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Merging into heavy motorway traffic by young and elderly drivers

Dick de Waard, Chris Dijksterhuis, & Karel A. Brookhuis

1. Introduction

Due to increasing numbers of Heavy Goods Vehicles (HGVs) in the slow lanes of motorways the coming 20 years, merging into traffic will become more mentally demanding for passenger car drivers than at present (De Waard, Kruizinga, & Brookhuis, 2008). Increases in HGVs have been shown to coincide with increases in subjective mental effort and risk ratings. Another potential effect of a column of HGVs in the slow lane is that it might stimulate drivers to stay in the faster lane. This will potentially lead to reduced road capacity, and more missed exits, since columns of HGVs block the view on exit signs. The manoeuvre of lane changing from the fast lane to the slow lane with a column of HGVs is also more demanding compared with a slow lane filled with other passenger cars (De Waard et al., 2008).

Research on ramp-related crashes has been rather restricted. McCartt, Shabanova Northrup, and Retting (2004) studied this type of crash in Northern Virginia, USA, and found that 50% of the crashes occurred when at-fault drivers were leaving the highway, 36% when at-fault drivers were entering, and 16% when traffic was weaving. Running off the road was the most common exiting crash, rear-end or sideswipe was the most common entering crash. Exit crashes often occurred in bad weather, or at night, entering crashes often involved merging into the side of large trucks (McCartt et al., 2004). With a growing number of HGVs on the motorway this type of crash can be expected to increase.

In addition to the forecasted growth in number of HGVs, the proportion of elderly drivers will also increase the coming years (Waller, 1991, Wood, 2002). Not only will the number of elderly drivers increase, these drivers will also drive more miles, and continue to drive into old age. With increasing age visual functions and cognitive performance, such as divided attention performance decline (McGwin, Chapman, & Owsley, 2000, Wood, 2002), which contribute to increased crash involvement of elderly drivers (Shinar & Schieber, 1991, Lundberg, Hakamies-Blomqvist, Almkvist, & Johansson, 1998). Taking the two trends into consideration, increased mental workload in conditions of large numbers of HGVs and decreased cognitive functions for a group of traffic participants that increases in size, dangerous situations may arise when elderly drivers have to merge into motorway traffic. Elderly drivers usually compensate effectively, e.g., create more time (Brundell-Freij & Ericsson, 2005). This has been found in conditions when they have to turn left in a right hand driving countries (Brouwer & Ponds, 1994). However, this countermeasure, creating more time by slowing down, is not effective when they have to merge into traffic. On the contrary, it worsens problems as the speed difference between their speed and the speed of traffic on the main road may increase. Also reduced joint flexibility leading to reduced neck rotation, which is important during merging into traffic (Davidse, 2007), can cause problems for elderly drivers. Checking the blind spot when changing lane has been shown to be a common problem for the elderly driver (Kay, Bundy, Clemson, & Jolly, 2008). If the current trends continue as predicted it would be useful to know whether effective countermeasures are feasible. Countermeasures on two levels can be envisaged, infrastructural and in-vehicle. One infrastructural measure would be to provide more time to merge, e.g. an extended acceleration lane, also suggested by McCartt et al. (2004) to reduce sideswipe crashes. In-vehicle countermeasures include advanced driver assistance systems (ADAS), e.g., a blind spot detector that warns drivers when they overlook a vehicle next to them (e.g., Kiefer & Hankey, 2008). An alternative ADAS could be a system that takes care that the speed difference between the car that has to merge into traffic and the speed of traffic on the main road is as small as possible. In practice this would mean a system that encourages the car on the acceleration lane to accelerate. In contrast with an extended acceleration lane, short acceleration lanes (e.g. due to physical limitations) will create the largest problems related to merging into traffic if the slow lane is filled with HGVs. Finally, behaviour of other traffic on the acceleration lane can limit speed choice and deteriorate the lane change manoeuvre.

A simulator study was performed to evaluate the following hypotheses;

1. With increased proportions HGVs merging into traffic will require more mental effort, and safety margins will decrease
2. Merging into traffic is more demanding for elderly than for young drivers, safety margins are further decreased for elderly
3. Both an in-car support system and an extended acceleration lane will reduce mental workload during merging into heavy motorway traffic
4. Merging from a short acceleration lane is more demanding than from a standard acceleration lane, after merging from the short lane safety margins are further decreased
5. Merging with a slowly driving lead car is more demanding than without other traffic on the acceleration lane

2. Method

2.1 Participants

The intention was to include at least 32 participants, 16 younger drivers (25-40 years) and 16 elderly drivers (65 years or older). All drivers had to be experienced, i.e., hold a licence for at least five years and drive more than 5000 km/year. Participants were invited to the institute twice, the first time to give information and sign an informed consent after a test ride in the simulator. The second visit was for the real experiment that took about two hours. Participants received a financial compensation for their participation. Thirty-five participants completed the test ride during the first visit. Two elderly drivers preferred not to join in in the experiment due to mild feelings of nausea caused by simulator driving. In the end 17 young (13 men, 4 women, average age 29.5 years, SD 4.7, range 24-39) and 16 elderly drivers (14 men, 2 women, average age 70.3 years, SD 4.9, range 64-81) completed the experiment. Average mileage was 14 000 km/year for the young drivers, and 10 000 km/year for the elderly. The young drivers held their licence on average 10 years, the elderly 47 years.

2.2 Simulator

The driving simulator (figure 1) consisted of a vehicle mock-up with a functional steering wheel, indicators, and pedals. In the experiment the simulator car was equipped with an automatic gear. The simulator was surrounded by three frontal 32-inch diagonal LCD screens, and one additional screen on the left-hand side behind the participant, to enable the “look over the left shoulder” when merging. Each screen provided a 70° view, leading to a total 280° view. The driving simulation software was developed by ST Software©, and is capable of simulating fully interactive traffic.

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For the experiment a section of Dutch motorway was prepared, consisting of two 3.6 metre wide lanes and a hard shoulder of 3 metres. One acceleration lane and three exits provided entrance to and exit from the motorway. The acceleration lane and exits were each 300 metres in length. The distance between the entrance and the first exit, and between the consecutive exits, was 2 kilometres. Signage was according to Dutch motorway regulations, at respectively 1200 metres, 600 metres, 300 metres and 0 metres in advance of the exit. On the 1200, 600 and 0 metre signs, names of the exit destinations were displayed. On the 300 metre sign a long-distance destination of the motorway was displayed.

