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ARIEN, Caroline; BRIJS, Kris; VANROELEN, Giovanni; CEULEMANS, Wesley; JONGEN, Ellen; DANIELS, Stijn; BRIJS, Tom & WETS, Geert (2016) The effect of pavement markings on driving behaviour in curves: a simulator study.. In: ERGONOMICS, 60 (5), pag. 701-713.

DOI: 10.1080/00140139.2016.1200749
Handle: http://hdl.handle.net/1942/22661

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Conference Paper · January 2012


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THE EFFECT OF PAVEMENT MARKINGS ON DRIVING BEHAVIOR IN CURVES: A DRIVING SIMULATOR STUDY

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Number of words = 6,308
Number of Figures = 4
Number of Tables = 1
Words counted: 7,558

Paper submitted: Monday, August 1, 2011
Paper resubmitted: Saturday, October 29, 2011

ABSTRACT

This study investigates the effect of two pavement markings (i.e., transverse rumble strips (TRS) and a backward pointing herringbone pattern (HP)) on speed and lateral control in and nearby curves. Two real-world curves with strong indications of a safety problem were replicated as realistic as possible in the driving simulator. Thirty-five participants completed two 16.2 km test-drives within a randomized 2 (location: A, B) × 2 (direction: left, right) × 3 (condition: control, TRS, HP) within-subject design.

Results show that both speed and lateral control differ between the two curves. These behavioral differences are probably due to curve-related dissimilarities with respect to geometric alignment, cross-sectional design and speed limit. TRS and HP both influenced speed but not lateral control. TRS generated an earlier and more stable speed reduction than HP. Additionally, at curve entry, speed was significantly lower for curves with TRS than for curves with HP. Based on these results, we recommend TRS rather than HP as a traffic calming measure nearby dangerous curves.

1 INTRODUCTION

Curves typically go together with an increased safety risk: accident rates are 1.5 to 4 times higher than in tangents (i.e. straight road sections) and 25 to 30% of all fatal accidents occur in curves. Single-vehicle run-of-road accidents represent approximately 60 to 70% of all fatal curve-related accidents, whereas head-on collisions occur in 11% of the fatal crashes (2, 3).

Charlton (4) proposed three main behavioral causative factors for accidents in curves, i.e., inappropriate speed monitoring, failure to maintain proper lateral position, and inability to meet increased attentional demands.

Extensive experimental research on human factors and road design determined that these behavioral problems often relate to the geometric properties of curves (2, 5). Among curve design aspects most frequently mentioned as having detrimental effects on road safety are low curve radii, inappropriate superelevation and too narrow road lanes. Accident risk rates significantly increase for curves with a radius smaller than 200m (2). In addition to that, accident risk in curves is dependent on the extent to which geometry of individual curves fits with the design standards of the surrounding road environment. For instance, road sections where curves with more gentle design standards and higher radii are suddenly followed by a sharp curve appear to be very dangerous. Another well-known problem is the succession of a long tangent and a sharp curve (2). As indicated by Comte & Jamson (6), curves at two-lane rural highways are most problematic given their lower design standards in comparison with those for freeways or urban streets.

In order to induce appropriate speed and lateral control in curves, a wide variety of additional infrastructural traffic control devices has been proposed such as signs (i.e., (dynamic) warning signs, advisory speed signs, (chevron) alignment signs and delineators) and pavement markings (i.e., directional arrows, centerline or shoulder rumble strips and (peripheral) transversal strips) (4, 6, 7, 8, 9, 10).

Since this study focuses on the use of pavement markings, we will briefly elaborate on what are assumed to be the main working mechanisms behind this specific type of countermeasure. Pavement markings are primarily qualified as perceptual countermeasures (PCM), meaning they are intended to regulate driving behavior mostly by manipulating the visual driving scene, but sometimes also by means of additional auditory and/or tactile feedback (11). More specifically, the sensory feedback cues generated by pavement markings are meant to create particular illusionary effects such as the impression of increased motion or a lane narrowing effect. These illusions are not only aimed at assisting drivers in more optimally monitoring their speed and/or lateral control. In addition to that, they can also have an important alerting function (11).

The impression of increased motion is often generated optically by means of a sequence of transverse colored lines at decreasing distances apart in the travel direction, thereby stimulating drivers to slow down while approaching a dangerous road section. In case of so-called transverse rumble strips (TRS) (cf. FIGURE 1d), this optical effect is accompanied by auditory and tactile feedback to drivers (11). Although both field studies and simulator experiments have demonstrated the effectiveness of TRS as a speed reducing measure in the presence of intersections, rural-urban transitions and work zones (11, 12), there is no clear evidence whether TRS are effective as a traffic calming measure nearby curves (9, 11).

