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Standard freeway merge designs support safer driver behaviour compared to taper designs: A driving simulator study

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Road geometric design standards provide various possibilities for merging freeways with a decreasing number of lanes. In this study, an alternative design (i.e. taper design) is investigated and compared with the standard design under three different heavy vehicle compositions to understand driving performance in relation to the flow of traffic. Taper design is not always the first choice in the road geometric design guidelines and the designer has to provide arguments for selecting this design. Taper design and its comparison with other alternatives are also not well explored in literature. In this study, a driving simulator was used to examine and compare the performance of these two designs under different heavy vehicle compositions. Qualitative results showed that the perceived safety was better for the standard design compared to the taper design. Mean speed, acceleration, standard deviation of acceleration/deceleration, and cumulative lane changes were chosen as behavioural parameters to compare these two designs using MANOVA and repeated measures ANOVA. Results revealed that drivers' discomfort in performing merging manoeuvres was greatest in case of a taper design and when the percentage of heavy vehicles was moderate (15%). Overall, the standard design was found to be more favourable.

Keywords: Merging of freeways, taper design, heavy vehicles, vehicle compositions, driving behaviour, driving simulator

Practitioner Summary:

Driving behaviour at merging freeways with a decreasing number of lanes is underexplored. We analysed safety in driving behaviour considering heavy vehicles for taper and standard designs provided in Dutch guidelines using a driving simulator. The standard design was found to be safer and the presence of moderate heavy vehicles caused more disturbances in driving behaviour.

Introduction:

Freeways provide a free flow of traffic at higher speeds. The merging of freeways, hence, has to be designed in such a way that its impact on the traffic flow is minimal. The principles underlying the safe design of road elements are widely accepted and often they are translated by local road authorities into custom road design standards e.g. PIARC (2012). As a result, different design solutions arise for the same design problem. Merging freeways at a very small angle can be carried out either with the same number of lanes or with a decreasing number of lanes. Dutch standards provide various designs to merge freeways with a decreasing number of lanes as shown in Figure 1 (ROA 2017). The preferable method is to reduce the number of lanes either on the left side or the right side of the freeway before the merging point. Lane reduction at the right side of the freeway has an extra advantage as heavy vehicles on the main freeway only have to change one lane in order to drive in the rightmost lane. This will cause less disturbance in the traffic stream of the right lane as one lane of the merging freeway is dropped before the lane reduction. The taper design is another method to merge freeways in the same manner. According to Ruyter's study (Ruyter 2016), there are more than 10 sites where a taper design is built in the Netherlands. However, the constructed taper design dimensions are not in line with those provided in the Dutch guidelines. The standards provide a complete taper design with respect to the design speed. However, the taper design is not preferred in the Dutch guidelines and appropriate reasons have to be provided by the designer in order to justify the use of taper design. The Dutch guidelines, however, do not specify reasons for the non-preference of taper design. Furthermore, literature comparing the performance of such designs is scarce. In this study, a comparison is made between the two standard Dutch designs to find out which design facilitates safe driving behaviour under the given traffic conditions. Similarly, American Association of State Highway and Transportation Officials (AASHTO) standards provide two types of acceleration lane designs for freeway merging points. They are discussed here because of similar manoeuvring operations. These acceleration lanes are designated as parallel and taper. AASHTO standards also prefer the parallel design. A detailed reasoning for this preference of parallel design is also not provided in the AASHTO guidelines (AASHTO 2011).

According to the concept of sustainable safety, the entire system and infrastructure is designed considering the road user as the focus. In this way, road safety is a responsibility shared by all stakeholders (such as designer, road authorities, police, road users, etc.). Three key concepts of functionality, homogeneity and predictability are included in the sustainable safety concept. Functionality is described as the similarity between the actual and intended use of the facility. Homogeneity refers to the similarities in speed, direction, and the type of road user. Predictability is defined as a road design that road users can understand more easily and where they can easily recognize what kind of driving behaviour is required (Wegman et al. 2005). The concept of self-explaining roads advises that road designs must be simple and easy to understand in order to evoke the correct behaviour from road users (Herrstedt 2006). In essence, these principles suggest that human driving behaviour should be examined while evaluating road design (NHTSA 2015).

The driving simulator study examined in this paper would also help to understand about the degree to which standard and taper designs follow the principles of sustainability and self-explaining roads, especially in relation to evoking the correct driving behaviour from drivers.

Two road designs (standard (Figure 1a) and taper (Figure 1d)) with the same intensity to capacity (I/C) ratio were created in the driving simulator. The designs were compared with each other to find out which design can better accommodate drivers' behaviour. This was tested by means of a number of human behaviour parameters. In this study, mean speed, acceleration, standard deviation of acceleration/deceleration and lateral position are considered as safety indicators of human driving behaviour. A driving simulator was used to collect data for the above-mentioned parameters as it is a safe, effective, efficient and economical approach to conduct such research. Furthermore, it was hypothesized that changes in the number of heavy vehicles may influence human driving behaviour in the vicinity of the merging section. Heavy vehicles have been known to have an impact on the traffic stream due to their size, slow lane changing manoeuvres, low speed and acceleration/deceleration (Moridpour, Mazloumi, and Mesbah 2015). Results also showed that an increase in the percentage of heavy vehicles of up to 30% can increase the probability of crash occurrence by up to 5%. To study the effects of heavy traffic on drivers' behaviour, three different heavy vehicle percentages, i.e. less, moderate and high (0, 15 and 30%) were applied on both main and merging freeways.

Merging freeway designs and their safety:

The AASHTO guidelines (AASHTO 2011) do not provide design guidelines for merging two freeways with a decreasing number of lanes. However, they provide the design of acceleration lanes as parallel and taper. Furthermore, it is mentioned in the guidelines that parallel designs should be preferred over taper designs as they are considered safer by several road agencies in the US. The AASHTO (2011) and also Dutch standards do not provide any detailed explanation and reasoning of this preference. The Dutch standards (ROA 2017) provide designs for the merging of two freeways which are called standard and taper designs. These can be seen in Figure 1. Among the four designs shown in Figure 1, three designs i.e. Figure 1(a), 1(b) and 1(c) are referred to as 'standard designs', where merging is done by reducing the number of lanes either downstream or upstream of the nose point. The fourth design (Figure 1(d)) is the taper design where merging and lane reduction take place simultaneously. The Dutch standards also specify that the standard design should be preferred over the taper design as it is safer. However, the underlying reason is not provided in detail. A potential reason for the taper design to still be used under certain circumstances is that it requires less space. Hence, if there is a lack of available space, the taper design can be used (ROA 2017).