Each participant completed a total of 10 merge manoeuvres with varying traffic conditions, lead cars present or absent, different acceleration lane lengths, and the presence of a support system. Details on the different conditions are given in paragraph 2.3 to 2.5. In all conditions drivers started their ride on a road leading to the acceleration lane. They had to filter into traffic, and leave the motorway at a previously instructed exit. At the start of the acceleration lane the speed of traffic on the main road was coupled to the participant’s speed to take care that there was always a vehicle next to the participant’s car. For this reason HGVs sometimes were speeding. Other variables such as the variation between vehicles in time-headway was as observed in real traffic, average time-headway between vehicles was 2 seconds.

2.3 Acceleration lanes

Standard length of the acceleration lane was 300 metres, but the effects of an extended acceleration lane and a short acceleration lane were also evaluated. The extended lane was 450 m in length, the short lane was 150 metres.

2.4 ADAS

An Advanced Driver Assistance System (ADAS) was included that encouraged drivers to speed up if their speed was below a target speed. On the acceleration lane the target speed was set to 80 km/h at 400 m in advance of the point where the acceleration lane joined the motorway (the point from which in principle a lane change was possible), and set to 90 km/h at 100 metres in advance of that point. If drivers drove more slowly the vocal message “accelerate!” was issued. Per merge manoeuvre, the message could be issued maximum twice.

2.5 Lead car

The effect of a slowly driving lead car was tested in a condition where the lead car did not drive faster than 80 km/h. Behind the simulator car there was also a car, to induce a feeling of time pressure. At the start of the acceleration lane the road forked, the simulator car had to merge into the acceleration lane first and in that way the lead car drove in front of the participant in a natural way. After that point the acceleration lane joined the main motorway.

2.6 Instructions

Participants started each ride standing still. That lane joined another lane, merging into the acceleration lane that joined the motorway (see 2.5). Participants were instructed to drive to a destination that they had to read off the exit signs. They were also instructed that after joining the motorway they should, if traffic conditions allowed, go to the fast lane. This instruction was given to study the effects of the potentially blocked view on the exit signs.

2.7 Design

Each participant completed 10 rides. Each ride took about 4 minutes, depending on driving speed and the exit instruction. The following factors were manipulated:

a. Traffic on the motorway, three levels

- Passenger cars: Only private cars, relative high traffic volume of a total of 3600 vehicles/hour (1800 per lane), average speed 110 km/h (Standard Deviation, SD 9 km/h), average time-headway was 2 seconds on the right hand (merge) lane, and 3 seconds in the left hand (fast) lane.
- Mix: The at present common mix of HGVs and private cars, about 200-250 HGVs /hour all on the right hand (slow) lane, about 1500 private cars / hour. Average time-headway was 2 seconds. Target speeds were 80 km/h for HGVs, and 120 km/h for passenger cars. Passenger cars adapt their speed to HGVs if they cannot overtake.
- HGV Column: A column of HGVs, on average 950 HGVs/hour, all in the slow lane. Average speed was 80 km/h, SD 4 km/h, and average time-headway was 2 seconds. In addition to HGVs there were also private cars, mainly in the left hand lane.

b. ADAS, two levels

- Off: No support
- On: Messages to accelerate were only issued if the participant’s speed was below the target speed, else the system remained silent.

c. Acceleration lane, three levels

- Standard: 300 metres
- Extended: 450 metres
- Short: 150 metres

d. Time pressure, two levels

- Normal, no lead car, no following car
- High, slowly (maximum 80 km/h) driving lead car, following car

As not all factors could be manipulated separately and in combination, a selection was made (see Table 1). This resulted in a total of 10 trials per participant. A within-subjects design was used, the order of rides A-J was counterbalanced across the participants to control for order-effects. Ride K was fixed as an additional final ride for all, as here all problems were supposed to come together: a short acceleration lane, a column of HGVs, and a slowly driving lead car.

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The following main effects are studied (letters refer to the rides listed in Table 1):
- Effect of *Group* (Young vs. Elderly; Between-subjects factor)
- Effect of *Traffic* (A+B vs. C+D vs. E+F; Within-subjects factor)
- Effect of *ADAS* (A+C+E vs. B+D+F; Within-subjects factor)
- Effect of *acceleration lane* length (E vs. G, and E vs. H; Within-subjects factor)
- Effect of *time pressure* (E vs. J, ride G vs. K is not considered because of order effects, ride K was always the last ride)
- *Interaction* with Group is of interest for all above within-subjects effects.

Analysis of vehicle parameters and self-reports focussed on two manoeuvres, merging into traffic, and the lane change from the fast to the slow lane before exiting the motorway. Figure 2 displays these two manoeuvres, and defines the location where vehicle measures were assessed.

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2.8 Performance measures

During the trials, driving speed, time-headway, and lane position were sampled at 10 Hz and stored to disk. During manoeuvre ‘a’ (Figure 2), the average and SD of driving speed and lateral position were determined. Directly after merging (manoeuvre ‘b’), the minimum time-headway to the lead vehicle was determined in a time window of 5 seconds, as to assess how safety-critical the manoeuvre had been. After that, participants drove in the left hand lane until they spotted the instructed exit. From that point they were allowed to change to the slow lane to comfortably exit the motorway. The moment of merging back into the right hand lane (manoeuvre ‘d’) was stored as distance to the start of the exit ramp. Directly after that lane change, the minimum time-headway to lead cars was determined, again in a time window of 5 seconds (manoeuvre ‘d’).

2.9 Observed behaviour

During each trial the location where the participant merged was recorded; where on the acceleration lane the participant changed lane, and whether the participant merged in front or behind the vehicle on the main road (manoeuvre ‘b’). Whether the participant took the correct exit was also noted (manoeuvres ‘d’ and ‘e’).