Optical lane narrowing illusions can serve both purposes of speed reduction and lateral control and are induced by other pavement markings, such as chevron and herringbone patterns

(HP) (11). Godley (11) investigated the impact of both forward and backward pointing HP on driving behavior at intersections. Results obtained in a driving simulator indicated no significant speed reductions. An additional computer-based image evaluation task was conducted to assess whether the different HP created a lane narrowing illusion. Participants had to judge lane width of both lanes with and without the different HP. The backward pointing HP (cf. FIGURE 1d) was able to induce a lane narrowing illusion, but only from a plan view, not from a driver's perspective view. More recently, Charlton (4) investigated the usefulness of still another HP and focused on its application nearby curves. He only found effects on lateral position, not on speed.

In conclusion, various studies already examined the effect of pavement markings on driving behavior. Potential as a traffic calming measure has been found for TRS and HP. However, results for these two pavement markings are not conclusive and were obtained mostly when applied nearby intersections. This study will contribute to prior research by examining whether TRS and HP can regulate speed and/or lateral control in and nearby curves. The more precise objectives will be outlined below.

2 OBJECTIVES

The primary objective of this study is to investigate the influence of transversal rumble strips (TRS) and a backward pointing herringbone pattern (HB) on both speed and lateral control in and nearby curves. For this purpose, the existing Flemish road network was screened for dangerous curves situated within a two-lane rural highway environment (cf. paragraph 3.3).

As will be further highlighted under section 3.3, the curves finally selected were replicated as realistic and detailed as possible in the driving simulator, following the so-called geo-specific database modeling approach as proposed and recommended by Yan, Abdel-Aty, Radwan, Wang, & Chilakapati (1). More detailed insight into the methodological design of this study will be provided below.

3 METHODOLOGY

3.1 Participants

Thirty-eight volunteers participated in the study. All gave informed consent. Three participants were excluded. Two did not finish the experiment due to simulator sickness and one was identified as outlier with a mean speed more than three SD from the group's mean. Thus, 35 participants (23 men) between 18 and 54 years old (mean age 26.1; SD age 10.4) remained in the sample.

3.2 Driving simulator

The experiment was conducted on a high-fidelity driving simulator (STISIM M400; Systems Technology Incorporated). It is a fixed-based (drivers do not get kinesthetic feedback) driving simulator with a force-feedback steering wheel, brake pedal, and accelerator. The simulation includes vehicle dynamics, visual and auditory feedback and a performance measurement system. The visual virtual environment was presented on a large 180° field of view seamless curved screen, with rear view and side-view mirror images. Three projectors offer a resolution of 1024 × 768 pixels and a 60 Hz frame rate. The sound of traffic in the environment and of the participant's car were presented. Data were collected at frame rate.

3.3 Scenario

Curve selection and description

Two specific requirements were kept in mind while selecting curves for this study. Firstly, we wanted to make sure the curves selected could be considered as dangerous, i.e., that risky driving had occurred not just coincidentally before. Secondly, in order to have some variation, we looked for two curves sufficiently different in terms of geometry, surrounding road environment and speed limit. The search for candidate curves within the existing Flemish road network was therefore based on the official Belgian accident database, which is the most complete and detailed accident dataset available in Flanders. It contains data covering the period from 1997 to 2007 and is provided by the Belgian Federal Government (13). Several queries were performed on this dataset making use of different selection criteria. For instance, curves had to be situated within a two-lane rural highway environment, accidents recorded had to have occurred at curves situated far enough outside intersections or roundabouts, curve accidents could not be related to causative factors such as the presence of intersections or roundabouts, alcohol, drugs, fatigue or bad weather conditions, etc. In addition to that, Google Earth satellite images and cross-sectional street views were analyzed to get a better idea of the surrounding road environment and to be able to evaluate to what extent curve geometry was (or was not) in line with the road's overall trajectory. Finally, local police administrations were contacted to find out whether more detailed accident maneuver diagrams could be retrieved and the research team went *in situ* to make a final selection.

The result was two left-oriented compound curves, both preceded by a long tangent and characterized by complex geometrical alignment with radii of different sizes combined with each other. More detailed information on these two curves can be found under FIGURE 1a. As further outlined below, these two curves, together with their mirror images (i.e., right-oriented) were replicated as realistic as possible in the simulator.

