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THE RELATIONSHIP BETWEEN ROAD DESIGN AND DRIVING BEHAVIOR

A SIMULATOR STUDY

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ABSTRACT

Speed is a substantial factor contributing to road safety. Currently, speed reduction is mainly achieved through law enforcement and the implementation of traffic calming measures. An alternative speed reducing approach is to encourage drivers to voluntarily choose an appropriate driving speed. Improving road infrastructure safety can be achieved by making roads forgiving and self-explaining. This could be done by clarifying the road design characteristics for each road category. The effect on driver behavior by varying road-shoulders and presence of roadside trees was tested by means of a fixed-driving simulator experiment. Speed and lateral position were used as performance indicators. The results indicated that shoulders might not be applied to decrease the speed on the experimental road stretch, but their presence cause drivers to drive closer to the road edge, hence eliminating the probability of head- on collisions. Roadside trees did not cause drivers to adjust their driving speed; possibly due to trees not being perceived as a threat to safety by the drivers. Due to a relatively small sample size the findings of this study should be considered provisional and as pilot results for further simulator experiments using larger sample sizes to visualize the impact of different road designs on the driving behavior prior to costly deployment. However, the results are highly relevant for the understanding of the influence of road design features on driver behavior as well as for the understanding of the use of the simulator in this field of road safety research.

Key words: Transport safety; Driving simulator; Driving behavior; Driving speed; Road design.

INTRODUCTION

In 2000 the Danish Road Safety Commission set the target to reduce the number of fatal and serious injury accidents by 40 % by 2012 (DRSC, 2000). Recently, the EU has adopted a new 2020 target of reducing the number of fatal accidents by 50 % (ETSC, 2011).

One of the greatest potentials for improving road safety lies in reducing driving speed (Aarts and van Schagen, 2006). A 5% increase in average driving speed leads approximately to a 10 %

increase in injury accidents and a 20 % increase in fatal accidents. Similarly, a reduction of 10 % and 20 % respectively in injury and fatal accidents follows from a 5 % reduction in average driving speed (OECD/ECMT, 2006). It is estimated that speed is the main cause in 25 – 50 % of all road accidents in Denmark (DRSC, 2000).

In most European countries rural roads are the most dangerous type of road. On a European level approximately 56 % of all road deaths happen on rural roads (ETSC, 2011). In Denmark 3/4 of road fatalities happen on rural roads (SafetyNet, 2008). The mean speed on Danish rural roads, with a speed limit of 80 km/h, is 84 km/h and 14% of cars and vans exceeded the speed limit by more than 20 km/h (DRSC, 2000).

Currently, speed reduction is mainly achieved through law enforcement and the implementation of traffic calming measures. Law enforcement only works if the drivers are aware that they are speeding and if they consider the risk of being caught as large enough to encourage them to modify their behavior (OECD/ECMT, 2006). However, enforcement does not have long lasting effects, as the behavioral change is not caused by a change in attitude towards the unsafe behavior. The drivers feel they are being forced to drive at an inappropriately low speed (Martens et al., 1997).

An alternative speed reducing approach is to encourage drivers to voluntarily choose an appropriate driving speed. One way to achieve this could be to make the roads more predictable and “self-explaining”, through clear road type characteristics that show the driver what road type he is driving on, which driving behavior is expected and appropriate, and which other types of road users share the space. This makes the traffic system more predictable and prevents uncertain behavior and resulting crashes (SWOV, 2010). Influencing the driver’s perception of the traffic situation is an important aspect of the safety effect of the self-explaining road (Martens et al., 1997). Road width, horizontal and vertical alignment, roadsides and road markings are all identified as factors influencing the driver’s perception of the traffic situation as well as the perception of his own driving speed thereby contributing to road safety, especially in rural areas (Zakowska, 1997; Sagberg, 2003).

Shoulders are important features of all roads. They serve a wide range of functions. From a human factors standpoint these functions include: provision for sufficient horizontal distance, as it is an obstacle free zone. The shoulder serves as a primary area clear of obstacles, for recovery of temporary loss of control, or as a provision of space to perform emergency actions (RIPCORDER-ISEREST, 2007). Hard shoulders are perceived as an extra driving space. During the last decades, numerous studies have been carried out to identify the road safety effects of shoulder surfacing. For example, in the Netherlands a 20% reduction of accidents on rural single carriageway roads has been estimated (SWOV, 2007). Benefits are found in shoulder paving especially in sharp curves, but there is no clear indication about chosen speed on rural roads where paved shoulders were constructed (RIPCORDER, 2007).