2.10 ECG

The participant’s Electrocardiogram (ECG) was registered using three small Ag/AgCl electrodes that were attached to the chest. The R-peak in the ECG signal was detected with 1 ms accuracy, time-stamped, and stored to disk. Inter-beat-interval times were analysed, and the power spectrum of heart rate variation in the 0.10 Hz band were calculated by the programme CARSPAN (Mulder et al., 1995). Heart rate variability, in particular variability in the 0.10 Hz band, is suppressed during mental effort (e.g. Mulder et al., 2005). Heart rate was compared between conditions and with three-minute rest measurements that were completed both before and after the experiment. Power spectral data of the 0.10 Hz component were Ln-transformed to reduce inter-individual differences in range and to normalise the spectral data (Van Roon, 1998).

2.11 Questionnaires

After each trial a subjective rating on the unidimensional Rating Scale Mental Effort (RSME, Zijlstra, 1993) was requested, a separate rating for joining and for exiting traffic. The RSME is a unidimensional scale on which participants indicate how effortful it was to complete the task they just performed. The scale runs from zero ("No effort at all") to 150 ("Extremely effortful"). Ratings of experienced risk were asked on a similar continuous scale, again separately for joining the traffic and for merging out of traffic. Participants were asked to indicate "how risky joining [leaving] the motorway had been". This type of questionnaire has been used before by Heino (1996). Also, over each trial a rating of self-confidence was assessed on a continuous scale ranging from very insecure to very confident.
Acceptance of the ADAS was assessed with a standard acceptance scale (Van der Laan et al., 1997), before and after experience with the system.

2.12 Analyses

The data were analysed using the General Linear Model Repeated Measures test of SPSS. Repeated Measures MANOVAs were run on speed variables (average and SD of speed), lateral control variables (average and SD of the lateral position), and headway variables (minimum time-headway, see also Figure 2). ANOVAs were run on the continuous rating scale scores. Alpha was set to 5% for all tests.

Variables were evaluated on main effects of Group (between subjects) and Traffic (within subjects). For Traffic, two contrasts were used, the effect of the *increase in HGV* was evaluated by contrasting the '*Mix*' with the '*HGV Column*' condition, the effect of *HGV presence* was evaluated by contrasting the '*Passenger car*' condition with the two other Traffic conditions.

Effects of Countermeasures (ADAS, Extended lane) were evaluated as follows: for effects of ADAS the conditions B, D, and E were contrasted with conditions A, C, and D (Table 1). This was done in one analysis, together with the evaluation of the effect of Traffic.

The effect of the extended lane was evaluated separately, by contrasting the HGV Column condition (E) with the Extended lane condition (H in Table 1).

Effects of Critical Situations (short acceleration lane and slowly driving lead car) were evaluated similarly, by contrasting the baseline HGV Column condition (E) with respectively the short acceleration lane condition (G) and with the slowly driving lead car condition (J, see Table 1).

For all analyses SPSS for Windows version 14.0.2 was used.

3. Results

The effects of the different manipulations have been summarised in Table 2.

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Table 2 about here

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3.1 Main effects of group

The group of elderly drivers drove more slowly on the acceleration lane than the group of younger drivers (manoeuvre a in Figure 2, Multivariate analysis on speed & SD speed; Hotelling's T= 0.61, $p = 0.001$, $\eta^2 = 0.38$). On average the speed of the elderly drivers was 16 km/h lower (Figure 3). This effect remained after merging into traffic (manoeuvre b in

Figure 2, on average the elderly drove 13.8 km/h more slowly; Hotelling's T= 0.40, $p = 0.007$, $\eta^2 = 0.28$). SD Speed on the acceleration lane was larger for the elderly, on average 3.58 km/h opposed to 2.36 km/h for the young. After merging, this difference was reduced to 0.6 km/h, SD speed was respectively 4.88 and 4.28 km/h for the younger drivers.
Driving speed directly after changing lane to the slow lane before exiting the motorway (manoeuvre d) still differed between groups, but had been reduced to an average difference of 8.7 km/h.

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Figure 3 about here [speed]
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No difference between groups was found on the location of lane change, however, there was a difference on location of lane change before exiting (manoeuvre 'd'). It was found that elderly drivers returned to the right hand (slow) lane earlier than young drivers, on average 365 metres earlier ($F(1,31)=13.8$, $p = 0.001$, $\eta^2 = 0.31$).

Other main effects of group were found on self-reported effort, risk, and self-confidence. When asked to rate the merge manoeuvre elderly drivers, compared with the group young drivers, reported less mental effort on the RSME ($F(1,31)=6.66$, $p = 0.015$, $\eta^2 = 0.18$), less risk ($F(1,31)=5.08$, $p=0.031 \eta^2 = 0.14$), and there was a trend to report higher self-confidence ($F(1,31)=3.51$, $p=0.070$, $\eta^2 = 0.10$). The RSME results are depicted in figure 4.

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Figure 4 about here
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3.2 Effects of traffic –Merging into traffic

With more HGVs on the main road, average speed on the acceleration lane was lower. Both the presence of HGVs ($F(1,31)=16.0$, $p<0.001$, $\eta^2= 0.34$), and the increase from Mix to the HGV Column condition had a significant effect on speed ($F(1,31)=18.8$, $p<0.001$, $\eta^2= 0.38$). As the speed of the participant's car was linked to the vehicle on the main road, driving speed was relatively high, also in the HGV Column condition (see figure 3). The speed difference between conditions remained intact after merging into traffic (manoeuvre 'b', HGV presence: $F(1,31)=17.5$, $p<0.001$, $\eta^2= 0.36$ and HGV increase: $F(1,31)=25.3$, $p<0.001$, $\eta^2= 0.45$).

Average lateral position on the acceleration lane shifted towards the edge as a result of HGV increase ($F(1,31)=4.64$, $p=0.039$, $\eta^2= 0.13$). The interaction effect with group is significant ($F(1,31)=7.49$, $p=0.010$, $\eta^2= 0.20$); the effect is predominantly present in the group elderly drivers.

Minimum time headway directly after merging was reduced both as a result of the presence ($F(1,31)=8.73$, $p=0.006$, $\eta^2= 0.22$) and as a result of an increase in HGVs ($F(1,31)=46.95$, $p<0.001$, $\eta^2= 0.60$). From figure 5 it becomes clear that in all conditions with a column of HGVs the average minimum time headway became dangerously small, around 0.5 s.

