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Research Article

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Using Driving Simulators in Road Design–A Road Safety Study of Merging Traffic in Tunnels

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Abstract

The present study describes a simulator study on the merging of traffic from entry-ramp tunnels into the main Stockholm bypass tunnel. The present study focuses on two of the five junctions with connections at Lovö and Vinsta. Three research questions were formulated relating to 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)? 2) Is driver performance when merging affected by the drivers' experience when entering the main tunnel from the entry-ramp tunnel? 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?

Twenty-one participants completed the study. 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. For the Vinsta (0.5 km) merging zone with heavy traffic the distance-to-wall measure (the measure that gauges how much of the merging zone 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 merging zone 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 merging zone also tapers to the width of a car (approx. 2 m) 40 m from the end of the merging zone.

Keywords: Driving simulators; Road safety; Traffic

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.

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 [1]. Some typical issues that need attention are the signal and sign systems of the new infrastructure systems. 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 and the focus for the present study, viz. merging zones in entry-ramp tunnels and merging behaviour.

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 loads and buses. Earlier studies have suggested that drivers' ability to gauge speed can be affected by visual design concepts [2]. 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 [3-5]. 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 [6]. Driving in tunnels is unlikely to improve performance and may even exacerbate effects on driver workload and glance behaviour when the driving task becomes more demanding [7].

A recent simulator study with a dissimilar design investigated traffic scenarios in a model of the Stockholm bypass tunnel [8]. 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-ramp tunnels 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 (ibid.) suggesting that unrestricted sight lines facilitated a reduction in mean speeds on the main route when encountering merging traffic from entry-ramp tunnels.

The present study describes a simulator study on the merging of traffic from entry-ramp tunnels into the main tunnel. The entry-ramp tunnels in the Stockholm bypass project are planned to let traffic in to the main motorway tunnel from five specified locations. An entry ramp tunnel is a dedicated auxiliary tunnel that starts on the surface and leads the road traffic down to the main subterranean motorway tunnel. The last portion of this auxiliary tunnel (approx. 300 m) has a merging zone comprising 1) an observation section, 2) an adjustment section and 3) a completion/taper section as shown in Figure 1. 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 could also be argued that this may lead to difficulties in judging and maintain speed and distances between vehicles.

The present study focused upon the specific situation of driving down the entry-ramps tunnels 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 merging zone?

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?

Method

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 ≥ 5000 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.

Equipment and materials

Simulator: The study was performed in VTI's driving simulator III in Linköping using the car set-up. 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 sec (www.vti.se).

Rating scale CR10: The Category Ratio scale 10 (CR10), developed by Borg [9] and Borg and Borg [10], was used for the participants' self-rating of the following CR10 dimensions. 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:

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

The CR10 scale ranges from 0 to ≥ 11 with clear verbal anchors that describe the experience exertion. 0 equates to "Nothing at all", 0.5 equates to "Extremely weak", 1 equates to "Very weak", 2 equates to "Weak", 3 equates to "Moderate", 5 equates to "Strong", 7 equates to "Very strong" and 10 equates to "Extremely strong". There is however a level greater than ten which equates to "Absolute maximum" in accordance with Borg [10].

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 (STA, 2011) [11] 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. The reference to a long and a short entry-ramp tunnel is merely a way of verbally distinguishing the two entry-ramp tunnels because they are both unique and most notably, one of them is much longer than the other, hence the *long* and *short* allusions.

There were two entry-ramps 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 tunnel ramps there were merging zones according to the illustration in Figure 1. 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:

The long entry-ramp tunnel (1.5 km) at Lovö (no. 1) had the following design [11]:

- Observation section=100 m
- Adjustment section=125 m

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- Completion (taper) section=100 m
- Summa=325 m

The short entry-ramp tunnel (0.5 km) at Vinsta (no. 2) had the following design [11]:

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

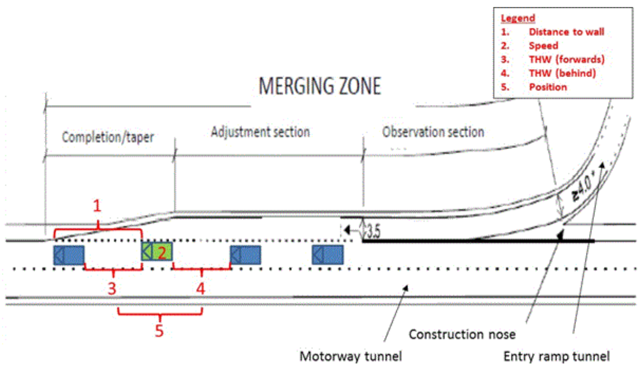

Figure 1: The measurement window for driving performance dependent variables. The last section of the entry ramp tunnel comprises a merging zone with an observation section, an adjustment section and a completion/taper section.

Traffic of two different intensities was simulated in the main tunnel; medium traffic (2.5 s gap size between vehicles) and dense traffic (1.5 sec 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.

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. 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. Therefore, to reflect real traffic situations, gap sizes in this study were set to 1.5 sec and 2.5 sec between vehicles. A time gap of 1.5 sec at a speed of 80 km/h equates to a distance gap of 33.3 m and a 2.5 sec time gap at the same speed equates to a distance gap of 55.5 m between vehicles.

Design

The study had a 2 (gap size) x 2 (entry-ramp tunnel) x 2 (driver experience) design with gap size and entry-ramp tunnel 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 tunnels. The order was balanced for entry-ramp tunnel length and gap size. All participants drove the route through the tunnel in the same direction, from south to north.

The following dependent variables were used (Figure 1):

- 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 merging zone (the joining of the right-hand ramp lane marking and the right-hand motorway lane marking, Figure 1). 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 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 1. 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 1) from the point of merge-completion+25 m. The mean speed variable was calculated in metres per second (m/s).

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

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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 that they after having answered, the drive would continue going further in the tunnel, exiting at the first entry-ramp and then re-entering through the next 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. The whole procedure took approximately 1.5 hours.

Data analysis

The statistical analyses used were ANOVA repeated measures and *t-tests* (SPSS version 17.0). Classification of Cohen [12] was used, which classifies Eta squared effect sizes as small (0.01), medium (0.06) and large (0.14).

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 1. In Figure 1 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 (where they merged so close so that they merged into and struck a simulated car on the motorway with the rear of their car), one participant in the experimental condition with long entry-ramp tunnel and 1.5 sec gap size and three participants in the experimental condition with short entry-ramp tunnel and 1.5 sec 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. ≥ 3 z-scores from the mean) were excluded from analyses.

The significance level used in the statistical analyses was $\alpha=0.05$ ($p < 0.05$). 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.

Results

Distance-to-wall

The distance-to-wall variable was analysed with a 2x2x2 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 sec and 2.5 sec) and the between-subject independent variable was annual mileage (two groups; <15000 km and >15000 km). The analysis showed significant main effects of entry-ramp tunnel length ($F_{(1,19)}=50.735$, $p<0.001$, Eta squared=0.73 large effect size) and gap size ($F_{(1,19)}=5.376$, $p<0.05$, Eta squared=0.22 large effect size), but not of annual mileage ($F_{(1,19)}=3.435$, $p=0.08$ n.s.).

In Figure 2 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 2 indicate the median values as well as the quartile distributions for the distance-to-wall variable.

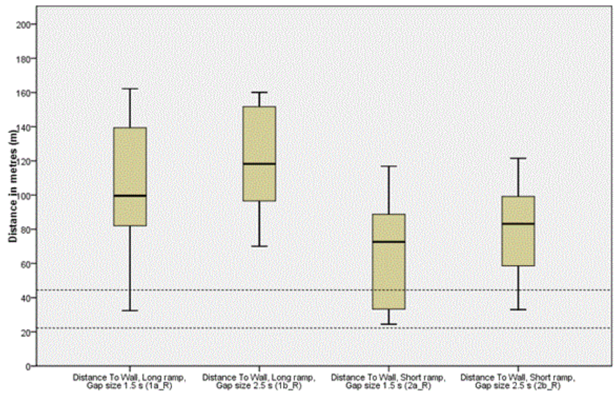

Figure 2: Distance-to-wall variable (m) at the time of merge-completion, divided by entry-ramp tunnel length and gap size. Boxplot diagram with median values and quartile distributions. Broken lines indicate 22.2 m and 44.4 m, i.e. 1 and 2 seconds of travel with 80 km/h, respectively.