Previous studies show that road users drive faster, farther from the road centre, grasp the steering wheel more often, and experience less stress in open landscapes, without trees along the road partly due to the lack of visual cues regarding own driving speed (Sagberg, 2003; Antonson et al., 2009). The risk of injury and fatal accidents may increase with trees along the road as trees are by far the most commonly struck object type in relation to run-of-the-road accidents (Mok et al., 2006).

The aim of this study was to assess the impact of varying road-shoulders and presence of roadside trees on driving speed and lateral position on rural roads based on 6 hypotheses:

1. Participants will drive more slowly on curves than on straight sections.
2. Participants will drive closer to the centre line on curves than on straight sections.
3. The presence of shoulders leads to higher driving speeds.
4. Participants will drive closer to the road edge when a hard shoulder is present.
5. The presence of trees on the roadside leads to lower driving speeds.
6. Participants will drive closer to the centre line when there are trees on the roadside.

In order to obtain a homogeneous group of participants, only drivers between 20 and 26 were included. In addition, increased knowledge about the behavior of young drivers is relevant from a road safety perspective. In Denmark, as in most other countries, young drivers are overrepresented in road traffic accidents (Clarke et al., 2005; OECD, 2006). One third of all road fatalities involve young drivers, even though this age group represents only about 10% of the licensed driver population in Denmark (CARE, 2008). Across EU more than 3/5 and in Denmark 59% of the road traffic fatalities amongst young people occur in rural areas (CARE, 2008).

The results of the study will contribute to increased knowledge about the relationship between road design and human behavior. In addition it will contribute to the knowledge about the usefulness of driving simulators as a tool for transport engineers to test and evaluate the effects of new road layout, work zones, signs and signals, pavement markings, new construction and vegetation designs etc. prior to costly deployment.

METHOD

In the driving simulator study driver behavior was examined on a rural road stretch. In order to achieve the most relevant results possible from this driving simulator study, it was decided to use a real road stretch as an experimental case. In accordance with the technical and visual abilities of the simulator, the stretch of Esrumvej, in Denmark, was chosen (see Figure 1). Driving speed and lateral position were used as driving performance indicators.

Participants

Twenty one young drivers, 8 females and 13 males, were involved in this study. Participants were recruited at the Technical University of Denmark. The participants were young drivers between the age of 20 and 26 (mean age 23.8, sd 1.58 years). All participants had a valid driving license, and their average driving experience was 4.9 years (sd 1.99).

Apparatus

The experiment was conducted in the STSoftware simulator of DTU Transport. The simulator is composed of a cockpit model STS Jentig. It is equipped with all the necessary control systems. The graphics system consists of three 42" plasma displays. The front screen has 1920X1080 dpi and the two side screens have 1360X768 dpi resolution. Displays are located around the cockpit providing an 180° horizontal and 40° vertical perspective. Rear and side-view mirrors are visible on the screens. Images are presented at a rate of 60 frames per second, creating the illusion of smooth movement. The visual objects are buildings, other vehicles, trees etc. Steering is performed using a steering wheel with force feedback. Furthermore, the driving simulator is equipped with a 5.1-channel 3D sound system, which provides the driver with the sound of the

engine, wind and tires thus enhancing the realism of the driving environment. All the systems mentioned can be controlled in a way to give the participant the most realistic possible driving experience.

Experimental Road

Road Esumvej is located in the north of Denmark (see Figure 1). It can be classified as a middle speed distribution road. It is a two lane rural road (see Figure 2). In general the speed limit is 80 km/h, dropping to 70 km/h or 60 km/h on several stretches. All along the route the road has a varying lane width from 3 to 3.5 meters and there are no bicycle and pedestrian facilities along the road and at intersections. According to the traffic count on Esumvej its annual average daily traffic was estimated to 2.800-3.700 vehicles in 2003.