Curve development

In programming the two selected curve sections, we closely followed a procedure called geo-specific database modeling, as it was described and recommended by Yan et al. (1). Geo-specific database modeling is defined by the authors as replicating a real-world driving environment in a simulated virtual world (1) and is to be differentiated from simulator research where often, the driving scenarios offered to participants are fictive. As the purpose is to reproduce an existent driving scene as detailed and realistic as possible, the procedure for curve programming was based on a combination of blueprints, AutoCAD simulations, and detailed field measurements performed by the research team. Pictures of the two real world curve scenes and their virtual replica can be found under FIGURE 1b and 1c respectively.

Scenario design

Once the curve sections were finalized, the overall scenario could be programmed (for a visual overview, we refer to FIGURE 1e). As can be seen, the scenario is a systematic combination of the curve sections of interest with a set of filler pieces, differing from curve sections with respect to design, speed limit and surrounding environment and meant to provide some variation while driving.

Sections that were to be statistically analyzed combined a tangent (1,200 meters) followed by one of the curves selected and ending again with tangents of 300 to 375 meters.

Filler pieces were always 1,000m long, starting with a stretch of 100m falling still outside a built-up area (speed limit: 70kph), succeeded by an inside built-up area of 800m (speed limit: 50kph), and ending with another stretch of 100m outside the built-up area (speed limit: 70kph or 90kph, depending on which of the curves (i.e., location A or B) followed). Study participants met some random traffic in the opposite direction, except from 400m before the curve until the next filler piece. This was done mainly in order not to influence participants' self-selected speed and/or lateral position in the curves. Weather conditions were sunny and dry.

TRS were located at a range from 150 to 66m before the curve (14). Both auditory and tactile feedback were provided by the simulator each time participants drove over a strip. The backward pointing HP reached from curve entry to exit and appeared at both sides of participants' driving lane (i.e., at the edge- and centerline). Both markings are illustrated in FIGURE 1d.

Procedure and design

Participants were asked for their informed consent and to fill out a form with their personal data (e.g. gender, date of birth). The simulator session consisted of a practice session and an experimental session. During two practice trips of 4.5km with a variety of traffic situations (i.e., urban areas, sharp curves, traffic lights) drivers acquainted themselves with the driving simulator. The experimental session contained two trips of 16,2km. Combining the different manipulated factors, i.e., location (A vs. B), direction (left vs. right) and condition (control vs. TRS vs. HP), twelve curve sections were created and randomized over a 2×2×3 full within-subject design with 6 curves per trip and the order of conditions, curve sections and filler pieces counterbalanced over participants. Subjects were instructed to drive as they normally do.

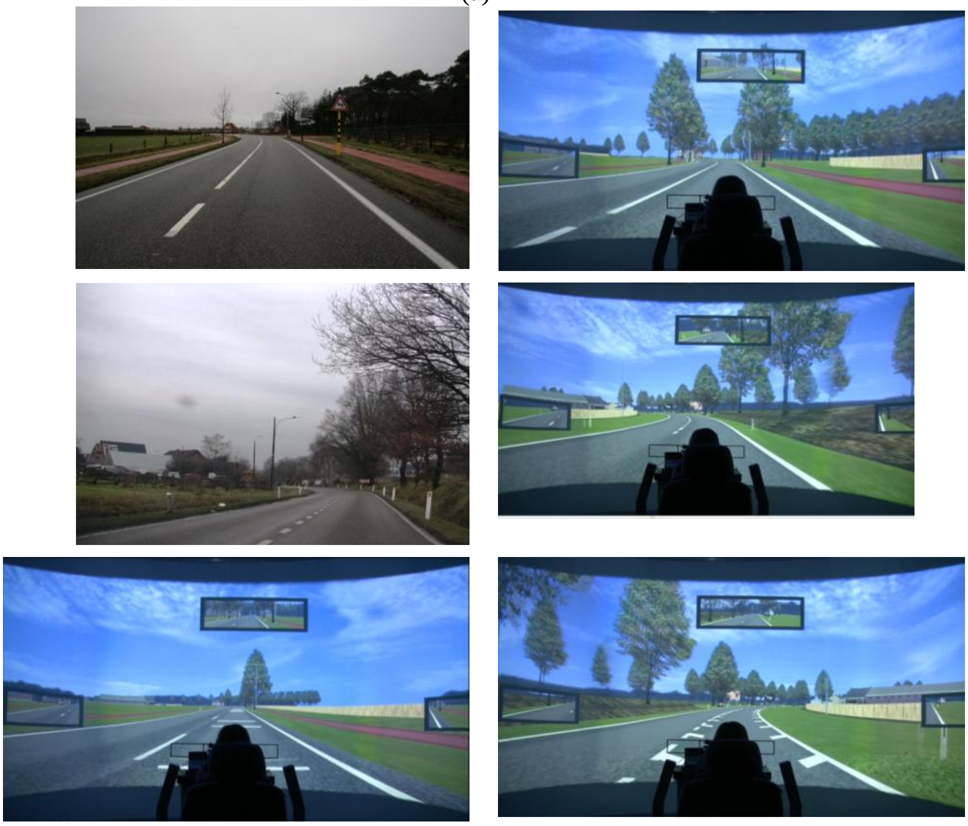
	Location A	*Location B*		*Location A*	*Location B*
Curve radius 1	170m	169m	Total curve length	200m	125m
Curve radius 2	94m	92m	Speed limit	90kph	70kph
Curve radius 3	161m	97m	Road lane width	3.2m	2.8m
Curve radius 4	219m	688m	Bicycle facilities	Yes	No