Various studies have been conducted to study driver behaviour when merging onto freeways. However, studies investigating the safety of taper designs are limited and in terms of a comparative analysis of the taper design with the standard design, only a single study from Ruyter (2016) is found after a detailed literature search. Ruyter (2016) conducted a driving simulator study in which a taper design was compared with a design in which a lane reduction takes place on the left, downstream of the merging point. The results of the comparison were non-significant and, therefore, it was concluded that both designs were safe. However, it was found that the taper length had a positive effect and heavy traffic had a negative effect on road safety. Road safety was measured through the examination of speed, acceleration/deceleration, lane changing and time-to-collision profiles over the length of the analysed section of the road.

In human factor guidelines (Woodson, Tillman, and Tillman 1992), the merging task on a freeway entrance ramp is divided into various subtasks. These tasks are separated across the given lengths of the ramp and the acceleration lane. For the Dutch preferred design (called standard design in this paper: Figure 1a), the merging task can be divided as follows: lane changing upstream of the lane reduction, finding a suitable gap, adjusting speed by accelerating/decelerating, accelerating to match the speed with that of the traffic stream on the main freeway and then merging into the traffic stream on the main freeway after the nose point. In this scenario, adequate time and distance are available to the drivers to accomplish each task. In contrast, in the taper design, drivers are forced into a dilemma situation where they must choose a lane. This situation is in contrast with the concept of predictability, where designs are made self-explanatory to road users in order to allow drivers to alter their behaviour accordingly. At the start of the taper, drivers could be in a difficult situation due to the start of a sudden lane drop where they need to make the decision to change lanes. Depending on the circumstances at that moment, some drivers may make an error thereby causing a crash.

Although literature on merging freeway designs with a decreasing number of lanes is scarce, this is not the case for literature on acceleration lane taper and parallel designs, which have been studied in detail. For example, Torbic et al. (2012) studied mainline freeway ramp terminals by observing field data, human behaviour and subsequently applying crash analysis data on the data collected from field observations. The parameters used in this study to investigate driving behaviour were mean speed and acceleration. They concluded that vehicle merging speeds on taper acceleration lanes were closer to the design speed of the main freeway than they were in parallel acceleration lanes. Several studies show that the geometry of the design influences driving behaviour on acceleration lanes (Ahammed, Hassan, and Sayed 2008; Hassan, Sarhan, and Salehi 2012; Hassan, Sayed, and Ahammed 2006). Elefteriadou and Kondyli (2009) investigated drivers' intended actions along a freeway-ramp merging segment under various scenarios by conducting focus group sessions in which participants elucidated their thinking process and possible actions while traversing a merging segment. The study considered non-congested and congested traffic conditions and also correlated the drivers' responses to their individual characteristics. They concluded that the majority of participants would speed up and be more aggressive on taper ramps compared to parallel ramps. De Blasiis and Calvi (2011) used a driving simulator to observe drivers' behaviour on various acceleration lanes with varying traffic conditions. In this study they used the lateral position (trajectory) of the drivers, mean speed, acceleration and number of gaps rejected. The study concluded that the merging lengths of the driver, acceleration oscillations and the number of gaps rejected while merging on to the main freeway was directly proportional to the traffic volume of the main freeway. Sarvi, Kuwahara, and Ceder (2004) conducted a driving simulator validation study by observing the freeway ramp merging phenomenon under congested traffic conditions. Mean speed, acceleration and lateral position were also used to study driving behaviour. The results indicated a significant speed reduction immediately prior to the merging maneuver into the freeway lane in all trajectories. The study also suggested that the driving simulator is a useful data collection tool and can be beneficial in the future investigation of ramp driver's merging behaviour. Several other studies support the same statement (de Winter et al. 2009; Godley, Triggs, and Fildes 2004; Kircher and Thorslund 2009; Melman et al. 2018; Zhang and Kaber 2013).

Heavy vehicles are known to have an impact on the traffic stream. Ahmed, Drakopoulos, and Ng (2013) found that headways between passenger cars increased due to the presence of heavy vehicles. They also found that the maximum throughput of the freeway decreased when the heavy vehicle percentage increased by more than 3 percent. Moridpour, Mazloumi, and Mesbah (2015) observed that large front and rear gaps exist in a traffic stream between heavy vehicles and passenger cars due to limited maneuverability and safety concerns respectively. Their results showed that an increase in the percentage of heavy vehicles of up to 30% can increase the probability of crash occurrence by up to 5%. This shows that an increase in heavy vehicles has an adverse effect on efficiency and traffic safety.

Literature review shows that the taper design is considered unsafe, however, no specific reasons are provided. Heavy vehicles are also known to influence road safety negatively. However, the threshold of the heavy vehicle percentage that can be accommodated by road designs is not provided in the Dutch standards. Based on these, the objectives of this study are defined. The first objective of the study is to compare road safety of the standard and taper design by means of driving behavioural parameters. The second objective is to find effects of different heavy vehicle percentages on driving behaviour parameters and to find which design performs well under these circumstances.

Methodology:

Scenario Design:

In this study, a comparison is made between the standard design (Figure 1a) and the taper design (Figure 1d), both retrieved from the Dutch guidelines (ROA 2017). The motivation for selecting these two designs is that in both designs merging manoeuvres and lane reduction take place in almost comparable longitudinal lengths (Figure 1a, length= 400 m; Figure 1d, length = 250 m). In other standard designs (Figure 1c), this longitudinal length is much higher. In this study, for the standard design in Figure 1a, dimension b was set to 100 meters as it is stated in the standards that this has to be greater than 50 meters. Both designs were designed for the design speed of 120 Km/h.