Esumvej is reported to be fraught with several so-called black spots. A survey, held on Esumvej during December 2002, indicated that according to drivers the main safety problems along the route were speeding, narrow traffic lanes, trees which are too close to the road edge and sharp bends (Wrisberg et al., 2005). As the road was designed and constructed several decades ago, it does not fulfill the safety requirements of nowadays.



Figure 1 Esumvej; Experimental road stretch



Figure 2 Esrumvej, 9,22 km

Chosen Road Stretch

The chosen road stretch (Figure 1) is five kilometers long. The road is characterized by many bends and for the most part there is forest, single trees or rows of bushes on both sides. Predictability on the route is limited and the clearance area is reduced. The edge strip is narrow. Existing edges of pavement show sharp drop-offs. In the case of a vehicle leaving the travel lane and entering the unimproved shoulder area, recovery becomes difficult and might result in the driver losing control.

Speed measurements in 2003 showed that the average speed on this road stretch is between 72 and 77 km/h. However, in some curves with such a narrow lane the speed even being below the speed limits is still too high for existing road geometry. On several road stretches speed registration data shows that 15% of drivers exceeded the posted speed limit (Wrisberg et al., 2005).

In total 39 accidents happened on this road section from January 2000 until October 2009. Most of them were run-off-the-road accidents (73%) and had occurred in curves (60%). Also four head-on collisions on straight stretches and three collisions with roadside trees have been registered. Young drivers (age of 20 to 26) are involved in 28% of the accidents.

Road Design in Simulator

The experimental stretch was reconstructed in the simulator using on-site photos, Google maps street view (MapsGoogle, 2011) and a topographical map of the road.

Each of the test conditions had surroundings as similar as possible to real life (see Figure 3). Introduction of other variables that might affect the participants' lateral position and speed was avoided.

There was occasional traffic going in both directions. Traffic was more intense in villages (where data were not recorded) to concentrate drivers' attention on the driving task more.

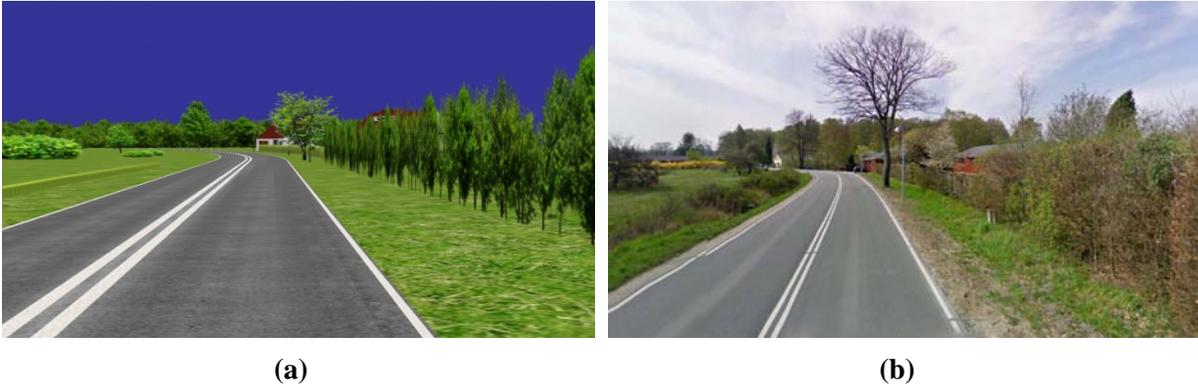


Figure 3 Reconstruction in a simulator (a) and photograph (b) of one section of the road.

Experimental Procedure

Prior to the experiment, the participants underwent a training phase, during which they were given the opportunity to familiarize themselves with the simulator. Then participants were instructed to experimental procedure. They were asked to choose what they considered to be an appropriate speed for that particular road environment. Afterwards six experimental sessions were carried out. Experimental conditions are depicted in Table 1. The visualization of each experimental condition is shown in Appendix A.

Table 1 Experimental conditions

Road without (existing) shoulders	with trees	(1)*
	without trees	(2)
Road with asphalt (hard) shoulders	with trees	(3)
	without trees	(4)
Road with gravel (soft) shoulders	with trees	(5)
	without trees	(6)

* All experimental conditions apply for curves and straight sections.

