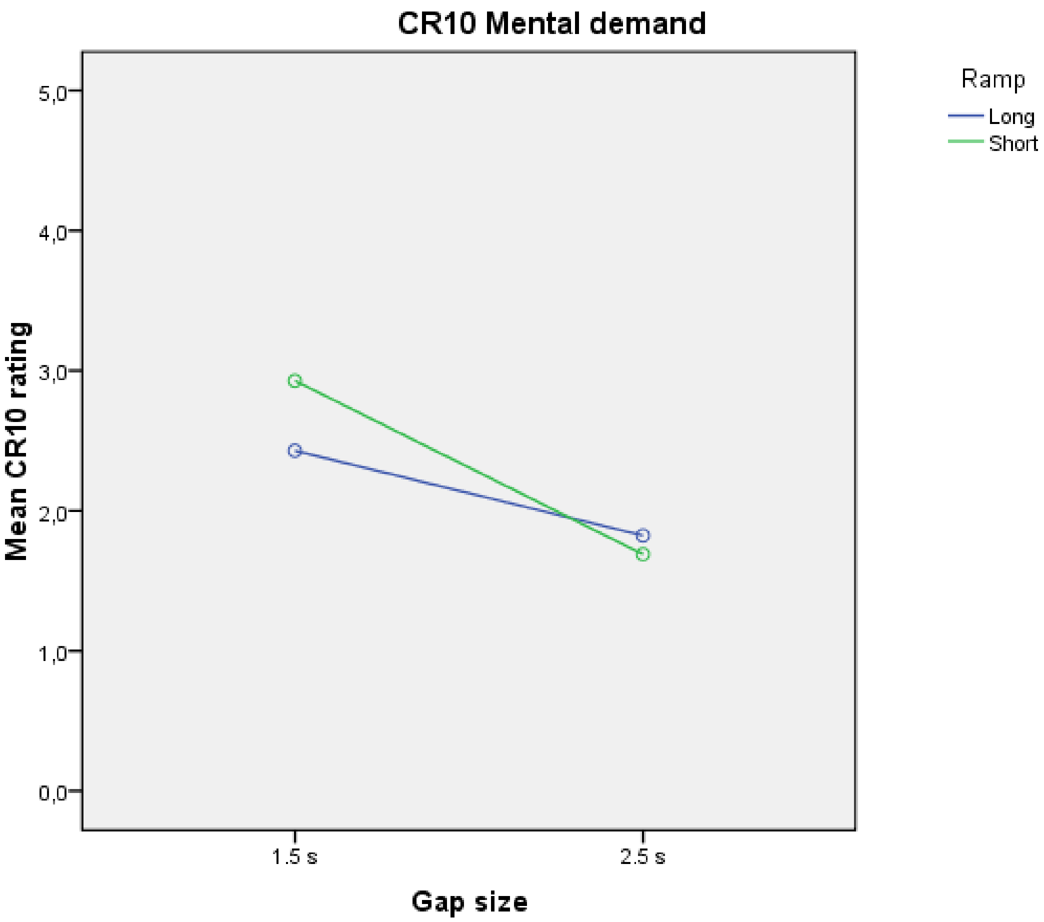


*Figure 10: Mean mental demand CR10 ratings by entry-ramp tunnel length and gap size.*

The mean and standard deviation (SD) values for the mental demand (CR10 rating) variable are reported below.

The long ramp with the 1.5 s gap size had a mean mental demand CR10 rating of 2.4 (SD = 1.4). The long ramp with the 2.5 s gap size had a mean mental demand CR10 rating of 1.8 (SD = 1.4).

The short ramp with the 1.5 s gap size had a mean mental demand CR10 rating of 2.9 (SD = 1.8). The short ramp with the 2.5 s gap size had a mean mental demand CR10 rating of 1.7 (SD =1.2).

## 3.6 Time pressure (temporal demand)

The time pressure (temporal demand) dependent variable (CR10 rating) was analysed with a 2 x 2 repeated measures ANOVA. The within-subject independent variables were entry-ramp tunnel length (1.5 km and 0.5 km) and gap size (1.5 s and 2.5 s). The analysis showed a significant main effect of gap size ($F(1, 20) = 19.24$, $p < .001$, Eta squared = .49 large effect size) but not of ramp length ($F(1, 20) = 1.264$, $p = .27$ n.s.). Figure 11 illustrates the results.