Three virtual scenarios with a two-lane 18 km long freeway containing the two aforementioned merging designs in a randomized order with three heavy traffic compositions (0, 15 and 30%) were created using the driving simulator program STISIM Drive Version 3. Heavy vehicles are classified as vehicles having a gross weight over 3.5 tons. In terms of length, heavy vehicles selected for this study were between 7.62 and 12.8 meters long (European Commission 27 September, 2018). In each scenario, merging designs were inserted in such a way that each participant drove through both designs twice in one run. As mentioned in ROA (2017) for these designs, the intensity to capacity ratio on both merging and the main freeway has to be under 0.7. Hence, the intensity to capacity ratio was kept constant at 0.6 on both freeways. According to the traffic volume given in ROA (2017) and the intensity to capacity ratio of 0.6, the total number of vehicles per lane per minute for 0% heavy traffic was 24. For 15 and 30% of heavy vehicles, the total number of vehicles turned out to be 18 and 15 with 4 and 6 heavy vehicles per lane per minute respectively. Drivers were informed of a merging freeway ahead on both designs by means of a merging sign placed 550 and 400 meters before the nose point on the standard and taper design respectively. The difference in distance for the sign locations of the two designs is due to their different longitudinal dimensions. In both cases drivers are notified 150 m ahead of the change in geometry. The initial position of the drivers is set in lane 3 (based on figure 1) in both designs as this initial position has more critical driving conditions compared to setting the initial position in lane 4, which requires a lower number of changes in manoeuvring while merging.

Driving Simulator:

The driving simulator used in this study was a medium-fidelity, fixed-base driving simulator (Figure 2). It consisted of an actual car (Ford Mondeo) with a steering wheel, brake pedal, clutch, and accelerator. Interior car functions such as a music system, windows, GPS etc. were idle except for the turn indicators. The sound of the driver’s vehicle and traffic in the environment were also present. The virtual environment was projected on a large 180 degree, seamless curved screen at a resolution of 4200 by 1050 pixels and a 60 Hz refresh rate. The driving simulator was set to an automatic gearbox configuration and data was collected at frame rate.

Participants:

A convenience sample of 52 participants with a valid driving license volunteered for this study. After screening for outliers, the data of 49 participants (63% male, 37% female) were used for the analysis. The outliers were identified on the basis of speed (i.e. if the speed was higher than three times the standard deviation of the mean speed of all drivers they were considered as outliers) (Arien et al. 2013). The mean speed of the outliers throughout the design section was 160 km/h as opposed to the mean speed of the remaining participants which was between 80-110 km/h, depending on the traffic conditions. The mean age and mean driving experience of the participants were 31.13 years (standard deviation = 7.3) and 10.9 years (standard deviation = 7), respectively. Each participant signed a consent form before participation. The study protocol was approved by the ethical committee of Hasselt University. Before the experimental data collection, each participant started with a warmup drive (2 to 5 minutes) to familiarize themselves with the driving simulator. After the experiment, participants were asked to fill out a post-experiment questionnaire to select one of the two geometric designs in which they felt safe while driving in the simulator. They were informed about the order in which they drove their scenarios and were asked to select the proportion of heavy vehicles they felt comfortable with by writing down the most favourable option. In the questionnaire, percentages of heavy vehicles were mentioned as small, moderate and high, corresponding to 0, 15 and 30% respectively.

Data Collection:

Data for longitudinal speed, longitudinal acceleration and lateral position across the entire length of the scenario (18 km) for all three heavy vehicle percentages were obtained from the driving simulator. From these data, 1.5 km long sections for the standard and the taper designs were extracted as shown in Figure 3. Each merging section was then further divided into 75 zones of 20 m length each for analysis. Driving behaviour parameters such as speed, acceleration/deceleration, standard deviation of the acceleration/deceleration and the cumulative number of lane changes were examined to study the effects of the three heavy vehicle compositions and the two merging designs. The inherit nature of the two designs are such that their direct point-to-point comparison is not feasible as they split different driving tasks (lane changing/merging) over time and space. Additionally, for the same reason, comparing the collective analysis for the entire length of the standard design with the same length before and after the nose point of the taper design is also not a sound approach (i.e. a simplistic comparison of the cumulative lane change for these designs may not depict the true picture as in the standard design lane change and merging are separated over length and in the taper design these two tasks need to be done simultaneously). As both designs are used to merge two freeways, the most critical section for comparison is the length downstream of the nose point. For comparison, a 360 m long (18 zones) section was selected downstream of the nose point for both designs and is labelled ‘analysis section A’. For the standard design to be safe, the lane change manoeuvre should also take place smoothly and safely. For this, a 360 m long section (analysis section B) upstream of the lane reduction was defined and the effects of different heavy vehicle percentages were observed on the driving behaviour parameters.

Data Analysis:

From the lateral position data, the cumulative number of lane changes for each participant was calculated from the starting point to the end point of the 1.5 km long section. The cumulative lane change means that each time a participant changes lanes, the lane change count increases by one. For example, in the standard design, all drivers will have a cumulative lane change value of 0 at the beginning. As they progress through the section, they are required to change lanes because of the geometrical design of the lane reduction when driving in the left lane, as a result of which their cumulative lane change value will increase to 1. This cumulative lane change value is then averaged for all drivers for each zone in the 1.5 km section. When they reach the nose point (analysis section A), their cumulative lane change value will again increase by 1 and their new cumulative value will become 2. So, the possible minimum value at the nose point is one and zero for the standard and taper design respectively. The difference between the cumulative lane change values at the start and the end of analysis section A represents the number of lane changes that occurred in that section.

The effects of different heavy vehicles percentages and two geometric designs are investigated based on driving behaviour parameters, i.e. mean speed, mean acceleration/deceleration, standard deviation of acceleration/deceleration, and the cumulative number of lane changes for analysis sections A and B. There is no threshold limit for these behaviour parameters to define the merging movements as safe and smooth. However, the considerable variations in these parameters over short distances and time give an indication of smooth and safe manoeuvring while merging and changing lanes. Therefore, conclusions made about safer design are based on examining the profiles of these parameters. Multivariate analysis of variance (MANOVA) is applied to study the overall effects of the independent variables (the heavy vehicles percentage and geometric design) on the dependent variables simultaneously, similar to the study from Ariën et al. (2017). The effects of a two-way interaction between traffic conditions and geometric designs were also investigated. Repeated measures ANOVA was applied to investigate the effects of the independent variables on each dependent variable separately as each participant drove through all scenarios one after the other in randomized order. This is also recommended in Calvi (2015).