Each session was conducted over a five kilometers long road stretch. It consisted of 11 different curves (1990 m) and 8 straight sections (1425 m). The cross-section of each type of the experimental road is shown in Figure 4. In all conditions, the experimental road had the same lane width (3.5 m). Shoulders are located on both sides of the road and they are 1.25 m wide which is in accordance to the proposal for Danish road design standards (Vejregel, 2008). The centre line is doubled continuous, and the edge line is continuous for the road with hard shoulders and dashed for existing and soft shoulder conditions.

All participants were assigned randomly to all experimental conditions (counterbalance measures design). Each experimental session lasted for approximately four minutes and there was a short break between the sessions.

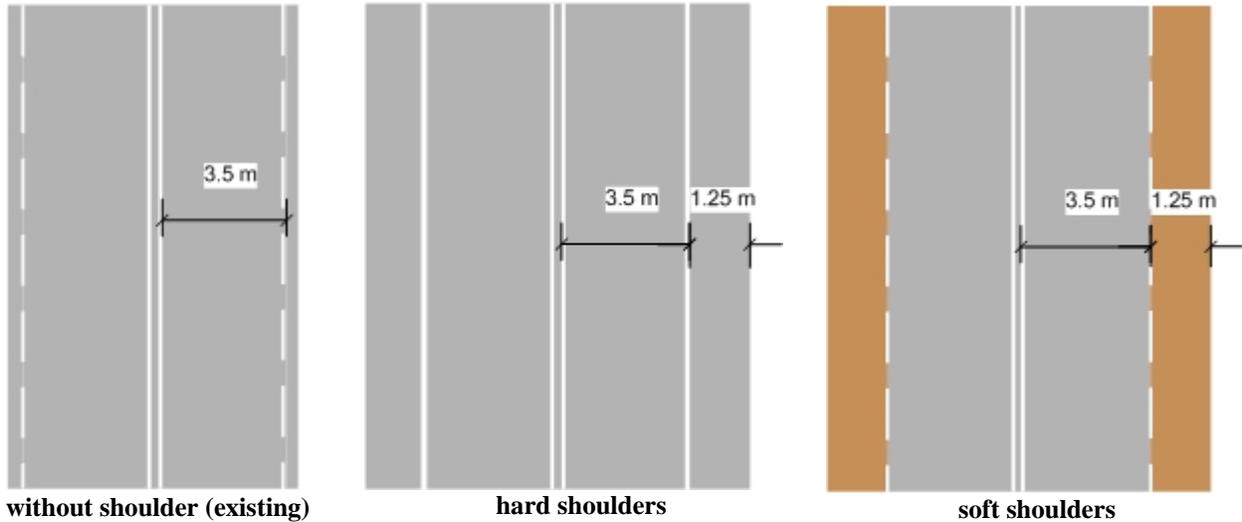


Figure 4: Cross- sections of the experimental road stretch

Statistical analysis

During each experimental session, the speed in meters per second and the lateral position in meters were continuously recorded. The lateral position was measured as the distance between the center of the front bumper of the simulation car and the centre-line of the driving lane. If the center of the front bumper was to the left of this line, the value was positive and vice versa. The mean value of the lateral position states where exactly on the driving lane participants prefer to drive. A negative value indicates that the participant was driving closer to the edge of the road and a positive value indicates that the participant chose to drive closer to the center line.

The sampling frequency used was set to 10 Hz. The data set of each condition consisted of approximately 2200 observations, corresponding to 3 minutes and 40 seconds recording time. The measurements were done for curves and straight sections separately.

The present study deals with matters related to the effects of independent variables (see Table 2) rather than observing absolute speed and lateral position.

Table 2: Independent variables

Variable	Name	Range
Type of shoulders	Shoulder	1: Existing 2: Hard 3: Soft
Presence of trees	Trees	1: Roadside with trees 2: Roadside without trees
Road horizontal geometry	Road	1: Curves 2: Straight

Speed and lateral position measures were analyzed using a mixed-model analysis of variance (ANOVA). Firstly, a mixed-design ANOVA model was created with all fixed factors and their interactions. Since interactions were insignificant for both speed and lateral position measures, they were excluded from the model. In the end, to compare the significance in the variations

between shoulder types a Tukey-Kramer test was used to compare the pairs of group means. A significance level of $\alpha = 5\%$ was used.