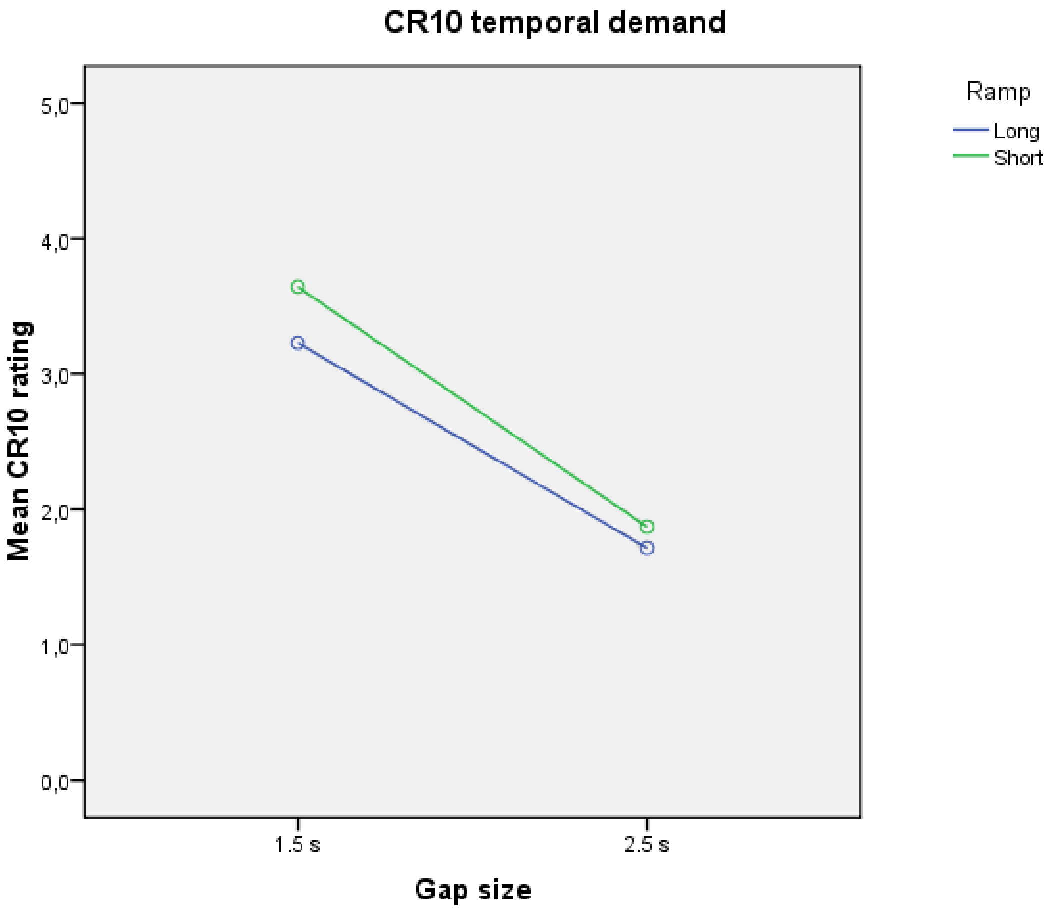


*Figure 11: Mean time pressure (temporal demand) CR10 ratings by entry-ramp tunnel length and gap size.*

The mean and standard deviation (SD) values for the temporal demand (CR10 rating) variable are reported below.

The long ramp with the 1.5 s gap size had a mean temporal demand CR10 rating of 3.2 (SD = 1.8). The long ramp with the 2.5 s gap size had a mean temporal demand CR10 rating of 1.7 (SD = 1.4).

The short ramp with the 1.5 s gap size had a mean temporal demand CR10 rating of 3.6 (SD = 2.6). The short ramp with the 2.5 s gap size had a mean temporal demand CR10 rating of 1.9 (SD =1.4).

## 3.7 Frustration

The frustration dependent variable (CR10 rating) was analysed with a 2 x 2 repeated measures ANOVA. The within-subject independent variables were entry-ramp tunnel length (1.5 km and 0.5 km) and gap size (1.5 s and 2.5 s). The analysis showed a significant main effect of gap size ($F (1, 20) = 17.559$, $p < .001$, Eta squared = .47 large effect size) but not of ramp length ($F (1, 20) = .114$, $p= .74$ n.s.). Figure 12 illustrates the results.