Results and Discussion:

For subjective safety, the main results from the post-experiment questionnaire demonstrated that:

(1) 42 out of 49 participants (86%) felt more comfortable in less heavy traffic conditions whereas 5 (10%) and 2 (4%) participants also felt comfortable driving in moderate and high traffic conditions respectively.
(2) 30 out of 49 participants (61%) chose the standard design as safest in contrast to 19 participants (39%) who indicated the taper design as the safest option for merging freeways.

Consequently, the majority of participants perceived the standard design to be safer than the taper design. Also, the presence of heavy vehicles is not preferred. The results of the driving simulator experiment are discussed next.

Comparison of two geometrical designs (Analysis Section A):

The results in Table 1 show that traffic conditions and geometric design and their two-way interaction have an overall significant effect on all dependent variables based on Wilks' Lambda (p-value<0.05). The significance of two-way interaction implies that for heavy vehicle composition, each variable has a different magnitude in both geometric designs. This indicates that average driving behaviour is different in all conditions of dependent variables.

To further investigate, Figure 4 shows the average speed profile for the standard and taper design of analysis section A. It indicates that the speed profile for each traffic condition of both designs is different. Table 1 reveals this difference is statistically significant as traffic conditions, design, and their two-way interaction all have p-values under 0.05. In case of the standard design, the average speed at the nose point for 30% heavy traffic is higher than for 0 and 15% and after this point, the speed for all traffic conditions starts to increase. This speed behaviour may be due to the geometry of the standard design as there is a lane reduction upstream of the nose point which may cause lower values of the mean speed. The mean speed is lower for the 0 and 15% heavy vehicles conditions due to the high vehicle density compared to 30%. However, due to the low density in the 30% heavy vehicles condition and due to the lower speed of heavy vehicles, drivers were able to overtake most of the heavy vehicles before the lane reduction, hence they did not have to reduce speed before the nose point. Another reason for the higher speed at the nose point for the 30% heavy vehicles condition could be that in this scenario, drivers may have found a suitable gap for merging before the nose point (due to an overall low vehicle density on both freeways and the lower speed of the heavy vehicles). The lowest speed values were found for 15% of heavy traffic downstream of the nose point till the end of analysis section A. This might be due to the mixed composition of passenger cars and heavy vehicles in this scenario and therefore, drivers were more careful.

In case of the taper design, the mean speed reduced after the nose point and continued to reduce until approximately 100 meters downstream of the nose point. This is because no lane was reduced upstream of the nose point and drivers had freedom of lane choice. When drivers arrived at the nose point they may have realized that they had to merge soon and hence, started to find gaps in the traffic from the main freeway which made them reduce their speed. The mean speed reduction was largest for 15% heavy vehicles and was smallest for 30% due to the reasons stated above. After 100 m downstream of the nose point, the mean speed started to increase again.

Figure 5a and 5b show the acceleration profiles for both designs in analysis section A. Statistical analysis shows no significant differences between the acceleration profiles for different heavy vehicle percentages (Table 1, p-value=0.295). The two-way interaction factor was also found to be insignificant (p-value = 0.089). Indeed, for the standard design, acceleration values are higher at the beginning of the analysis section which is not surprising as the speed values started to increase from this point. For the taper design, acceleration values for all three traffic conditions decrease at the start of the section, probably because drivers realized that the merging of freeways had begun and they needed to reduce their speed to find a suitable gap in the traffic stream of the main freeway.

Interestingly, the standard deviation of acceleration/deceleration profiles for the standard design also shows that there is little variation in the standard deviation of acceleration/deceleration (Figure 5c) for each of the three heavy vehicles compositions, which means that participants drove smoothly 360 meters downstream of the nose point. However, the taper design shows much larger and statistically significant variations in the standard deviation of acceleration/deceleration (p-value <0.05, Table 1). In case of the taper design, the standard deviation of acceleration/deceleration variations were highest in case of 15% heavy vehicles. For 0% and 30%, the standard deviation of the acceleration/deceleration values do not show much variation. It can be assumed that drivers found it more difficult to select a suitable gap and to merge when the heavy vehicle composition was 15%. This may be because in the 15% heavy vehicles composition, both passenger cars and heavy vehicles were present in the right lane of the main freeway and gap acceptance may be difficult compared to the 30% and 0% scenarios. To explain this further, with 15% heavy traffic, drivers are dealing with a mixed situation and face a dilemma. Consequently, some drivers tend to speed up while others decide not to take over the vehicles in the adjacent lane. The situation is more straightforward when there are no trucks or more trucks on the road (i.e. 0% and 30%). In the latter two circumstances drivers find it easier to decide what to do.

Figures 6a and 6b show the number of cumulative lane changes for the standard and taper design after the nose point. For the standard design (Figure 6a), the difference between the start and end of the analysis zone for 0, 15 and 30% heavy vehicles were found to be 1.14, 1.18 and 1.16 respectively. For the taper design, these values were 1.37, 1.86 and 1.60 respectively. These differences were found to be statistically significant for heavy vehicles percentages, design and their two-way interaction (Table 1, p-value<0.05). From the mean lateral driving profile shown in Figures 3a and 3b, it can be observed that on average, drivers merged into the middle lane of the main freeway (lane 2 in Figure 1). Hence, values greater than 1 indicate that drivers changed lanes more than once (i.e. after merging, they moved to the leftmost lane or to the rightmost lane of the freeway). It was observed for both merging designs that most drivers decided to move to the leftmost lane of the freeway (lane 1 in Figure 1). This is not surprising as the rightmost lane of the freeway (lane 3 in Figure 1) was more heavily occupied.