Position-between-vehicles at merging

The position-between-vehicles (decimal notation) variable was analysed with a 2x2x2 repeated measures ANOVA. The within-subject

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independent variables were entry-ramp tunnel length (1.5 km and 0.5 km) and gap size (1.5 sec and 2.5 sec) and the between-subject independent variable was annual mileage (two groups; <15000 km and >15000 km). The analysis showed a significant main effect of gap size (F (1,18)=16.01, p <0.001, Eta squared=0.47 large effect size), but neither of ramp length (F (1,18)=1.401, p=0.25 n.s.) nor of annual mileage (F (1,18)=0.118, p=0.74 n.s.).

In Figure 3 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.

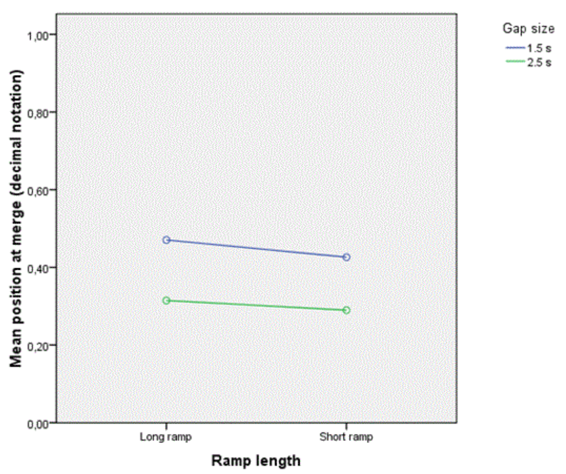

Figure 3: The mean position-between-vehicles (decimal notation) at merging, divided by entry-ramp tunnel length and gap size.

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

THW-behind

The time headway to the rearward vehicle (THW-behind) variable was analysed with a 2x2x2 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 sec and 2.5 sec) and the between-subject independent variable was annual mileage (two groups; <15000 km and >15000 km). The analysis showed a significant main effect of gap size (F (1,16)=355.95, p<0.001, Eta squared=0.96 which is large), but neither for the entry-ramp tunnel length (F (1,16)=1.533, p=0.23 n.s.) nor for annual mileage (F (1,16)=0.138, p=0.72 n.s.) were significant.

The results are shown in Figure 4. Outliers (i.e. ≥ 3 z-scores from the mean) are shown in Figure 4 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 4 indicate the median values as well as the quartile distributions for the THW-behind.

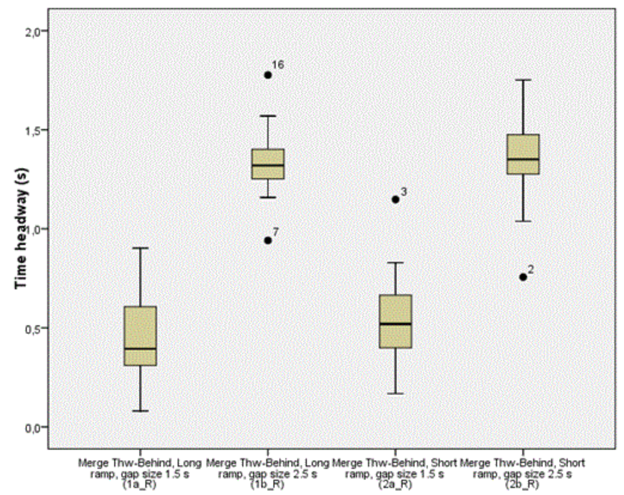

Figure 4: The time headway to the rearward vehicle (THW-behind) (s) at merging, divided by entry-ramp tunnel length and gap size. Boxplot diagram with median values and quartile distributions.