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Figure 5 about here

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As it matters whether one changes lane behind or in front of a HGV, this division has been analysed. During all rides the simulator car drove at the start of the acceleration lane next to a vehicle on the main road. Over all conditions, the group of young drivers merged slightly more frequently into traffic in front of the vehicle on the main road (57.6%) compared with the elderly (54.4%). In the three traffic conditions these percentages were respectively 90.8 % (passenger cars only), 87.9 % (Mix of traffic), and 63.7 % changed lane in front of the HGV in the HGV Column condition. When time headway is further explored in the latter condition, where participants differed in behaviour, no differences were found between drivers merging in front or behind the HGV (on average 0.50 s. time headway in front versus 0.55 s. behind). The location where drivers left the acceleration lane and moved to the main road did not differ between the three traffic conditions, on average they changed lane 181 metres after the start of the 300 metre long acceleration lane.

In figure 4 self-reported mental effort is shown. The increase coinciding with an increase in HGVs over the first three conditions is clearly visible (HGV presence ($F(1,31)=11.95$, $p=0.002$, $\eta^2= 0.28$, HGV increase ($F(1,31)=9.62$, $p=0.004$, $\eta^2= 0.24$).

3.2 Countermeasures, effect of an ADAS

A total of 21 messages to accelerate were issued over the 99 rides where the ADAS system was switched on, i.e. in 21.2 % of the rides. In the rest of the ADAS rides the system remained silent because participants drove above minimum threshold speed. As expected, elderly drivers received most messages: in total in 39.6% of the rides, opposed to only 3.9% of the rides of the young participants. In the HGV Column condition 50% of the elderly drivers were urged to speed up, in the Mix condition this was the case in 25% of the rides, and in the passenger car condition in 43.8%. For the young participants these percentages were respectively 5.9, 5.9, and 0%. Most drivers received the message only once, evenly spread between 400 and 100 metres before the acceleration lane joined the main road. In only two rides the driver received the message at both locations.

In sum, elderly drivers 19 times received the ADAS message, during two rides young drivers received the message. In the analyses the ADAS condition was taken as it was, i.e. independent of whether a message was issued performance was compared with the baseline rides (rides A, C, E).

A main effect of condition was found on speed, sd speed, location of merging into traffic, and reported self-confidence. Speed was on average 5.5 km/h higher in the ADAS conditions ($F(1,31)=7.01$, $p = 0.013$, $\eta^2=0.18$, see also figure 3 for the HGV Column condition), SD speed was also higher in the ADAS condition (on average +0.7 km/h,

$F(1,31)=5.43$, $p = 0.026$, $\eta^2=0.15$). Location of lane change was 24 metres later for the group elderly who most frequently received messages, and increased with 4 metres for the young who hardly ever received a message ($F(1,31)=4.55$, $p = 0.041$, $\eta^2=0.13$). Self-reported confidence decreased with 4.3 scale points (scale range 0-100) in the ADAS condition ($F(1,31)=5.53$, $p = 0.025$, $\eta^2=0.15$).
Post-hoc data of rides with and without messages were separately analysed. Difference scores of ADAS rides with and without messages, compared with the baseline rides were calculated. Rides without messages could be considered a repetition (r) of the baseline rides, rides with messages were experimental rides (e). Differences over rides A,C, E vs. B, D, F, were as follows: Speed (r) +4.5 km/h, (e) +9.1 km/h; SD Speed (r) +1.5 km/h, (e) +0.5 km/h; Location lane change (r) +33.5 m, (e) +8 m. Thus, overall effects were much stronger in the conditions with an actual message.

3.3 Countermeasures, effect of an extended acceleration lane

The extended acceleration lane had as result a higher speed when merging (+ 12 km/h, $F(1,31)=4.13$, $p = 0.051$, $\eta^2=0.12$, see also figure 3). Drivers also merged later, the location was on average 43 metres further on the acceleration lane ($F(1,31)=8.31$, $p = 0.007$, $\eta^2=0.22$).
In the condition of the extended acceleration lane drivers also merged more frequently in front of the HGV. In the baseline condition 29% of the young and 38% of the elderly drivers merged in front of the HGV, in the extended acceleration lane these percentages increased to 71% and 56 % respectively. Thus, more drivers, but in particular more young drivers changed lane in front of the HGV in this condition.

3.4 Critical situations, effect of a short acceleration lane

The short acceleration lane obviously had an effect on location of lane change, the lane was 150 metres and drivers changed lane on average 50 metres earlier compared with the baseline. None continued on the emergency lane (hard shoulder).

Speed on the acceleration lane and time headway after merging did not differ significantly from the baseline condition ($F(1,31)<1$, NS for both).
There was an effect of position on the acceleration lane, in the short acceleration lane drivers drove more in the centre of the lane compared to driving to the right of the centre in the baseline condition ($F(1,31)=8.81$, $p = 0.006$, $\eta^2=0.22$).
In the baseline condition 29% of the young and 38% of the elderly drivers merged in front of the HGV, in the short acceleration lane this percentage remained the same for the young drivers, but decreased to 19% for the elderly drivers.

3.5 Critical situations, effect of a slowly driving lead vehicle

The slowly driving lead car restricted driving speed, which was lower in this condition. Again elderly drivers drove more slowly (see figure 3). Drivers also changed lane much earlier (after 62 metres compared to 156 metres in the baseline condition, $F(1,31)=5.21$, $p = 0.029$, $\eta^2=0.14$), this is even earlier than in the short acceleration lane condition (115 metres).
Mean lateral position in the acceleration lane was more in the centre of the lane than in the baseline condition ($F(1,31)=11.8$, $p = 0.002$, $\eta^2=0.28$). Swerving behaviour (SDLP), which could reflect impatience, was not affected.

3.6 Critical situations; short acceleration lane and a slowly driving lead vehicle

No statistical analyses were performed on this condition, as it was always the final condition participants drove. Purpose was to bring critical elements together, both a short lane, and an annoying slow lead car. Lateral position in the acceleration lane shifted to the left hand side of the lane, and drivers changed lane very early (after 42 metres).