When examining the differential values of cumulative lane changes for the standard design in light of speed values, it turns out that the mean speed at the start of the section was less than 90 km/h, which means that participants were driving slower than the heavy vehicles. After the nose point, when they started to merge into the middle lane, they increased their speed. However, fewer variations in the standard deviation of the acceleration/deceleration values throughout the analysis section show that these lane changing manoeuvers took place in a safe manner i.e. without many abrupt changes in acceleration/deceleration. There are no threshold values available in literature in relation to merging manoeuvres, though Lamm and Choueiri (1987) considered the manoeuvre to be safe when deceleration is not beyond $-0.85 m/s^2$, when drivers approach a horizontal curve. In our study, deceleration values were always less than the value mentioned by Lamm and Choueiri (1987) in both designs. For the taper design, during the first 80 meters downstream of the nose point, the cumulative lane change values do not increase. This may be because drivers found suitable gaps to merge during this length. The decrease in the mean speed during this length supports this argument. The maximum decrease in the mean speed and a larger variation in the standard deviation of the acceleration/deceleration values during this length for 15% heavy traffic shows that gap acceptance was harder when passenger cars and heavy vehicles were mixed. Hence, for the 15% heavy vehicles composition, lane changing manoeuvres after merging were not executed smoothly. The difference in values of cumulative lane changes for the 0, 15 and 30% heavy vehicles composition for the taper design is higher than it is for the standard design. This shows that on average, more drivers moved to the left lane after merging into the middle lane in case of the taper design when heavy vehicles were present. This also demonstrates that there is a higher number of conflict points, and hence the probability of crash occurrence in the taper design is higher than that of the standard design.

Lane changing upstream of the lane reduction (Analysis Section B):

For the standard design, the lane changing manoeuvre at the point of lane reduction upstream of the nose point is also a potential zone of conflict. Therefore, the effects of heavy traffic on driving behaviour parameters were also analysed in the section 360 m upstream of the lane reduction point (analysis section B), as shown in Figure 3a.

From Table 2, based on Wilks' lambda values, it can be observed that traffic conditions have an overall significant effect on driving parameters (*p-value*< 0.05). Repeated measures ANOVA results also show the significant effect of traffic conditions on all driving behaviour parameters (*p-value*<0.05). Figure 7a shows the mean speed before the final point of lane reduction. Results show that despite the absence of speed signs, drivers reduced their speed in all three heavy vehicles composition scenarios. This reduction in the mean speed took place because of the 'lane reduction ahead' road sign placed 400 m upstream of the lane reduction. The decrease in the mean speed was significantly different for the three heavy vehicles conditions (p-value<0.05 of Table 2) and it was highest for 0% heavy vehicles. This might be due to the absence of heavy vehicles, which corresponds to a high vehicle density. Participants in the right lane reduced their speed because vehicles from the left lane started to merge into the right lane due to the lane closure ahead. When the heavy vehicles composition was 15 and 30%, it was easier for drivers to change lanes before the lane reduction by overtaking slower heavy vehicles. Hence, the reduction in the mean speed was lower.

From Figure 7b, it can be observed that at the beginning of analysis section B there was a deceleration, followed by a gradual acceleration. The deceleration was highest in case of 30% heavy vehicles while it was lowest for 15% and the gradual acceleration was highest for 30% whereas it was lowest for 0% heavy vehicles. However, acceleration values for all three traffic conditions were less than zero, indicating drivers applied their brakes before the lane reduction. From the mean speed (Figure 7a) and the acceleration profiles (Figure 7b), it can be observed that drivers reduced their speed throughout this 360 meter section. Initially, they applied hard brakes, probably to find a suitable gap in the right lane, subsequently they braked slowly until they changed lanes. The standard deviation of the acceleration/deceleration values (Figure 7c) shows that there was a small variation in the acceleration/deceleration for all three heavy vehicles compositions which shows that drivers reduced their speed safely. To observe the cumulative lane change, similar differential values to the ones taken for analysis section A were calculated for each heavy vehicles composition and were compared with each other. The difference in the start and end cumulative lane change values for 0, 15 and 30% heavy traffic was found to be 0.67, 0.81 and 0.71 respectively. Values below 1 show that few drivers chose to drive in the right lane (lane 4 in Figure 1). From observations made for all four driving behaviour parameters, it is safe to assume that lane changing before the nose point for the standard design took place safely and smoothly.

Key findings and their comparison with existing studies:

The main findings of the study from the results described in the previous section can be summarised as:

- The qualitative data shows that the standard design is safer than the taper design. However, the data provides perceived safety of the designs.
- Downstream of the nose point, the standard design was safer as mean speed, acceleration, standard deviation of acceleration deceleration, and cumulative lane change values for the standard design were safer than they were for the taper design.
- Values of the investigated parameters show that lane changing manoeuvers upstream of the nose point in the standard design were also performed safely. This further increases the safety of the standard design.

As mentioned earlier in the introduction and literature review sections, there is a lack of literature and there is only one similar study investigating the safety of such designs. Therefore, the discussion in this section is primarily based on the findings and the experimental composition of the study from Ruyter (2016). The driving simulator experiment designed by Ruyter (2016) to evaluate the safety of the taper design has a number of differences when compared to our experiment. In his study, the effects of two heavy vehicles percentages (0 and 20%), and various taper lengths were analysed and compared with the standard design. However, the standard design selected for the comparison was not comparable to the taper design in terms of longitudinal dimensions and lane reduction (a standard design length of 850 m with a lane reduction 750 m downstream of the nose point (standard design 3 Figure 1 a), vs a taper design length of 250 m including lane reduction (taper design Figure 1 d)). Ruyter (2016) found indications from his driving simulator experiments that the taper design could be even safer than the standard design. However, this conclusion was to be interpreted with caution as a number of surrogate safety measures were not statistically different between both designs. In our study, the standard design selected for comparison with the taper design was comparable in terms of longitudinal dimensions (a standard design of 400 m (Figure 1 a) vs. a taper design of 250 m (Figure 1 d)). Our results show that the standard design is safer as the mean speed, acceleration and the standard deviation of acceleration/deceleration profiles were smoother and safer than they were for the taper design.

This finding is also in line with the Dutch and AASHTO guidelines where they mentioned preferences for the standard design in relation to the taper design without providing underlying reasons. On sites where the taper design already exists, road safety can be improved by controlling lane changing manoeuvers on both the main and merging freeway using different techniques (i.e. road markings, road signs, etc.). These are important as they can simultaneously regulate the lane changes (i.e. no overtaking zone, no excessive lane changes (i.e. use of a solid lane marking to avoid lane change from lane 1 to lane 2)) and warn drivers about the lane merge ahead. This study recommends the use of the standard design for new infrastructure due to the fact that lane changing and merging manoeuvres are separated in the standard design through space and time, which reduces the number of conflict points and hence, also reduces the probability of crash occurrence.