THW-forward

The time headway to the vehicle in front (THW-forward) variable was analysed with a 2x2x2 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 sec and 2.5 sec) and the between-subject independent variable was annual mileage (two groups; <15000 km and >15000 km). The analysis showed a significant main effect of gap size (F (1,15)=4.719, p <0.05, Eta squared=0.24 which is large), but neither of entry-ramp tunnel length (F (1,15)=0.61, p=0.81 n.s.) nor of annual mileage (F (1,17)=0, p=0.95 n.s.). There was also a significant interaction effect between entry-ramp tunnel length x gap size x mileage group (F (1,15)=4.568, p<0.05, Eta squared=0.23 which is a large effect size).

The results are shown in Figure 5. Outliers (i.e. ≥ 3 z-scores from the mean) are shown in Figure 5 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 5 indicate the median values as well as the quartile distributions for the THW-forward variable.

Speed at merging

No significant differences were found for the mean speed variable at the point of merging. The mean speed aggregated over all conditions was 21.53 m/s (SD=0.92) (or 77.5 km/h).

Speed for three different sections of the ramp

Speed was analysed with a 3x2x2x2 repeated measures ANOVA. The within-subject independent variables were section-on-ramp (construction nose before merging, at merging and at merging+25 m), ramp length (1.5 km and 0.5 km) and gap size (1.5 sec and 2.5 sec). The between-subject independent variable was annual mileage (two

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groups; <15000 km and >15000 km). The analysis showed a significant main effect of section-on-ramp (F (1.215,20.663)=5.855, p<0.05 Greenhouse-Geisser, Eta squared=0.26 large effect), but no effects of entry-ramp tunnel length (F (1,17)=4.145, p=0.058 n.s.), gap size (F (1,17)=0.2, p=0.66 n.s.) and annual mileage group (F (1,17)=3.557, p=0.077 n.s.).

There was a significant interaction effect between section-on-ramp and annual mileage group variables (F (2,34)=4.11, p<0.05, Eta squared=0.2 large effect). Figure 6 illustrates the interaction, i.e. the mean speed (m/s) in different ramp sections by section-on-ramp and annual mileage group. Entry-ramp tunnel length and gap size are aggregated in Figure 6. The speed of the traffic in the main tunnel was set at 80 km/h which is equivalent to 22.2 m/s.

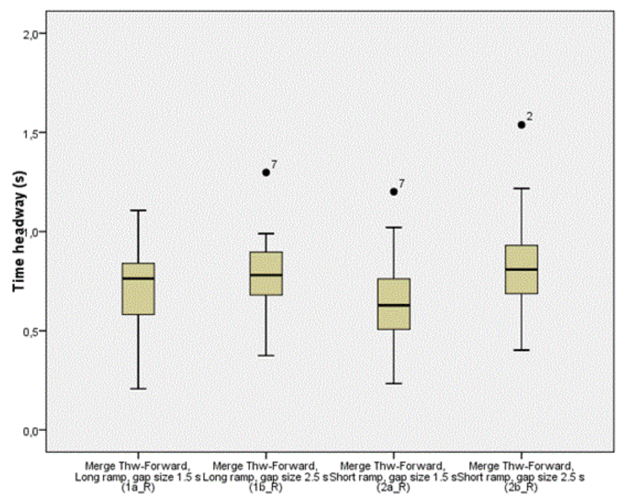

Figure 5: The time headway to the vehicle in front (THW-forward) (s) at merging, divided by entry-ramp tunnel length and gap size. Boxplot diagram with median values and quartile distributions.

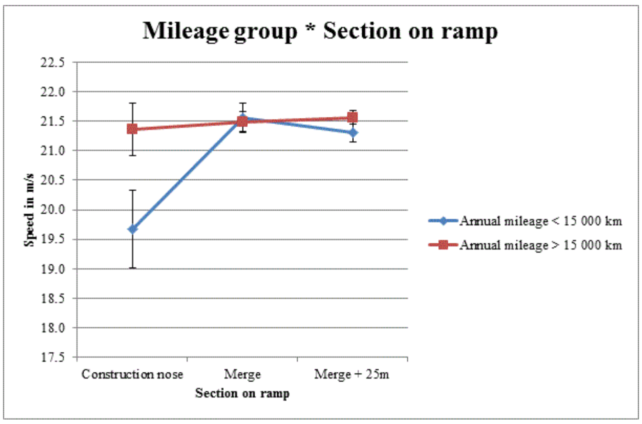

Figure 6: Speed (m/s) in three different merging zone sections on the ramp by mileage group and section-on-ramp. Means ± standard error bars.