RESULTS

Results of the driving speed and lateral position are presented separately.

Driving speed

The mean speed on curves is considerably lower than on straight sections (See Figure 5). The mean speed is highest when a soft shoulder is present and lowest in the existing situation (road without shoulders) both on straight and curved sections.

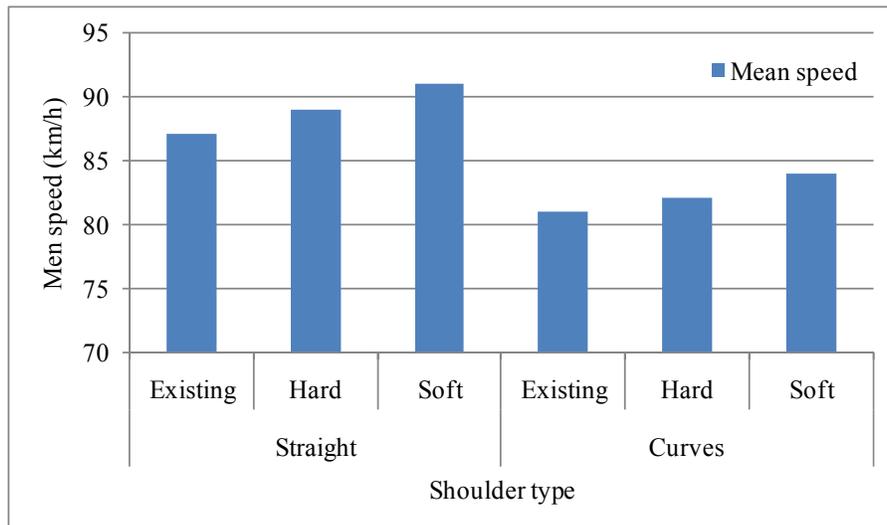


Figure 5: Mean speed on straight sections and curves for each shoulder type

The null hypothesis that mean speeds on roads with different types of shoulders are equal, was rejected ($F=6.59$, $p=0.0017$). The highest mean driving speed is observed on roads with soft shoulders (3.53 km/h higher than on existing road), and the lowest on existing road (see Table 3). The mean speeds on curves were significantly different compared with straight sections ($F=84.41$, $p<0.0001$). The parameter estimate shows that speed was 7.34 km/h higher on straight sections.

The presence of trees does not influence the mean driving speed significantly.

Table 3: Details of Mixed-design ANOVA model for mean speed

Factor	Parameter estimate	numDF*	denDF**	F-value	p-value
Shoulders	Existing: ref	2	214	6.59	0.0017
	Hard: 1.27				
	Soft: 3.53				
Road	Curves: ref	1	214	84.41	< 0.001
	Straight: 7.34				
Trees	Trees: ref	1	209	1.64	0.20
	No trees: -1.37				

*-The number of degrees of freedom in the model; **- The residual degrees of freedom.

Post-hoc analysis

Estimates showed that shoulders are significantly different within the group. The result of post-hoc analysis which uses correction of p-values and confidence limits (a 95% confidence interval) is shown in Table 4.

It can be seen that driving speed is highest when a soft shoulder is present and lowest on existing road. There is significant difference between the existing road and road with soft shoulders ($t = 0.001$), and between road with hard shoulders and road with soft shoulders ($t = 0.06$).

Table 4: Details of Turkey – Kramer test for mean speed

	Estimate	Std. Error	Adj Lower CI	Adj Upper CI	Adj Pr(> /t/)
Hard - Existing	1.27	0.99	-1.07	3.60	0.41
Soft - Existing	3.53	0.99	1.19	5.87	0.001
Hard - Soft	-2.26	0.99	-4.60	0.07	0.06

Lateral position

In general, participants drove closer to the centre line on curves (see Figure 6 and Figure 7). The mean lateral position on curves and straight sections for each shoulder type is depicted in Figure 6. It can be seen that when a hard shoulder was present, participants drove slightly closer to the road edge whilst on a straight section. In all other cases the car is positioned closer to the centre line; more in the existing condition and less when a hard shoulder is present.