Literature on acceleration lanes also indicates that drivers tend to accelerate more on tapered lanes compared to parallel lanes (Torbic et al 2012; DeBlasiis and Calvi 2011) and therefore tapered lanes are not recommended when the main freeway traffic flow is higher, to ensure there is sufficient time available to drivers for adjusting their speed before merging. This is required to maintain an appropriate level of safety. This signifies that parallel acceleration lanes divide the tasks of speed adjustment and merging, whereas in tapered lanes both tasks are done simultaneously. The situation is more or less similar when comparing the standard and the taper design, which are investigated in detail in this study. A quantitative comparison cannot be made with regard to acceleration lanes. However, it can be asserted that in some traffic conditions, the taper design can create situations which may be unsafe compared to the standard design.

However, limitations of this study should be considered when selecting a geometric design to merge freeways. This study only provides an indication of the direction of the effect (such as that the taper design is not as safe as the standard design), rather than a definite answer (the manoeuver was not safe in the taper design). The traffic intensity to capacity ratio (I/C) was intentionally kept constant at 0.6 so as to keep the traffic volume under the specified limit of 0.7 as the results could be different for other values. The time to collision and eye and facial movements were not considered in this study as a safety measure because of the driving simulator limitations. Their consideration might provide further insights on driving behaviour at merging freeways.

Conclusions and Future Research:

The main purpose of this study was to investigate the driving behaviour on standard merging and taper designs with a decreasing number of lanes according to the Dutch standards and to find which of these two designs can be considered safer. Moreover, effects of the different composition of heavy vehicles on road safety were studied by studying driving behaviour parameters. The results obtained by comparing the standard and taper design with regard to mean speed, mean acceleration, standard deviation of acceleration/deceleration and cumulative lane change values show that the standard design can be considered to be safer than the taper design. Further analysis of driving behaviour parameters for the standard design before the lane reduction shows that drivers were able to switch lanes safely for all three heavy vehicles conditions. This makes the standard design more favourable and safer.

Future extensions of the study can include investigating the effects of other driving behaviour parameters such as time-to-collision and eye and facial movements. Eye and facial movements should be studied as they depict the actual anxiety state of the driver while performing the manoeuver. A comparison of the driving simulator data with real-life crash data may give more insight on which geometric design is the safest. The use of different road markings might increase the safety of the taper design which can further be tested in the driving simulator before application in the real world. Driving tests can also be performed to evaluate the safety status of each design and reveal their weaknesses.

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Table 1: Statistical Results for comparison of merging and taper design

MANOVA results for comparison of merging and taper design (Wilks' Lambda)

Independent factor	F	p-value
Traffic Conditions	20.623	<0.001
Geometric Design	498.632	<0.001
Traffic Conditions * Geometric Design	9.979	<0.001

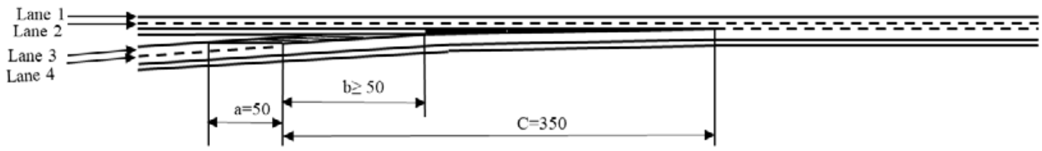
Test of with-in Subject Effects (Greenhouse-Geisser)

Independent Factor	Speed		Acceleration/ deceleration		Standard deviation of acceleration/deceleration		Cumulative Lane Change	
	F	p-value	F	p-value	F	p-value	F	p-value
Traffic Conditions	29.837	<0.001	1.220	.295	6.111	.003	79.807	<0.001
Geometric Design	37.054	<0.001	53.370	.001	4.953	.026	1607.394	<0.001
Traffic Conditions * Geometric Design	9.691	<0.001	2.430	.089	5.881	.003	31.469	<0.001

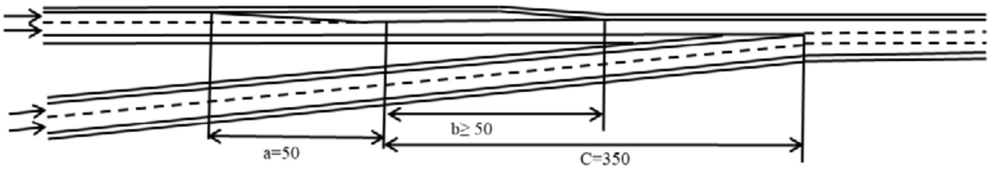
Table 2: Results for merging design before lane reduction

MANOVA results for merging design Analysis Section B (Wilks' Lambda)		
Independent factor	**F value**	***p-value***
Traffic Conditions	8.823	.001

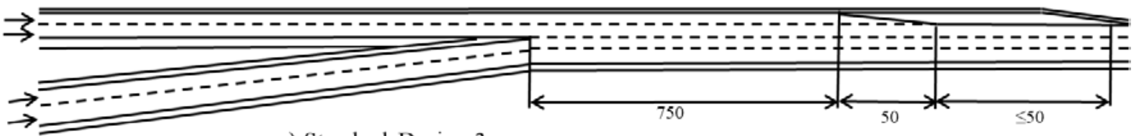
Test of With-in Subject Effects (Greenhouse-Geisser)								
Independent Factor	**Speed**		**Acceleration/ deceleration**		**Standard deviation of acceleration/deceleration**		**Cumulative Lane Change**	
	F value	***p-value***	**F value**	***p-value***	**F value**	***p-value***	**F value**	***p-value***
Traffic Conditions	19.081	<0.001	4.083	.018	5.761	.003	10.471	<0.001