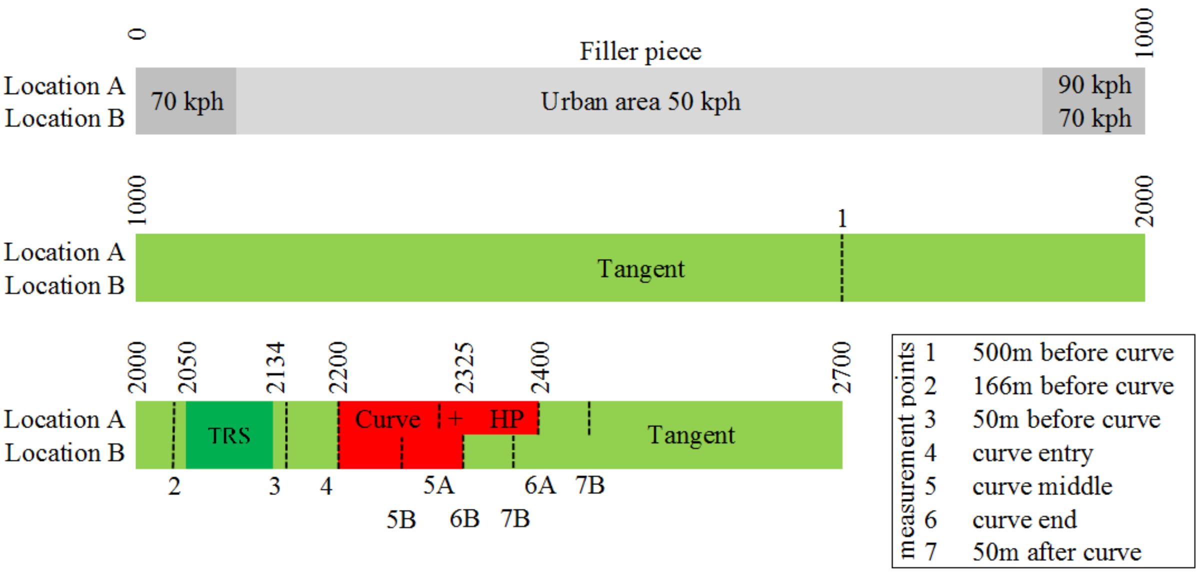
(a)

(b)

(c)

(d)





(e)

FIGURE 1 (a) Curve properties; real world vs. simulator images nearby curve entry at (b) location A and (c) location B; (d) simulator image of TRS (left) and HP (right); (e) scenario overview

3.4 Data collection and analysis

Dependent measures

Driving performance measures for both speed and lateral control were recorded (15). More in detail, speed control was assessed by means of mean speed [kph] and mean acceleration and deceleration (acc/dec) [m/s²]. Measures for lateral control were mean lateral position (LP) [m] and standard deviation of lateral position (SDLP) [m].

We motivate selection of these specific parameters as follows: among the different speed-related parameters known in the literature, mean speed is used as a standard measure for safe driving (16). Mean longitudinal acc/dec in turn, is considered to be a good indicator of both driving safety and comfort. Large mean acc/dec increases the risk for skidding accidents because of reduced tire-road surface friction (17). In addition, the chance for rear-end collisions augments because unstable mean acc/dec means abrupt changes in speed which are difficult to be safely anticipated to by other drivers (18).

Lateral control relates more to managing the vehicle's horizontal position within the driving lane. Lack of a harmonized lane position is a primary cause of single-vehicle run-off the road accidents and head-on collisions, particularly in curves (1, 15). Mean values for lateral position together with their standard deviation are frequently used as indicators for lateral control (4, 19, 20, 21).