3.7 Exiting the motorway

For exiting the motorway, only the three traffic conditions were of interest. Average speed directly after the lane change (from the fast to the slow lane) was affected by these

conditions. Highest speed (91.5 km/h) was registered in the passenger cars only condition, followed by the Mix (89.9 km/h) and HGV Column (70.3 km/h) conditions (effect HGV presence: $F(1,31)=30.4$, $p < 0.001$, $\eta^2=0.49$, effect increase in HGVs: $F(1,31)=56.2$, $p < 0.001$, $\eta^2=0.64$). Elderly drivers drove on average 8.7 km/h slower (Hotellings' T =0.41, $p = 0.006$, $\eta^2=0.29$). Safety margins as reflected by minimal time headway were –remarkably– lowest in the passenger car condition (0.61 s), followed by the HGV Column condition (0.85 s). Largest average minimum time headway was for the Mix condition, 1.2 seconds (effect HGV presence: $F(1,31)=41.9$, $p < 0.001$, $\eta^2=0.58$, effect increase in HGVs: $F(1,31)=8.3$, $p = 0.007$, $\eta^2=0.21$).
Location of lane change was on average 365 metres earlier for the elderly drivers, they returned on average 944 metres before the exit to the slow lane, opposed to 578 metres for the young participants ($F(1,31)=13.8$, $p = 0.001$, $\eta^2=0.31$). The presence of HGVs also slightly, 70 metres, but significantly, $F(1,31)=4.3$, $p = 0.046$, $\eta^2=0.12$), advanced the lane change.
Not many exits were missed, of the in total 330 rides, 8 were missed (2.4 % of the rides). Seven out of these eight times the condition contained HGV Columns (67% of all rides contained a HGV Column). No differences between the two groups participants were found.
Self reported mental effort on the RSME was higher both as a result of HGV presence ($F(1,31)=12.0$, $p = 0.002$, $\eta^2=0.28$), and an increase in HGVs ($F(1,31)=9.6$, $p = 0.004$, $\eta^2=0.24$). Average values were 17 for the Passenger Car condition, 18 for the Mix condition, and 27 for the HGV Column condition. Elderly drivers again rated invested effort lower than the young drivers ($F(1,31)=6.7$, $p = 0.015$, $\eta^2=0.18$). There was also a significant effect of critical condition involving the lead car ($F(1,31)=6.2$, $p = 0.019$, $\eta^2=0.16$), which is likely a result of chance as the presence of a lead car was only manipulated during merging into traffic. Risk ratings showed a similar pattern as mental effort ratings.

All main effects on vehicle and self-report measures are listed in Table 2.

3.8 Psychophysiology

Heart rate analyses focussed on merging into traffic, and on exiting, i.e., the lane change from the fast to the slow lane preceding exiting. The moment of the lane changes can be seen in Figure 6. Top part of the figure depicts heart rate, which increases around the lane change manoeuvres, bottom part shows heart rate variability (HRV) in the 0.10 Hz band, a decrease here denotes increased mental effort. HRV is suppressed for the young drivers, but is not as one would expect for the elderly. In particular the low variability during before and after rest measurements is remarkable.
Between the different conditions no significant effects were found.

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Figure 6 about here
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3.9 Hand positions on the steering wheel

As a separate study hand positions on the steering wheel as a measure of perceived risk were evaluated. Results show minimal differences between conditions, although hand positions did shift to locations on the steering wheel where drivers can exert more control in the more demanding conditions, such as the merging into traffic manoeuvre. For details, see De Waard & Van den Bold (submitted).

3.10 Acceptance ADAS

Before and after experience, acceptance of the ADAS was assessed on an acceptance scale that loads on two dimensions, a usefulness dimension and an affective satisfying dimension. Before and after experience measurements allow for the evaluation of expectations. For the after measurement only participants who actually had received messages were included, i.e. two young drivers and eight elderly. The before measurement is based on the evaluation of 17 young and 15 elderly drivers (one elderly driver did not complete the form).

All expected a somewhat useful system (score +0.5 on a scale from -2 to +2), the satisfaction score was different, young drivers were neutral / slightly negative (-0.15), the elderly slightly positive (+0.35). Young drivers who had experienced the issued warning had a more negative score (-0.2 on usefulness, -0.6 on satisfying), elderly were more positive after this experience (+1.1 on usefulness, +0.5 on satisfying).

4. Discussion and conclusions

The effects on increases in HGVs on merging in and leaving motorway traffic were studied in a driving simulator. Critical situations, in particular problems elderly drivers may encounter, and potential solutions were studied. Differences between the two age groups were restricted, although some effects were found, in particular on driving speed: elderly drivers merged at lower speed. Countermeasures, such as an extended acceleration lane were found to have a positive effect on safety margins.

With regard to the formulated hypotheses, the following can be concluded:

1. With increased proportions HGVs merging into traffic will require more mental effort, and safety margins will decrease

Ratings of invested effort on the RSME indicate that an increase in HGVs coincides with increased mental effort. Safety margins, as reflected by minimal time headway decreased. However, the overload as suspected in the previous study (De Waard et al, 2008), was not found in heart rate variability results, nor in vehicle parameters.

2. Merging into traffic is more demanding for elderly than for young drivers, safety margins are further decreased for elderly

Elderly drivers merge at lower speed, potentially making the merge manoeuvre more difficult. As driving speed of the HGVs on the main road was coupled to driving speed of the participant, problems as a result of this have not become clear in the present experiment. It has been a tactical decision to couple the speed of the two vehicles, as only in this way the HGV would always drive next to the participant at the start of the acceleration lane. If the speed reduction of the elderly was a tactical compensational response as has been found in other fields (e.g., take more time when turning left in a right hand driving countries, Brouwer & Ponds, 1994, Brundell-Freij & Ericsson, 2005), then it could worsen problems as the speed difference between their speed and speed of traffic on the main road may increase.

Increased mental effort was not reflected in the self-reports. It was remarkable to find that the group of elderly drivers rated effort lower, self confidence higher, and experienced risk lower than the young drivers. It has been reported that elderly drivers overestimate their driving skills compared with young drivers (Groeger & Brown, 1989), even if there are indications of increased driving errors (Freund et al., 2005). It could also be that elderly drivers did not judge the situation to be loading, as they 'demanded' other road users to adapt their behaviour to them. Physiology unfortunately did not give much more information, the low variability during rest is remarkable and difficult to explain. However, the blood vessels of elderly are less flexible and physiological reactions change (see e.g. Uchino et al., 2005). As a consequence, vehicle parameters and observed behaviour should receive relatively more value.