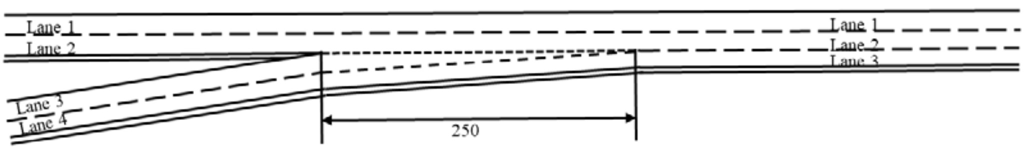
a) Standard Design 1



b) Standard Design 2



c) Standard Design 3

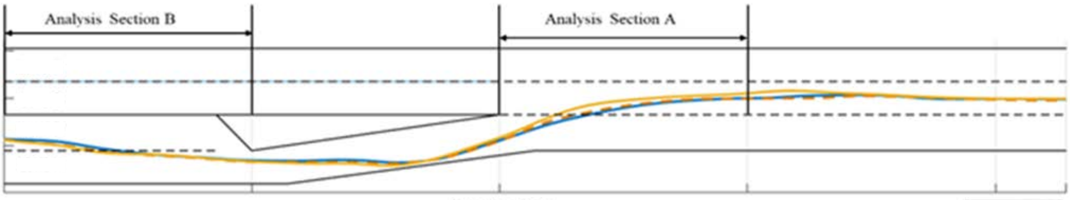


d) Taper Design

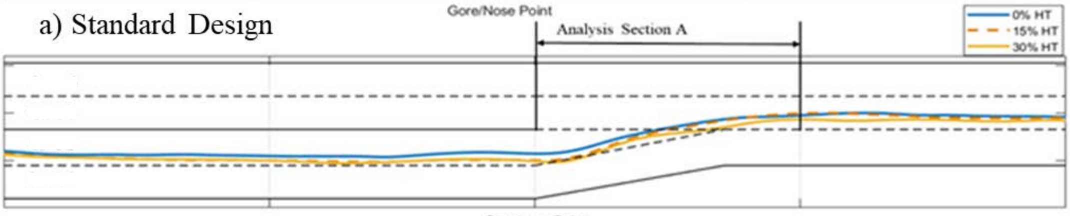
All dimension are in meters (Figure not to scale)

Figure 1: Standard and Taper designs according to Dutch Standards

Figure 2: Driving Simulator at IMOB University of Hasselt

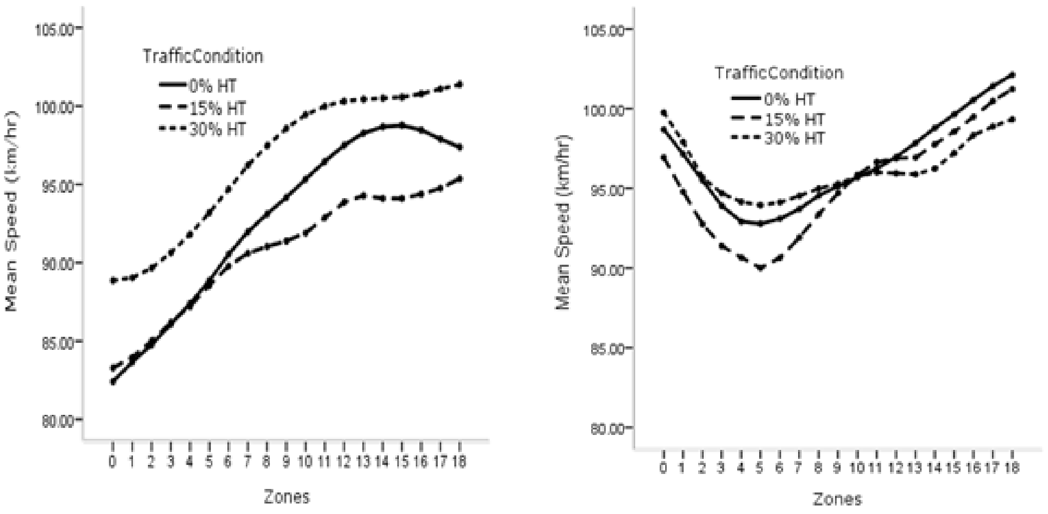


a) Standard Design



a) Taper Design

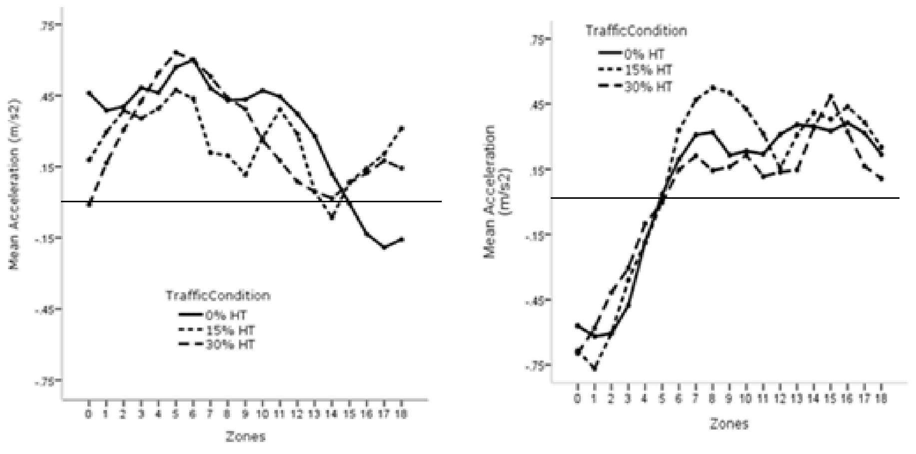
Figure 3: Lateral position profile for standard and taper design