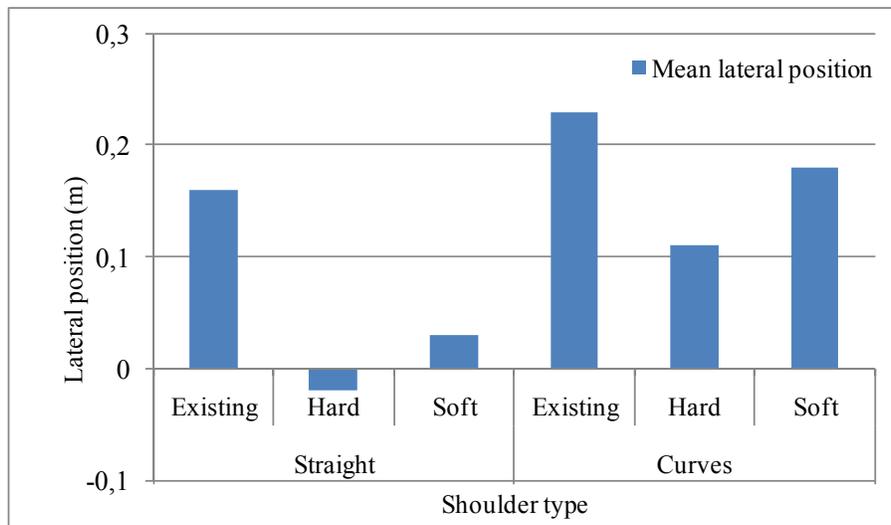


Figure 6: Mean lateral position on straight sections and curves for each shoulder type

When there are no trees on the road side, participants drove slightly closer to the road edge on straight sections, as it is shown in Figure 7. In curves, participants were driving closer to the centre line when there are trees on the roadside.

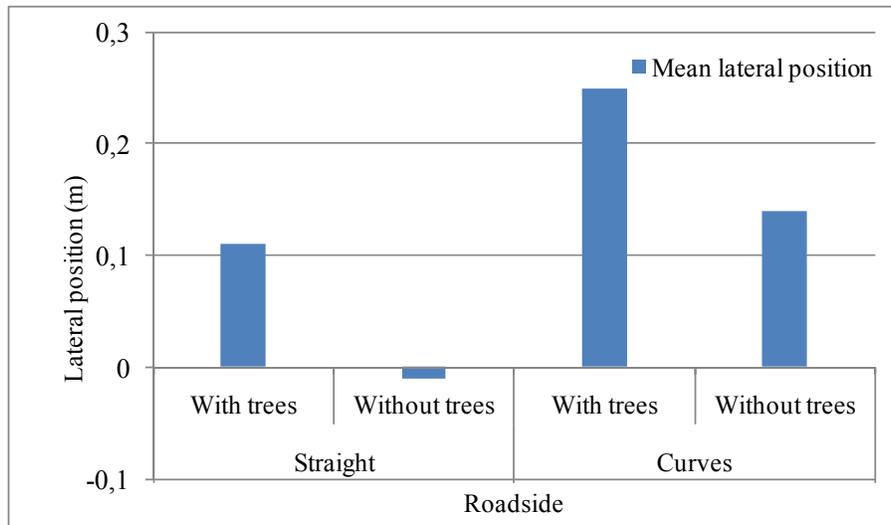


Figure 7 Mean lateral position on straight sections and curves for each roadside type

The null hypothesis stating that mean lateral position for each shoulder type is equal, was rejected ($F=10.36$, $p=0.0001$) (see Table 5). It can be seen that on average, participants were driving closer to the road edge when a hard shoulder was present and closer to the centre line in existing road condition. Similarly, mean lateral position for the road with trees along side was found to be different from the corresponding values for the road with trees ($F=19.74$, $p<0.0001$). Participants were driving closer to the road edge when there were no trees along the road. Also there was a significant difference between lateral position in curves and in straight sections ($F=32.09$, $p<0.0001$). Participants drove closer to the centre line in curves compared with straight sections.