Finally, there were no indications that minimum time-headways of the elderly driver were more critical than for the young drivers, although low values (high risk) were measured in the HGV conditions compared with the passenger car condition for both groups. From previous research (De Waard et al., 1997) it became clear that absolute values measured in the simulator cannot be transposed to real world absolute driving behaviour, but relative changes can be. So the lower minimum time headway values found in the HGV conditions also reflect lower time headway values in the real world. Moreover, in the real world also low minimum time headway values are found; according to the ministry of transport (Rijkswaterstaat, 2006) in 2005 10% of the time headways measured on motorways were below 0.5 s, and 27% was between 0.5-1.0 s.

3. Both an in-car support system and an extended acceleration lane will reduce mental workload during merging into heavy motorway traffic

It can be concluded that the extended acceleration lane had positive effects. Drivers merged later into traffic, and at higher speed. Minimum time headway after merging was also higher.

Although the ADAS messages increased driving speed, and drivers merged later into the main road traffic, the present ADAS was too simplistic. A simple criterion such as a minimum driving speed does not take the traffic situation on the main road into account. It was observed that sometimes drivers drove below the threshold speed, and accelerated after the message, which made the merge manoeuvre more critical. For instance, drivers were only just able to merge in front of a HGV. In those conditions driving more slowly and merging behind the HGV might have been a safer solution. Future ADAS should take the traffic on the main road into account. Even though self-confidence was lower in the ADAS conditions, the opinion about the ADAS of the elderly who had experienced messages was positive, which makes it a feasible aid for the future.

4. Merging into traffic from a short acceleration lane is more demanding than from a standard acceleration lane, after merging from the short lane safety margins are further decreased

Effects of the short acceleration lane were limited. Drivers did change lane earlier, but this was not experienced as more effortful, or more risky.

5. Merging into traffic with a slowly driving lead car is more demanding than without other traffic on the acceleration lane

Again effects were limited. Driving speed was restricted and thus drivers merged at slower speed. Lateral position on the lane was more towards the centre, as if the drivers tried to get a better view on traffic ahead.

Exiting traffic was in general without problems, only a few times, in 2 % of the rides that contained a HGV, the exit was missed due to HGVs blocking the view on the exit signs. Still, the lane change manoeuvre was experienced as more effortful if many HGVs were driving in the slow lane. This was also visible in the driver's physiology.

In this experiment experienced elderly drivers participated. Langford et al. (2006) showed that in particular elderly drivers who do not drive a lot (< 3000 km/year) have a higher crash incidence. This means that for those drivers merging into motorway traffic with a large proportion of HGVs may be more demanding. In real traffic the driving speed of traffic on the main road is not coupled to the car that wants to merge. This also may contribute to more critical situations, as differences in driving speed are the largest threat to safety (e.g., Garber & Gadirau, 1988). The effects of older age were restricted in this study, which is hopeful in an ageing society. However, future studies should take driving experience and speed differences between traffic streams into account, to find out if results hold under those conditions. A more advanced support system that considers average speed on the main road should also be considered, as driver's attitude towards these support devices is positive.

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Table Captions

Table 1. Conditions (10 rides) in the experiment

Table 2. Effects (all statistically significant).

Figure 1. The driving simulator used in the study.

Figure 2. The manoeuvres selected for analysis. In the images only the "*HGV Column condition*" is depicted, with HGVs (large rectangle), private cars (smaller recktangles), and the simulator car (red filled rectangle). Manoeuvres a, b, and c are performed during merging into traffic, manoeuvres d and e before and during the exit. A plus in the lower part indicates which measure was selected and analysed during the manoeuvres. SD = Standard Deviation

Figure 3. Average speed (and Standard Error, SE, as error bars) during manoeuvre a (figure 1) in the different conditions. Passenger cars = Only private cars on the motorway, Mix = present mix of HGV (Heavy Goods Vehicles) and private cars, an HGV next to simulator car when on the acceleration lane, HGV Column (Baseline) = a column of HGVs on the motorway, a HGV next to the simulator car when on the acceleration lane. HGV Column is Baseline as this condition is compared with other conditions with a HGV Column on the main road: ADAS (a support system), Extended lane (a longer than standard acceleration lane), Short Lane (a shorter than standard acceleration lane), and Lead car (a slowly driving lead car).

Figure 4. Average score on the Rating Scale Mental Effort (Zijlstra, 1993) for joining the traffic. The scale has a range from 0 to 150. A rating of 12 coincides with the investment of "hardly any effort", 28 = "a little effort", 38 = "some effort", 58 = "rather much effort", 112 = "extreme effort". Passenger cars = Only private cars on the motorway, Mix = a mix of HGV and private cars, HGV Column = a column of HGVs on the motorway.

Figure 5. Average minimum THW on the right hand lane of the motorway directly after merging

Figure 6. Top figure: average heart rate in beats/minute (bpm) during the before and after rest period (each 3 minutes), and during *joining* and *exiting from* traffic. All points are each based on 30 seconds of ECG data, the step size between separate points is 10 seconds. The plus symbol indicates the moment of lane change. Bottom figure: average heart rate variability in the 0.10 Hz band (normalised by Ln-transform). Data from all conditions were averaged.

Table 1. Conditions (10 rides) in the experiment

Ride	Traffic	ADAS	Length Acceleration lane	Lead and following car
A	Only passenger cars	No	Standard	No
B	Only passenger cars	Yes	Standard	No
C	Mix ("present situation")	No	Standard	No
D	Mix ("present situation")	Yes	Standard	No
E	HGV Column	No	Standard	No
F	HGV Column	Yes	Standard	No
G	HGV Column	No	Short	No
H	HGV Column	No	Extended	No
J	HGV Column	No	Standard	Yes
K	HGV Column	No	Short	Yes

Table 2

Table 2. Effects (all statistically significant).