Data analysis

Data analyses for mean speed, mean acc/dec and mean LP are based on values obtained at seven measurement points along the driving scenario (see FIGURE 1e). For SDLP, statistical analysis based on point-specific values would not be meaningful since these are very small and mostly equal to zero (19, 21). Therefore, reported findings for SDLP will be based on descriptive plots (see FIGURE 4). As can be seen under FIGURE 3b, such overview plot was also created for mean LP. Since this study focuses on driving behavior in and nearby curves, the scenario segments that were analyzed went from 500m before the curve until 100m after. The road segments for the descriptive plots were then further subdivided into successive 25 meter zones.

A 2 (location: A, B) × 2 (direction: left, right) × 3 (condition: control, TRS, HP) × 7 (measurement point) within-subject multivariate analyses of variance (MANOVA) with additional post-hoc univariate tests and ANOVA's were conducted on the speed parameters. The lateral parameter mean LP was analyzed by means of a repeated measure ANOVA including the same within-subject factors. Significant interactions between within-subject factors were only of interest when the factor Measurement point was part of the interaction since parameter values were averaged for the seven measurement points.

For all analyses, p-value was set at 0.05. For MANOVA's F- and probability values are reported. ANOVA's were corrected for deviation from sphericity (Greenhouse-Geisser epsilon correction) and the corrected F- and probability values are mentioned.

Before analyzing the data, outliers were detected by means of 84 box plots (2 location × 2 direction × 3 condition × 7 measurement point) for mean speed, mean acc/dec and mean LP. Participants were labeled as outlier when a parameter value three times exceeded the inter quartile distance in more than 2 of the 7 measurement points in one of the 12 conditions (2×2×3). One participant was identified as outlier on mean speed. Thus, 35 participants remained in the sample.

4 RESULTS

TABLE 1 presents both multi- and univariate statistics for speed parameters and ANOVA statistics for mean LP.

TABLE 1 Multivariate and univariate statistics for speed parameters and ANOVA statistics for mean LP

Variable	*Speed parameters* *Mean speed & mean acc/dec*		*Lateral parameter* *Mean LP*	
	F	*p*	*F*	*p*
	MANOVA *(dfs = 2, 33)*		ANOVA *(dfs = 1, 34)*	
Location	362.3	**< .0005**	507.1	**< .0005**
Direction	< 1	0.514	13.9	**0.001**
Condition	16.1	**< .0005**	< 1	0.786
Measurement point	21.7	**< .0005**	3.7	**0.010**
Location × Direction	2.1	0.135	< 1	0.661
Location × Condition	4.1	**0.008**	< 1	0.971
Direction × Condition	< 1	0.891	3.8	**0.029**
Location × Direction × Condition	2.3	*0.082*	< 1	0.827
Location × Measurement point	22.9	**< .0005**	< 1	0.516
Direction × Measurement point	3.3	**0.006**	95.4	**< .0005**
Location × Direction × Measurement point	1.4	0.218	18.3	**< .0005**
Condition × Measurement point	2.8	**0.039**	< 1	0.606
Location × Condition × Measurement point	2.3	*0.079*	< 1	0.547
Direction × Condition × Measurement point	1.3	0.319	2.0	*0.063*
Location × Direction × Condition × Measurement point	< 1	0.692	< 1	0.737
	Univariate statistics *(dfs = 1, 34)*			
Mean speed				
Location	639.2	**< .0005**		
Condition	24.0	**< .0005**		
Measurement point	152.7	**< .0005**		
Location × Condition	6.5	**0.003**		
Location × Measurement point	60.0	**< .0005**		
Direction × Measurement point	1.4	0.234		
Condition × Measurement point	17.0	**< .0005**		
Mean acc/dec				
Location	21.8	**< .0005**		
Condition	13.7	**< .0005**		
Measurement point	130.7	**< .0005**		
Location × Condition	< 1	0.434		
Location × Measurement point	44.5	**< .0005**		
Direction × Measurement point	2.5	*0.084*		
Condition × Measurement point	10.1	**< .0005**		

p ≤ 0.05; *p ≤ 0.1*; post-hoc test described below

4.1 Speed parameters

Mean speed

An overview of the results for mean speed can be found under FIGURE 2. More in detail, panel 2a contains one plot per test location, representing values for mean speed at each of the seven measurement points. As can be seen, irrespective of what the test condition is like, mean speed was consistently lower for curves at location B than at location A. At both locations mean speed was highest at 500m before the curve but while it decreased only until the curve entry at location B, it further decreased until the middle of the curve at location A. Put differently, drivers reached minimum mean speed sooner in curves situated at location B (i.e., at the curve entry) when compared with curves situated at location A (i.e., at the curve middle). In addition, panel 2a shows how at both locations, mean speed increased again once passed by the curve middle. Thus, while minimum speed was briefly maintained in curves at location B, namely from the entry to the middle, this was not the case for curves at location A.