Table 5 Details of Mixed-design ANOVA for mean lateral position

Factor	Parameter estimate	numDF*	denDF**	F-value	p-value
Shoulder	Existing: ref				
	Hard: -0.14	2	216	10.36	0.0001
	Soft: -0.07				
Road	Curves: ref				
	Straight: -0.14	1	216	32.09	< 0.001
Trees	Trees: ref				
	No trees: -0.11	1	216	19.74	< 0.001

*-The number of degrees of freedom in the model; **- The residual degrees of freedom.

Post-hoc analysis

Similarly as for mean speed, estimates showed that shoulders are significantly different within the group. The results of post-hoc test (Table 6) shows that there is a significant ($t = 5.79e-05$) difference in mean lateral position between the road with hard shoulder and on the existing road. Also, there is a tendency highlighted for all shoulder types to be different.

Table 6: Details of Turkey – Kramer test for lateral position

	Estimate	Std. Error	Adj Lower CI	Adj Upper CI	Adj Pr(> /t/))
Hard - Existing	-0.14	0.032	-0.22	-0.064	5.79e-05
Soft - Existing	-0.07	0.032	-0.15	0.004	0.079
Hard - Soft	-0.07	0.032	-0.14	0.007	0.082

DISCUSSION AND CONCLUSION

The aim of this study was to assess the impact of varying road-shoulders and presence of roadside trees on driving speed and lateral position on rural roads. The experiment was conducted using a fixed-based driving simulator. Five out of six hypotheses were confirmed, indicating that the results are generally in line with existing knowledge in the field. The driving speed was significantly lower and the participants drove closer to the centre line on curves than on straight sections. The shoulder presence influenced the driving speed and the lateral position both on curves and on straight sections. The participants were maintaining a higher driving speed when shoulders were present.

Two results related to driving speed appeared to be surprising considering the existing knowledge. Firstly, the result that trees did not influence driving speed significantly was surprising, as previous studies have found that the driving speed increases when no trees are present (Sagberg, 2003, Antonsen et al., 2009). Consistent with findings of other simulator studies (van der Horst, and de Ridder, 2007; Bella and Tulini, 2010), it may be that the trees were not perceived as a threat to safety by the drivers. On the other hand, the presence of roadside trees did affect the mean lateral position, meaning that the participants chose to drive closer to the centre line, especially on curves. This is in accordance with the driving simulator study by Antonson et al. (2009) and indicates an awareness of the trees and may serve as a behavioral strategy to avoid hitting the trees. By changing the lateral position to a position closer to the centre of the road, the sufficient time and space margins around the driver might be maintained more carefully. Sufficient safety margins are needed by the driver to feel safe and comfortable with no excessive mental load. This safety margin is used as a 'comfort zone' by Cacciabue (2007).

The second surprising result was that the drivers drove faster when soft shoulders were present. Previous studies have shown that hard shoulders are associated with a statistically significant reduction in collision frequencies on two-lane rural roads (e.g. Zegeer and Council, 1995; Ogden, 1997). That might indicate that hard shoulders serve as an area for recovery of temporary loss of control, or as a provision of space to perform emergency action, which the soft shoulders do not allow. More importantly, due to the color differences between the main road and the soft shoulder, the visual cues indicate a narrower driving lane compared to the hard shoulder condition, therefore a lower driving speed would be expected (Sagberg, 2003). A reason for the unexpected result might be the weakness of visual cues provided by the simulator (Kemeny and Panerai, 2003). It is also possible that the difference in shoulder pavement in the simulated driving was not obvious enough; soft shoulders may have been perceived as hard shoulders, just in a different color. To clarify this, it would be relevant to conduct a simulator study testing the

effect of different shoulder colors. In addition it would be relevant to conduct post-experimental interviews with all participants focusing on this issue.

The presence of shoulders in this study leads to increased driving speed and to driving closer to the road edge, might inspire the conclusion, that the presence of shoulders potentially decreases traffic safety. On one hand this situation may decrease the possibility of head-on collisions. On the other hand it may increase the possibility of run-off-the-road accidents, which are considered to be more frequent and severe and also have an unfavorable effect on the safety of cyclists driving on the right side of the road (Davidse et al., 2003). However, the extra space provided by the shoulders may allow correction of mistakes in steering and avoidance of collision with oncoming traffic thereby counterbalancing the increased accident risk caused by the increased driving speed. If no shoulder is present a momentary edge line crossing could possibly result in an accident whereas a well maintained shoulder would allow a safe correction (RIPCORDEREST, 2007).