Variable	Effect of Group(Age = Elderly)	Traffic		ADAS	Acceleration Lane		Time Pressure
Main Effects		HGV Present	HGV increase		Extended	Short	
on acceleration lane							
Average Speed	↓	↓	↓	↑	↑		↓
SD Speed				↑			↑
Average Lat. Position[1]			→			←	←
SDLP							
Location Lane Change[2]				→	→	←	←
RSME (Effort rating)	↓	↑	↑				
Risk rating	↓	↑	↑[3]				
Self-confidence	↑[3]	↓	↓	↓			
directly after filtering in							
Average Speed	↓	↓	↓				↓
SD Speed		↑					
Minimum time headway		↓	↓				
exiting traffic							
Average Speed	↓	↓	↓				
SD Speed							
Minimum time headway		↑	↓				
Location Lane Change[2]	←	→					
RSME (Effort)	↓	↑	↑				
Risk rating		↑[3]	↑				[↑]

[1]: → = more to the right (lane edge), ← = more to the left

[2]: → = later, ← = earlier

[3]: trend ($\alpha < 0.10$)

Figure 1
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Figure 2

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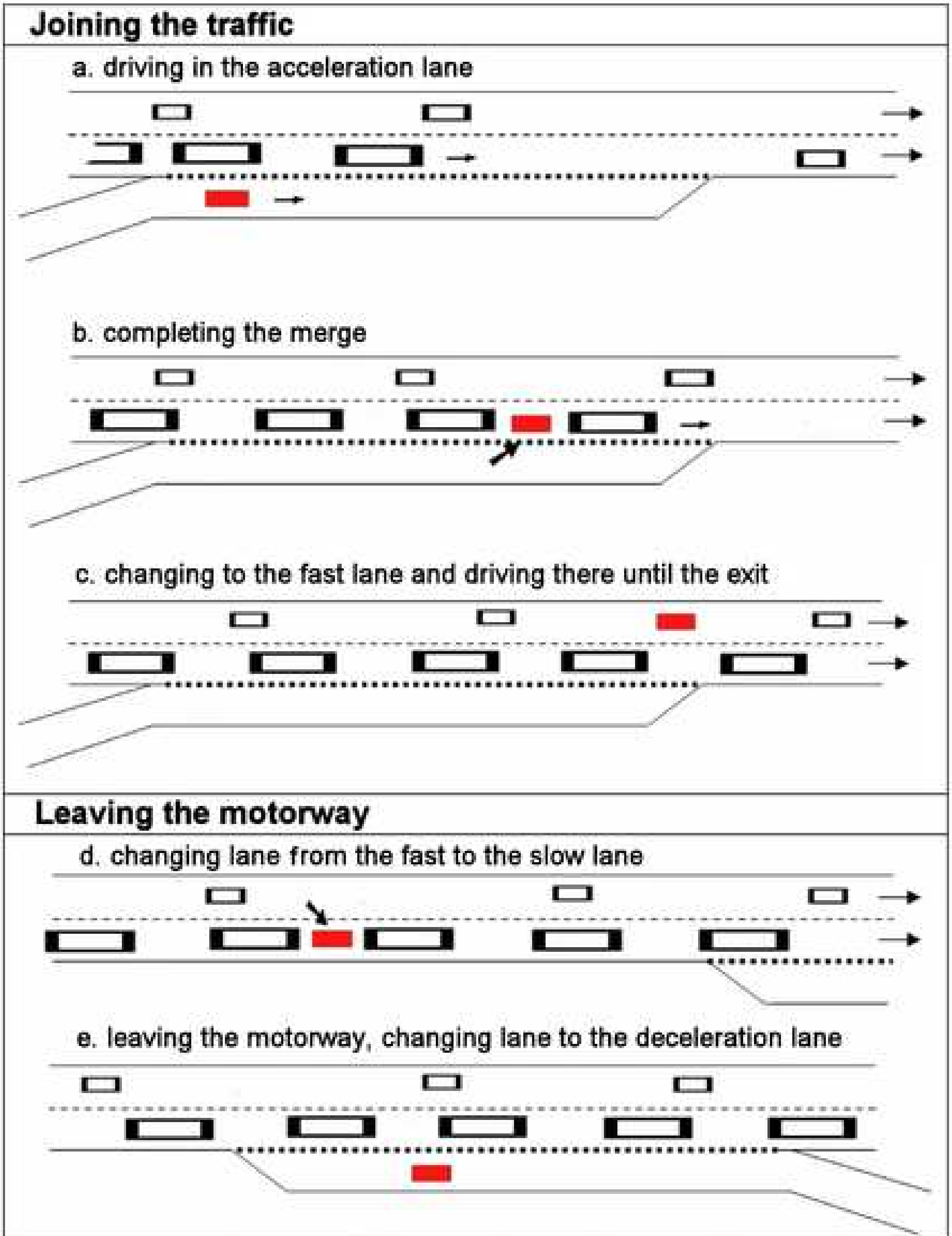

Measure \ manoeuvre	a.	b.	c.	d.	e.
Average speed	+	+		+	
SD speed	+	+		+	
Average lateral position	+				
SD lateral position	+				
Minimum time-headway		+		+	
Location lane change		+		+	