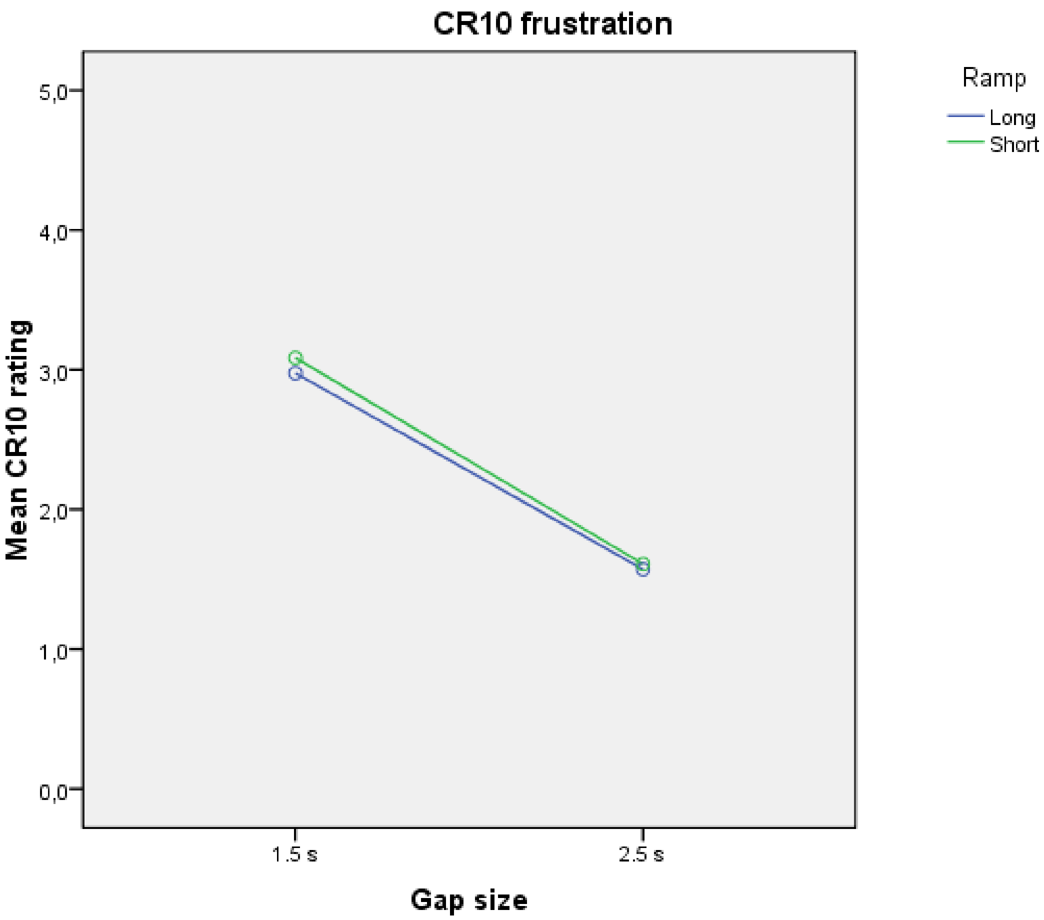


*Figure 12: Mean frustration CR10 ratings by entry-ramp tunnel length and gap size.*

The mean and standard deviation (SD) values for the frustration (CR10 rating) variable are reported below.

The long ramp with the 1.5 s gap size had a mean frustration CR10 rating of 3.0 (SD = 2.0). The long ramp with the 2.5 s gap size had a mean frustration CR10 rating of 1.6 (SD = 1.1).

The short ramp with the 1.5 s gap size had a mean frustration CR10 rating of 3.1 (SD = 2.5). The short ramp with the 2.5 s gap size had a mean frustration CR10 rating of 1.6 (SD =1.2).

## 3.8 Perceived risk

The perceived risk dependent variable (CR10 rating) was analysed with a 2 x 2 repeated measures ANOVA. The within-subject independent variables were entry-ramp tunnel length (1.5 km and 0.5 km) and gap size (1.5 s and 2.5 s). The analysis showed a significant main effect of gap size (F (1, 20) = 37.294, p < .001, Eta squared = .65 large effect size) but not of ramp length (F (1, 20) = .185, p = .67 n.s.). Figure 13 illustrates the results.