Panel 2b contains one plot per test condition, representing values for mean speed that were first averaged over the two different test locations and subsequently set out at each of the seven measurement points. It shows there was no significant difference for mean speed between the three conditions at 500m before the curve and at 50m after the curve. More detailed analyses indicated that, compared to the control condition, the TRS generated a significant speed reduction from 166m before the curve ($p < .0005$) until the end of the curve ($p = 0.015$) (50m before curve: $p < .0005$; curve entry: $p < .0005$; curve middle: $p = 0.008$). In comparison with the control condition, the HP generated a speed reduction at the entry ($p = 0.013$), the middle ($p < .0005$) and the end of the curve ($p = 0.001$). At the entry of the curve both markings generated a lower mean speed compared with the control condition but interestingly, mean speed was significantly lower for curves with TRS than for those with a HP ($p < .0005$). Contrary to this finding, at both the middle and the end of the curve, no such significant difference for mean speed could be found between the TRS and the HP. Further analysis showed that for the three test conditions highest mean speed was registered at 500m before the curve while lowest mean speed was recorded in the middle of the curve.

To summarize, mean speed was overall higher at location A than at location B. Drivers reached minimum mean speed at location B at the curve entry, whereas at location A drivers were still decelerating in the first section of the curve. Following the curve middle, mean speed was increasing again at both locations. Both the TRS and the HP generated significant speed reductions that persisted until reaching the curve end, only the former did so already 166m in advance of the curve while for the latter, the speed reducing effect was induced only when entering the curve. Also, to the difference of what can be observed at both curve middle and end, at the curve entry, mean speed for the TRS was significantly lower than for the HP. For the three conditions, highest mean speed was observed 500m before the curve while lowest mean speed was assessed at the curve middle.

Mean acc/dec

An overview of the results for mean acc/dec can be found under FIGURE 2. More specifically, panel 2c contains one plot per test location, representing values for mean acc/dec at each of the seven measurement points. It shows that at 500m before the curve mean acc/dec was lower at location B than at location A. At 166m before the curve and at the curve entry mean acc/dec was lower at location A than at location B. From the curve middle until 50m after the curve mean acc/dec was lower at location B than at location A. At 50m before the curve there was no difference for mean acc/dec between both locations. In other words, regardless of what the test condition is like, drivers overall decelerated more strongly up until the curve middle for curves at location A when compared to curves at location B. In addition, from the curve middle onwards, drivers' acceleration was more pronounced for curves at location A in comparison with curves at location B. Supplementary analyses showed that mean deceleration for curves at location A peaked at curve entry, whereas for location B, the highest mean deceleration was located at 50m before the curve. In order to be able to evaluate the extent to which these highest mean deceleration rates can be considered as acceptable in terms of safety, we performed a one-way sample T-test to compare them with the -0.85 m/s² value proposed by Lamm and Choueiri (22) as a recommended design guideline. It resulted from this test that mean deceleration at curve entry for curves at location A (-1.38 m/s²; SD = 0.76) was significantly higher ($t = -4.1$; $p < .0005$) whereas mean deceleration registered at 50m before curves at location B (-0.59 m/s²; SD = 0.34) was significantly lower ($t = 4.6$; $p < .0005$).

Panel 2d contains one plot per test condition, representing values for mean acc/dec that were first averaged over the two different test locations and subsequently set out at each of the seven measurement points. From a comparison of the three test conditions it resulted that significant differences for mean acc/dec could be detected at three specific measurement points, i.e., (1) at 166m before the curve, (2) at 50m before the curve, and (3) at curve entry. While at 166m in advance of the curve, mean deceleration was significantly higher for curves with TRS than for curves with a HP or control curves, the opposite counted for what happens at 50m before the curve and at curve entry. At these two measurement points, drivers decelerated significantly stronger in curves with a HP and in control curves than in curves provided with TRS. Further analysis indicated that for the three test conditions, highest mean deceleration was recorded at the curve entry (control: mean = -.956, SD = .103; TRS: mean = -.507, SD = .075; HP: mean = -.991, SD = .104) and highest mean acceleration was measured at the curve exit (control: mean = .700, SD = .064; TRS: mean = .710, SD = .062; HP: mean = .789, SD = .068). However, in the TRS condition mean acc/dec did not differ between 166m before the curve and curve entry. An additional one-way sample T-test demonstrated that neither of these values significantly exceeded the guideline rate of 0.85 m/s² (22). A final interesting finding was that deceleration with TRS appeared to be more stable when compared with the other two conditions.