Figure 3
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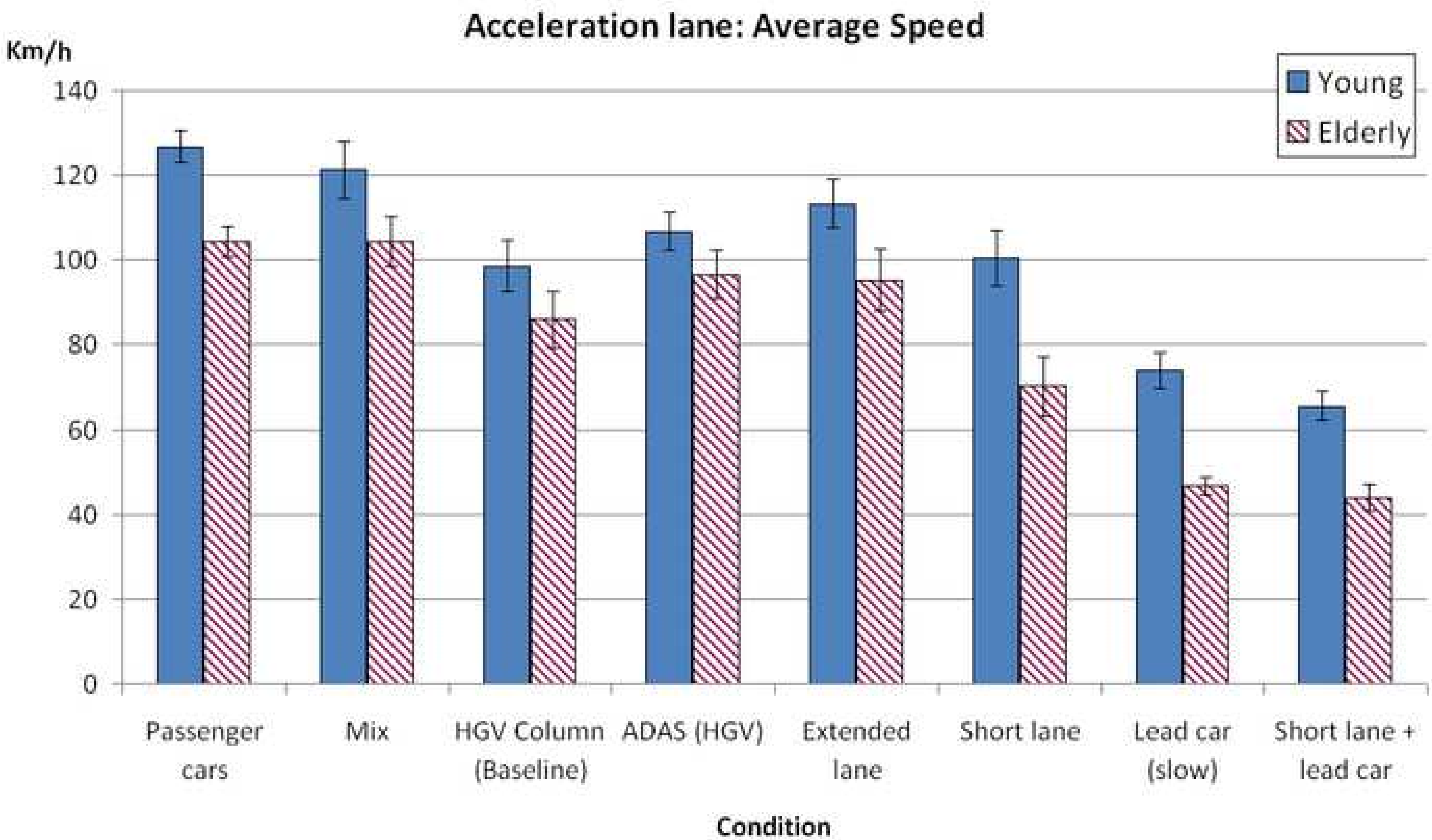

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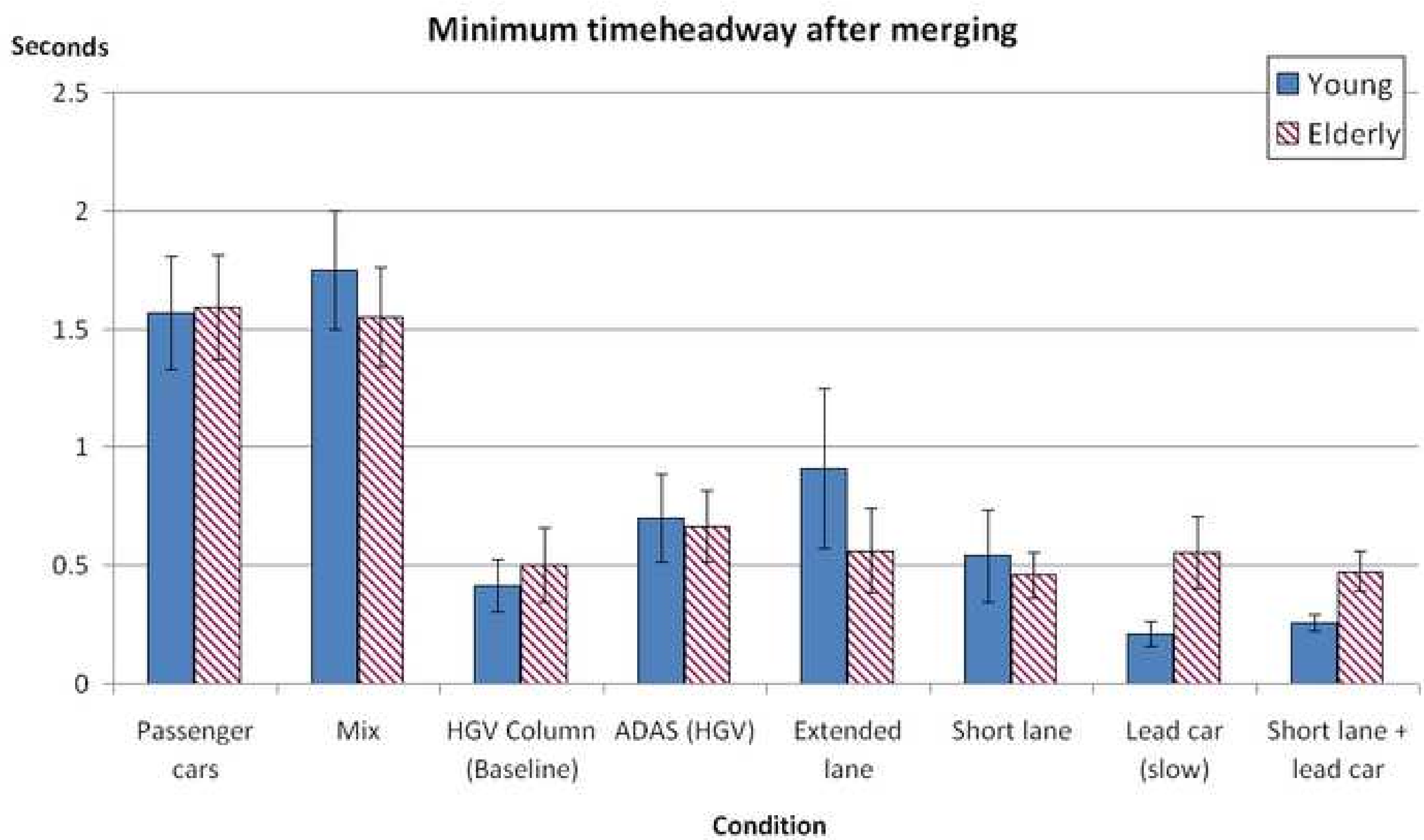

Figure 6
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