It was found that the results of this study concerning driving behavior on rural roads with varying road shoulders with different roadside surroundings do not have interaction effect on driving speed and lateral position on the experimental road stretch. Shoulder presence did not lead to decreased speeds but might have a beneficial influence if combined with other road design elements. For example, rumble strips along the road edge and centre line as it has been suggested by Davidse et al. (2003). Also as a previous study shows that characteristics of the edge line (e.g. continuous/dashed) have no influence on the speed and lateral position (van Driel et al., 2004), variations in the presence and type of edge lines and shoulders might be tools to inform users on which type of road they are driving and what behavior is expected from them. This could make the road more self-explaining. Further studies are needed to clarify this.

It has to be noted that several studies have been carried out in order to compare the speed and lateral position in the real-road and simulator environment. Blana and Golias (2002) found that the mean lateral position is lower in real-road driving than in simulator driving. These differences may be mainly assigned to the fact that cues adopted by real-road drivers for distance perception are misused by simulator drivers and to the fact that the latter seem to underestimate the risk associated with roadside environment.

The driving simulator can be a useful tool to visualize the impact of different road designs on the driving behavior. Only recently transportation engineers have begun to recognize this (Chrysler et al., 2006). The use of a driving simulator allows a better understanding of the physical space that is being designed without danger for the drivers. Also, quantitative evaluation of the safety of alternative designs can be examined, which enables the selection of the most appropriate before initiating real designs (Rosey et al., 2009). However, as the results regarding the effect of trees and shoulders indicate, it may be relevant to make adjustments when entering a real traffic environment into the driving simulator to achieve a similar behavioral effect in the simulated environment. Previous studies have found that an absolute validity may not be established in the driving simulator regarding driving speed, as participants generally drive faster in a simulated traffic environment compared to a real traffic environment (Godley et al., 2002). This may have influenced the choice of speed in this study. However, as this study does not deal with absolute speed, it does not have any major effect on the results of this study. Since most of the results are aligned with previous findings, relative validity of the simulator is obtained.

Participants in this study were all young drivers. This was partly to ensure a somewhat homogenous group of participants and partly to focus on a high risk group of drivers. However, due to the lack of other age groups in the study, it is not possible to verify, whether the results are related to the age of the drivers. Young drivers, especially men, have the greatest tendency to overestimate their driving skills and to underestimate the risk of being involved in an accident (Gregersen, 1996). Risky driving combined with a lack of driving experience are important factors contributing to the high accident risk among young drivers (Gulliver and Begg, 2007). Due to the age and experience factors influencing the driving behavior of the young drivers, a self-explaining road environment that influences the drivers to choose an appropriate driving speed may be even more relevant for this group of drivers. Further studies focusing on possible age and experience effects would be highly relevant. Furthermore, the driving simulator can be a valuable tool to identify those at high-risk for speeding and for research on speed reduction measures (Pyne et al. 1995; Godley et al., 1997) because of its high ecological validity and safety. So far it has rarely been used for this purpose. The use of questionnaires, a more common method for the prediction of risky driving behavior, has been criticized because of its susceptibility to response bias (Ouimet et al., 2002).

With regard to the safety impact of roadside trees and shoulders the results of this study indicate that a compromise should be sought between the positive and negative effects. Although this study offers no conclusions regarding this compromise, it does highlight the dilemma faced by road designers as they attempt to improve road safety, that measures increasing some aspects of road safety may decrease other aspects of road safety at the same time.

Due to a relatively small sample size the findings of this study should be considered provisional and as pilot results for further simulator experiments using larger sample sizes. However, the results are highly relevant for the understanding of the influence of road design features on driver behavior as well as for the understanding of the use of the simulator in this field of road safety research.

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APPENDIX A



Existing road, with trees (1)



Existing road, without trees (2)



Hard shoulders, with trees (3)



Hard shoulders, without trees (4)



Soft shoulders, with trees (5)



Soft shoulders, without trees (6)

Illustration of each experimental condition