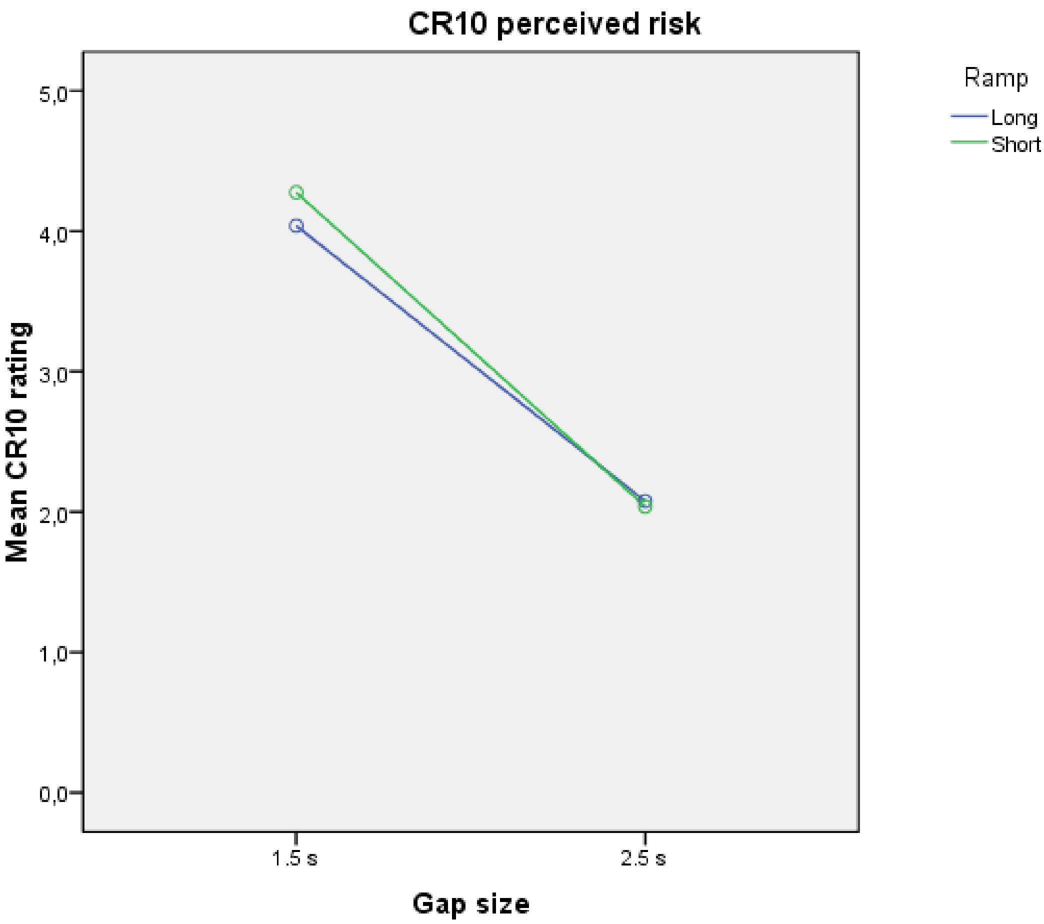


*Figure 13: Mean perceived level of risk CR10 ratings by entry-ramp tunnel length and gap size.*

The mean and standard deviation (SD) values for the perceived risk (CR10 rating) variable are reported below.

The long ramp with the 1.5 s gap size had a mean perceived risk CR10 rating of 4.0 (SD = 2.5). The long ramp with the 2.5 s gap size had a mean perceived risk CR10 rating of 2.1 (SD = 1.6).

The short ramp with the 1.5 s gap size had a mean perceived risk CR10 rating of 4.3 (SD = 2.7). The short ramp with the 2.5 s gap size had a mean perceived risk CR10 rating of 2.0 (SD =1.4).

## 3.9 Questionnaires

The participants' previous experiences of driving in tunnels and their feelings/emotions regarding tunnel driving are presented in Table 4 and Table 5, respectively. The information was collected from the pre-experimental questionnaire where the participants for each question indicated the response alternative that most accurately reflected their experiences and feelings/emotions regarding driving in tunnels. The questions were originally posed in Swedish.

Table 4 shows that the majority of the participants (95 %) had some previous experience of driving in tunnels and that 43 % of the participants regularly drive in tunnels. The information in Table 4 was recorded before the simulator driving.

*Table 3: The participants' experiences of driving in tunnels, before the simulator experiment.*

| | Frequency | Percent | Cumulative percent |
|---|---|---|---|
| Never driven in a tunnel | 1 | 4,8 | 4,8 |
| Driven in a tunnel a few times | 3 | 14,3 | 19,0 |
| Drive in a tunnel a few times per year | 8 | 38,1 | 57,1 |
| Drive in a tunnel weekly | 9 | 42,9 | 100,0 |
| **Total** | 21 | 100,0 | |

Table 5 shows the feelings or emotions that the participants had in regard to driving in tunnels. No specific feelings or emotions to tunnel driving was reported by 48 % whereas 38 % felt somewhat uncomfortable when driving in tunnels. None of the participants indicated that they were fearful of driving in tunnels. The information in Table 5 was recorded before the simulator driving.