Subjective rating scale

The mental demand dependent variable (CR10 rating) was analysed with a 2x2 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 sec and 2.5 sec). The analysis showed a significant main effect of gap size (F (1,20)=27.984, p<0.001, Eta squared=0.58 large effect size) but not of entry-ramp tunnel length (F (1,20)=1.236, p= 0.28 n.s.). 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 entry-ramp tunnel with the 1.5 sec gap size had a mean mental demand CR10 rating of 2.9 (SD=1.8). The short entry-ramp tunnel with the 2.5 sec gap size had a mean mental demand CR10 rating of 1.7 (SD=1.2).

The time pressure (temporal demand) dependent variable (CR10 rating) was analysed with a 2x2 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 sec and 2.5 sec). The analysis showed a significant main effect of gap size (F (1,20)=19.24, p< 0.001, Eta squared=0.49 large effect size) but not of entry-ramp tunnel length (F (1, 20)=1.264, p=0.27 n.s.). The long entry-ramp tunnel with the 1.5 s gap size had a mean temporal demand CR10 rating of 3.2 (SD=1.8). The long entry-ramp tunnel with the 2.5 s gap size had a mean temporal demand CR10 rating of 1.7 (SD=1.4). The short entry-ramp tunnel with the 1.5 sec gap size had a mean temporal demand CR10 rating of 3.6 (SD=2.6). The short entry-ramp tunnel with the 2.5 sec gap size had a mean temporal demand CR10 rating of 1.9 (SD =1.4).

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 sec and 2.5 sec). The analysis showed a significant main effect of gap size (F (1,20)=17.559, p<0.001, Eta squared=0.47 large effect size) but not of entry-ramp tunnel length (F (1,20)=0.114, p=0.74 n.s.). The long entry-ramp tunnel with the 1.5 sec gap size had a mean frustration CR10 rating of 3.0 (SD=2.0). The long entry-ramp tunnel with the 2.5 s gap size had a mean frustration CR10 rating of 1.6 (SD=1.1). The short entry-ramp tunnel with the 1.5 sec gap size had a mean frustration CR10 rating of 3.1 (SD=2.5). The short entry-ramp tunnel with the 2.5 sec gap size had a mean frustration CR10 rating of 1.6 (SD=1.2).

The perceived risk dependent variable (CR10 rating) was analysed with a 2x2 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 sec). The analysis showed a significant main effect of gap size (F (1, 20)=37.294, p <0.001, Eta squared=0.65 large effect size) but not of entry-ramp tunnel length (F (1,20)=0.185, p=0.67 n.s.). The long entry-ramp tunnel with the 1.5 s gap size had a mean perceived risk CR10 rating of 4.0 (SD=2.5). The long entry-ramp tunnel with the 2.5 s gap size had a mean perceived risk CR10 rating of 2.1 (SD=1.6). The short entry-ramp tunnel with the 1.5 s gap size had a mean perceived risk CR10 rating of 4.3 (SD=2.7). The short entry-ramp tunnel with the 2.5 s gap size had a mean perceived risk CR10 rating of 2.0 (SD=1.4).

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 and are found at the end (last 300 m) of each entry-ramp tunnel. For the Vinsta (0.5 km) entry-ramp tunnel 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 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 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 merging zone. 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 [13]. 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 merging zone. A distance of 93 m is roughly 4.2 s of travelling time at 80 km/h. This suggests that the Vinsta merging zone in particular, should be studied in more detail.

The results also suggest that drivers with more driving experience (>15000 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 (Figure 4 and Figure 5). 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 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) distinguish between the two ramp configurations (i.e. entry-ramp tunnel including 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 entry-ramp tunnels but did however suggest significantly increased levels of effort for the smaller gap size (1.5 s) on all four CR10 dimensions; mental demand, time pressure, frustration and perceived risk.

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.

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 [14].

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.

Conclusions

There are safety concerns relating to the design of the merging zones, in particular the Vinsta ramp tunnel comprising its merging zone. 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 merging zone. This 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 merging zone was considered to be the bare minimum in terms of safe driving and safe merging.

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