In sum, highest mean deceleration was recorded at curve entry at location A and at 50m before the curve at location B. At location A, mean deceleration at curve entry was significantly higher than the well known guideline value of -0.85 m/s². At both locations, from the curve middle onwards, drivers accelerated again but they did so more strongly in curves at location A. Comparison of the three test conditions showed that TRS generated larger mean deceleration than the other two conditions at 166m before the curve while at 50m before the curve and at curve entry, mean deceleration was lager in curves with a HP and control curves. Across the three conditions, highest mean deceleration occurred at the curve entry while highest acceleration was measured at curve exit with neither of these two values exceeding the earlier proposed guideline value of 0.85 m/s².

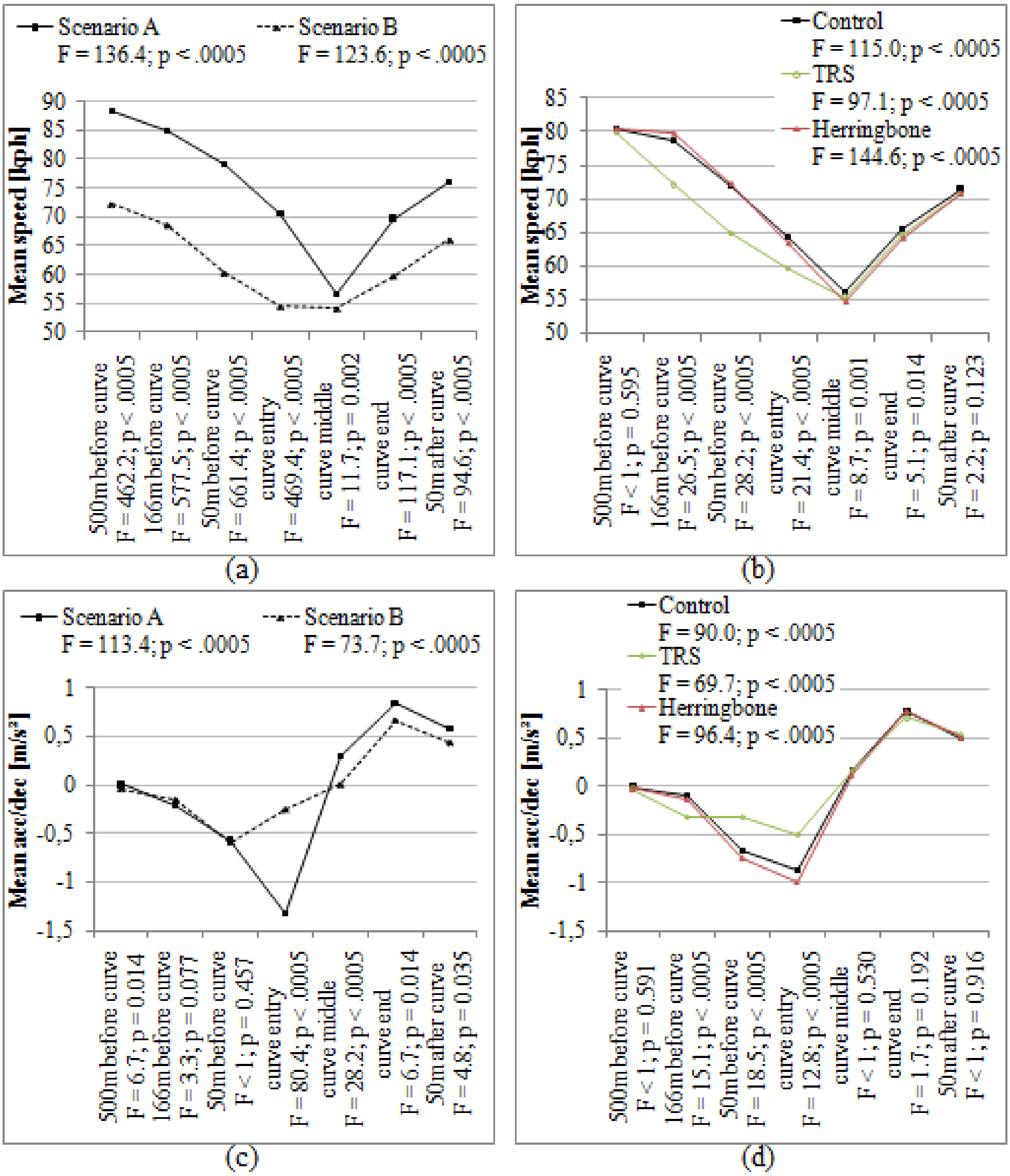


FIGURE 2 Mean speed, mean acc/dec and ANOVA statistics for the interaction of Location × Measurement point (mean speed (a) and mean acc/dec (c)) and Condition × Measurement point (mean speed (b) and mean acc/dec (d))