*Table 4: The participants' feelings/emotions regarding driving in tunnels, before the simulator experiment.*

| | Frequency | Percent | Cumulative percent |
|---|---|---|---|
| Fun/interesting | 3 | 14,3 | 14,3 |
| Nothing special | 10 | 47,6 | 61,9 |
| Somewhat uncomfortable | 8 | 38,1 | 100,0 |
| Fearful | 0 | 0 | 100,0 |
| **Total** | 21 | 100,0 | |

An excerpt of the participants' responses to the post-experimental questionnaire (i.e. to the questions about the merging zone) is reported in Table 6. The participants answered the questions by indicating the number that most accurately reflected their experiences from the simulator driving on a 7-point Likert scale from 1 "strongly disagree" to 7 "strongly agree". The questions were originally posed in Swedish. For the unabridged questionnaire results, see in Appendix.

*Table 5: The participants' responses to questions about the merging zone (excerpt of responses to the post-experimental questionnaire). 7-point Likert scale from 1 "strongly disagree" to 7 "strongly agree".*

| Question | Question number | Mean rating | Range | Frequency of responses |
|---|---|---|---|---|
| ”I experienced the line of sight as adequate enough to provide an overview of the surrounding traffic.” | Question 2 | 5.1 | (2-7) | 20 |
| ”I experienced the merging zone as long enough to provide an overview of the surrounding traffic.” | Question 3 | 4.35 | (2-7) | 20 |
| ”The design of the merging zone facilitated safe driving behaviour.” | Question 4 | 4.7 | (2-7) | 20 |
| Nine of 20 participants wrote that they thought that the merging zone was too short or should be longer. | Question 12† | - | - | 20 |

† Verbal responses/comments to open questions.

One of the general questions referred to the placing of the statutory speed limit sign posts in the tunnel, either by the side of the road (to the left and to the right) or in an overhead position on a gantry. The road side placing was preferred by 14 out of 20 participants with the comments that the roadside sign posts were more visible and that they were used to seeing them there.

## 3.10 Incidents

Four participants had rear-ended collisions when driving in the simulator. All four rear-ended collisions occurred in experimental conditions with 1.5 s gap size, one in the Lovö (long) ramp and the other three in the Vinsta (short) ramp.

# 4 Discussion

The main results of the reported study suggest that the merging zones were too short for some of the drivers in order to merge comfortably and safely. The merging zones are found at the point where the entry-ramp tunnel merges with the main motorway tunnel. The merging zones comprise an observation section, an adjustment section and a completion (/taper) section. For the Vinsta (0.5 km) ramp with heavy traffic the distance-to-wall measure (the measure that gauges how much of the entry-ramp remains at the time of merge-completion) is particularly concerning from a road traffic safety perspective because more than 25 % of the drivers completed the merging manoeuvre with less than two seconds of time headway (THW) remaining before the end of the completion section. Two seconds of travel before the ending of the tapered completion section of the entry-ramp was considered to be the bare minimum in terms of safe driving and safe merging. Two seconds equates to 44.4 m when travelling at 80 km/h. The completion section of the entry-ramp also tapers to the width of a car (approx. 2 m) 40 m from the end of the ramp. There is however, a right-hand lane hard shoulder with a width of approximately 2 m (i.e. wide) drawn on the blueprints after the end of the ramp. The motorway lanes are 3.5 m wide.

The point-of-no-return refers to the point in time when the driver has to either complete the merging manoeuvre or stop the vehicle on the ramp before the ramp becomes too narrow to safely and comfortably stop. In practical terms, the point-of-no-return for a driver wishing to stop on the ramp would be before the 40 m limit (mentioned above) due to the vehicle’s width. The stopping distance of an average car travelling at 80 km/h is approximately 53 m in good conditions, i.e, distance passed during reaction time, 15 m, and distance passed while braking, 38 m (HM Stationary Office, 2001). It could therefore be argued that for a driver wishing to abort the manoeuvre the point-of-no-return would be approximately 40 + 53 = 93 m (at 80 km/h) before the very end of the ramp. A distance of 93 m is roughly 4.2 s of travelling time at 80 km/h. This suggests that the Vinsta ramp in particular, should be studied in more detail.