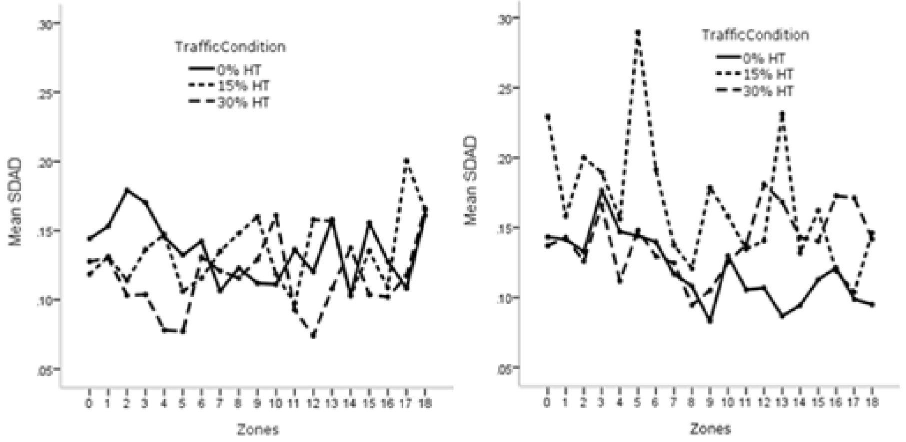
(a) Standard Design

(b) Taper Design

Figure 4: Average mean speed values (Km/h) for standard and taper design

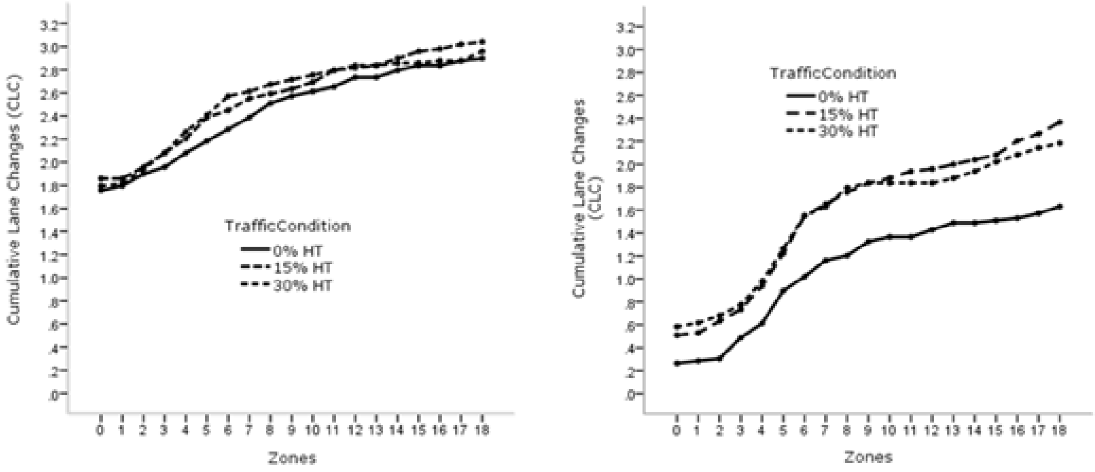


(a) Acceleration Standard Design (b) Acceleration Taper Design



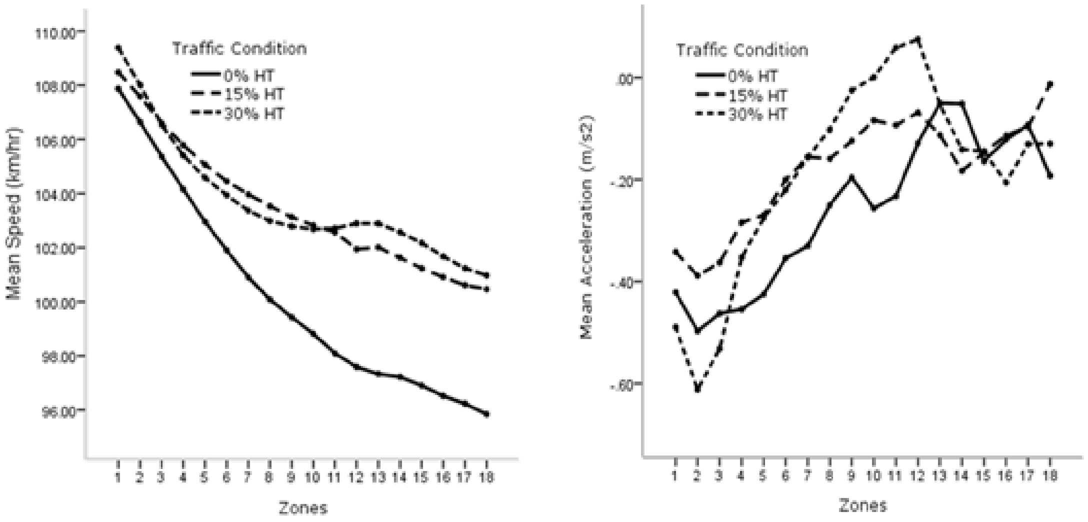
(c) SDAD Standard Design (d) SDAD Taper Design

Figure 5: Acceleration/deceleration and Standard deviation of acceleration/deceleration profiles for standard and taper design

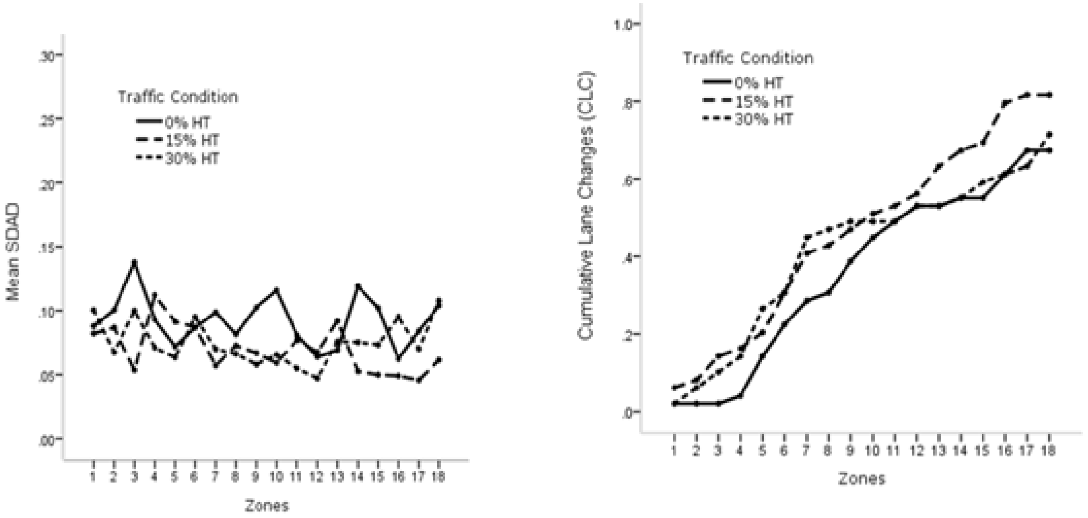


(a) Standard Design (b) Taper Design

Figure 6: Cumulative Lane Change values for Standard and taper designs



(a) Mean Speed (b) Mean Acceleration



(c) Mean SDAD (d) Mean CLC

Figure 7: Driving parameter profiles for standard design before lane reduction

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