The results also suggest that drivers with more driving experience (> 15 000 km/year) adopted a different strategy when merging. Their strategy could be described as active (instead of passive) where they appeared to use speed differently (higher constant speed) and merged earlier rather than later upon entering the merging zones. The active driving strategy appeared to be safer (in terms of longer distances to the end of the merging zone) than the passive or defensive driving style when merging from an entry-ramp onto a busy motorway.

Interestingly the mean time headway (THW) for merging was approximately 0.75 s to the vehicle in front irrespective of the distance to the vehicle behind (see Figures 7 and 8). The results for the THW-behind measure and the THW-forward measure indicated a behavioural preference of drivers to place themselves between vehicles using the THW-forward (as one would expect) and moreover, keeping the THW-forward relatively constant irrespective of gap size (/traffic intensity) and distance to the vehicle behind.

The two entry-ramp tunnels and their corresponding merging zones were slightly different in that the Lovö entry-ramp tunnel was 1.5 km and the adjustment section of the merging zone was 125 m, while the Vinsta entry-ramp tunnel was 0.5 km and the adjustment section of the merging zone was 80 m. The completion sections of both entry-ramps (merging zones) were similar and equally long, 100 m each. The total lengths of both merging zones (Lovö and Vinsta) were approximately the same (325 m and 330 m, respectively). The drivers did not appear to *subjectively* (CR10 ratings and post-experimental questionnaire) distinguish between the two ramp configurations (i.e. entry-ramp tunnels plus the merging zones) at Lovö and Vinsta. There were, however, notable differences for the distance-to-wall measure. The CR10 ratings generally suggest no subjective differences between ramps but did however suggest significantly increased levels for the smaller gap size (1.5 s) on all four CR10 dimensions; mental demand, time pressure, frustration and perceived risk.

Traffic intensity expressed indirectly by the gap size influenced the frequency and character of hazardous situations such as late merging. There were clear differences between the two gap sizes (1.5 s and 2.5 s) for the following measures: distance-to-wall; position-between-vehicles; THW-behind; THW-forward; CR10 ratings of mental demand, time pressure, frustration and perceived risk. The smaller gap size (1.5 s) was associated with more hazardous situations.

There were differences in mean speed depending on the section of ramp where a significant interaction was found between gap size (1.5 s and 2.5 s), ramp (Lovö and Vinsta) and driver experience (drivers with an annual mileage greater than or less than 15 000 km). This interaction effect between mean speed and the other measures is arguable a product of driver experience and subsequent differences in driving style, rather than differences in the ramps themselves.

This study has some limitations regarding sample size (i.e. the number of test participants), however, the size of the test group can be considered normal for this kind of study. The sample size used limits the generalisation possibility of the results, in particular regarding the effect size on a real population. It is, however, important to point out that even with this limitation, many of the results were statistically significant and many of the test participants encountered difficulties when merging, giving rise to serious safety concerns for drivers in real life if the tunnel is built using the present entry-ramp dimensions. It is proposed that longer merging zones would resolve many of the difficulties that drivers encountered and facilitate sizable safety benefits for road users in the tunnel.

An additional, more general limitation is that absolute judgement of distance and speed is not always easy in general and this difficulty applies to simulators in particular. However, in a recent validation study of the VTI Simulator III absolute validity between driving in the field and in the simulator was indicated for speed (Ahlström, Bolling, Sörensen, Eriksson, & Andersson, 2012). The distances between the autonomously generated vehicles, i.e. the traffic created in the simulator in the right-hand lane in the main tunnel, was equal; either 1.5 s gap sizes or 2.5 s gap sizes. This may appear a little unlikely in real traffic but was necessary for the experiment because the authors did not know a priori which gap the drivers would choose. However, once the drivers had completed the merging manoeuvre, the vehicle behind was programmed to avoid a rear-end collision. There were, however, four incidents where the drivers merged so late that there was a collision with the simulated vehicle behind. This data was excluded from the analyses. Moreover, one could argue that the drivers' merging behaviour might have been affected by the rather rigid following and braking behaviour of the simulated vehicles behind. There was also a restricted field of view due to the 120 degrees simulator screen but the simulator was programmed to not allow traffic to enter the drivers' blind spot. The concerns about the rigid traffic and the restricted field of view appear to be unfounded because analysis of the time headway (THW) data suggested that the drivers used the THW-forward to gauge their manoeuvre and appeared to disregard the THW-behind and the exact position of the vehicle behind. It would, however, be interesting to study this trait in a field study with eye tracking equipment.

Additionally, the simulated traffic in the main tunnel comprised only cars and there were no trucks or buses in the right-hand lane. This arguably made the merging task easier for the drivers in this study, in comparison to what could be expected in real life driving when the tunnel will be used by heavy vehicles. In peak hour traffic, the planned bus service using parts of the tunnel (but not all) is expected to be approximately one bus per minute. The length and frequency of heavy vehicles (trucks up to 24 m and buses up to 18 m length) in the main tunnel may cause additional difficulties for drivers hoping to merge into the main tunnel simply because of their greater length and the reduced number of viable gaps between vehicles.

The ratio between gap size and speed (m/s) used in the main tunnel was based on a relatively high, but still regularly occurring ratio as calculated from empirical traffic data from Swedish motorways. The empirical motorway data clearly illustrates that drivers in real traffic drive at 110 km/h even at peak-hour free-flowing traffic (Olstam, Carlsson, & Yahya, 2013). Olstam et al. (2013) found that free-flowing traffic on Swedish motorways had an hourly rate of 1650 vehicles per lane at 110 km/h. This equates to a mean gap size of 2.0 seconds per car at 110 km/h when accounting for vehicle length. Olstam et al. (20113) propose a traffic flow/speed model that projects the outcomes at different speeds and traffic intensity levels. The estimated traffic intensity per motorway lane at 80 km/h is 2000 vehicles per hour. This equates to a mean gap size between vehicles of 1.56 seconds. It should be noted that where the mean gap size is 1.56 s, there are many vehicles travelling with a gap size much shorter than 1.5 s.

The Stockholm bypass tunnel is planned to be completed in approximately eight to ten years from the present day. In the meantime the development of autonomous vehicles and platooning vehicles will have matured and the market penetration increased. A caveat is necessary regarding the possible effects that platooning and autonomous vehicles will have on traffic flow, gap sizes behaviour, merging and road safety in general.

# 5 Conclusions

There are safety concerns relating to the design of the entry-ramps, in particular the Vinsta ramp. The authors cannot categorically state that there is a road traffic safety problem with the entry-ramp tunnel at the subterranean Vinsta junction but we are concerned that if the merging zones are not lengthened or improved in some other suitable fashion, then there is a major likelihood of collisions and incidents on the entry-ramp. This will in turn lead to stationary traffic and queues all the way up the entry-ramp tunnels creating unwanted traffic congestions.

## 5.1 Future research

In order to establish the causes and to seek and verify possible solutions to the safety concerns arising from this study, a number of areas need to be explored. New research questions in relation to the merging zones of the subterranean junctions in the Stockholm bypass tunnel project are:

1. Would lengthening the merging zone at Vinsta improve the safety of that entry-ramp?
2. What are the characteristics of an entry-ramp into a motorway tunnel that gives provision for safe and well-working merging? On the other hand, what causes unsafe merging performance? Could it be other aspects apart from the actual length of the merging zones?
3. Only two of the five planned entry-ramps have been assessed in this study. What is the status of the remaining entry-ramps from a safety perspective?
4. Can we use micro-simulation data together with test drivers to assess the effects of different scenarios on traffic flow? This could include activated motorway control systems (MCS); having multiple vehicles on the entry-ramps as well as in the main tunnel.
5. How is the merging situation affected when heavy vehicles want to merge? There are issues on accelerating up to the speed of the traffic in the main tunnel in addition to visibility issues for heavy vehicles. E.g., what will happen to the traffic situation in the entry-ramps when the planned entry-ramps for buses are added to the existing entry-ramps?
6. Is it possible to manage traffic and modify driver behaviour to avoid critical situations merely by means of motorway control systems (MSC) preceding each of the merging zones in the main tunnel?

## 5.2 Benefits for ViP

This study has illustrated the unique potential of using a driving simulator to study road infrastructure from a design and safety perspective. Construction of the Stockholm bypass tunnel has not started and yet it was possible, using the simulator, to create the entire tunnel from the blueprints and evaluate different design features of this infrastructure project. The development of infrastructure models is highly relevant for the ViP partners and is especially useful for those who are already involved in similar projects e.g. Known Roads. The virtual tunnel environment developed in this project is now available within ViP and has also been implemented in a simulator at MUARC (Monash University Accident Research Centre, Melbourne) and used in collaborative studies.

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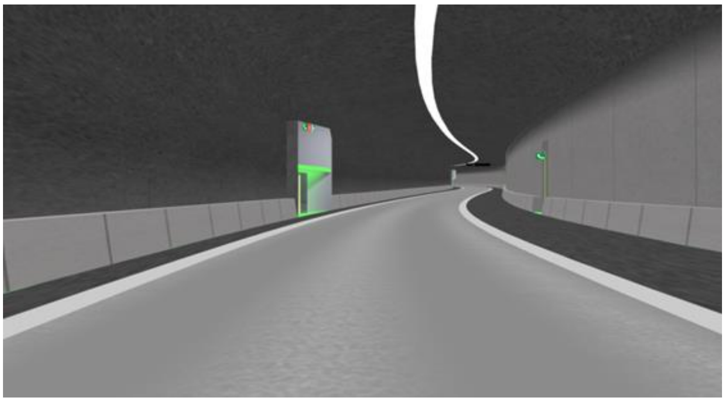
## Post-experimental questionnaire results (in Swedish)

Screen captures from the simulator were included in the questionnaire to remind the participants of the specific tunnel locations that the different sets of questions were related to.

### Entry tunnels



Tolv av 20 försökspersoner uppfattade att något skiljde påfarterna åt.
Av dessa upplevde 9 att vävningszonerna skiljde sig åt mellan påfarterna.

*Övriga kommentarer angående påfarterna:*

- Obehagligt att de var så svängiga.
- Svårt att få till en jämn körupplevelse.
- Frustrerande att svänga fram och tillbaka.
- Lagom hastighet (80km/h).
- Tryggt att se nödutgångar.
- Tycker vävningszonerna ska vara längre.
- Påfarterna hade generösa och behagliga kurvor.

### Merging zones - means (ranges)

Means and (in brackets) ranges of scores on the 7-point Likert scale from 1 “strongly disagree” to 7 “strongly agree” are reported in bold font under each question.

Tillräckligt lång siktsträcka för att få bra överblick över trafiken.
**5,1 (2-7)**

Vävningszonen tillräckligt lång för att skaffa mig bra överblick över trafiken.
**4,35 (2-7)**

Vävningszonens utformning bidrog till trafiksäkert beteende.
**4,7 (2-7)**

*Kommentarer*
Nio av 20 försökspersoner skrev att de tyckte vävningszonen var för kort/borde vara längre.

**Merging in the tunnel - means (ranges)**


Means and (in brackets) ranges of scores on the 7-point Likert scale from 1 “strongly disagree” to 7 “strongly agree” are reported in bold font under each question.

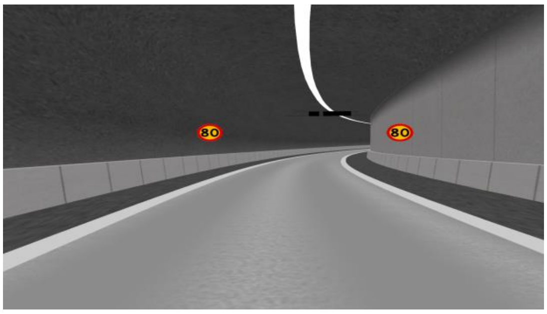
Vävningssträckan var tillräckligt lång.
**4 (2-7)**

Tillräckligt stor lucka mellan bilarna i tunneln för att kunna väva in bra.
**4,1 (2-7)**

Vävningssträckans utformning bidrog till trafiksäkert beteende.
**4,5 (2-7)**

*Kommentarer*
Sex av 20 skrev att de tyckte vävningssträckan var för kort, särskilt om något oväntat skulle inträffa, och 7 av 20 skrev att luckan mellan bilarna var för kort/för tight, etc.

**Speed signs**





Fjorton av 20 försökspersoner föredrog placeringen vid sidan av vägbanan, och 2 av 20 tyckte att båda placeringarna var lika bra.

*Motiveringar till sidoalternativet var bland annat:*
- Syns bättre.
- Van att ha hastighetsskyltar på sidan-
- Måste inte lyfta blicken från vägen för att se dem.
- Tar inte fokus från vägen.
- Stör inte.

# ViP

## Virtual Prototyping and Assessment by Simulation

ViP is a joint initiative for development and application of driving simulator methodology with a focus on the interaction between humans and technology (driver and vehicle and/or traffic environment). ViP aims at unifying the extended but distributed Swedish competence in the field of transport related real-time simulation by building and using a common simulator platform for extended co-operation, competence development and knowledge transfer. Thereby strengthen Swedish competitiveness and support prospective and efficient (costs, lead times) innovation and product development by enabling to explore and assess future vehicle and infrastructure solutions already today.

ViP
Virtual Prototyping and
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Olaus Magnus väg 35, SE-581 95 Linköping, Sweden – Phone +46 13 204000