4.2 Lateral parameters

Mean LP

An overview of the results for mean LP can be found under FIGURE 3. Mean LP is zero on the centerline and increases to the right lane side. Due to the different curve lane widths at both locations (cf. FIGURE 1a), the middle of the lane at location A is to be located at 1.6m from the centerline while at location B lane middle is at 1.4m from the centerline. For sake of clarity, panel 3a presents results for left and right curves separately. For each curve direction, one plot per location is offered, containing values for mean LP at each of the seven measurement points. It can be derived that, irrespective of curve direction and test condition, mean LP was (marginally) lower at each of the seven measurement points for curves at location B when compared with curves at location A. Put differently, drivers overall drove closer to the centerline at location B than at location A.

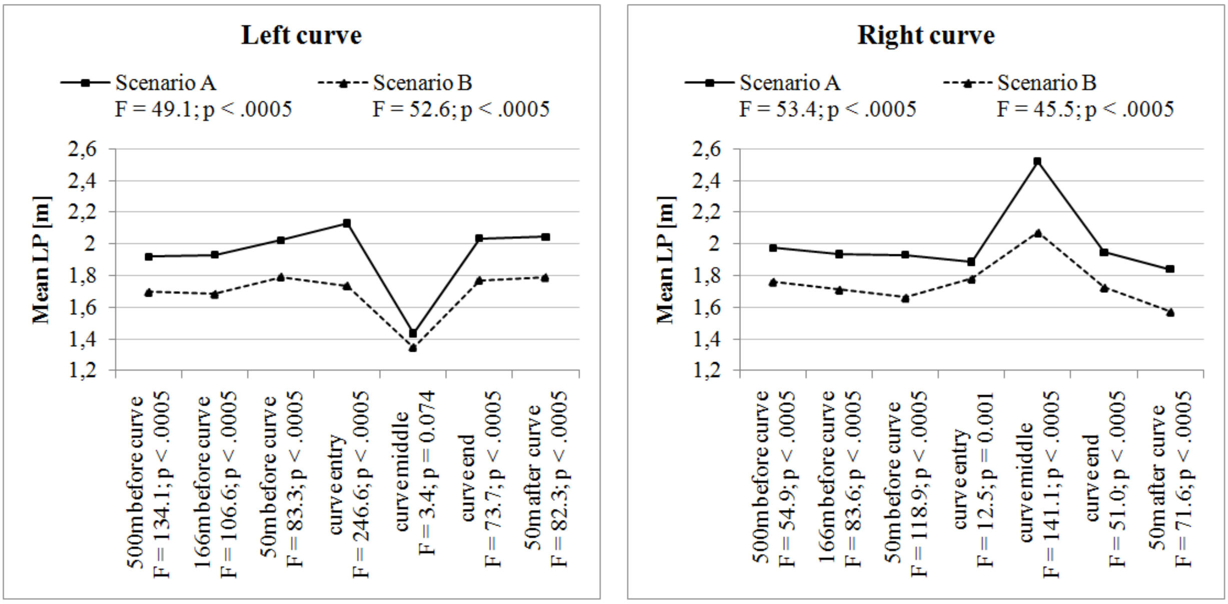
In left curves, mean LP increased from 500m before the curve until curve entry at location A and until 50m before curve entry at location B. At the curve middle mean LP reached minimum at both locations (location A: mean = 1.44; SD = 0.06 and location B: mean = 1.35; SD = 0.3). At the curve end at location B mean LP reached its curve entry level again while at location A mean LP stayed below the curve entry level. In other words, drivers drove closer to the edge line while approaching and entering left curves while they shifted to the centerline nearby the curve middle and then closer back again to the edge line at the end of the curve.

The opposite was found for right curves. Mean LP decreased from 500m before the curve until curve entry at location A and until 50m before the curve at location B. At both locations, maximum values were measured at curve middle (location A: mean = 2.52; SD = 0.06 and location B: mean = 2.07; SD = 0.03). At curve end, values for mean LP reached curve entry level again. Put differently, drivers drove closer to the centerline while approaching and entering right curves while they shifted to the edge line nearby the curve middle and then closer back again to the centerline at the curve end.

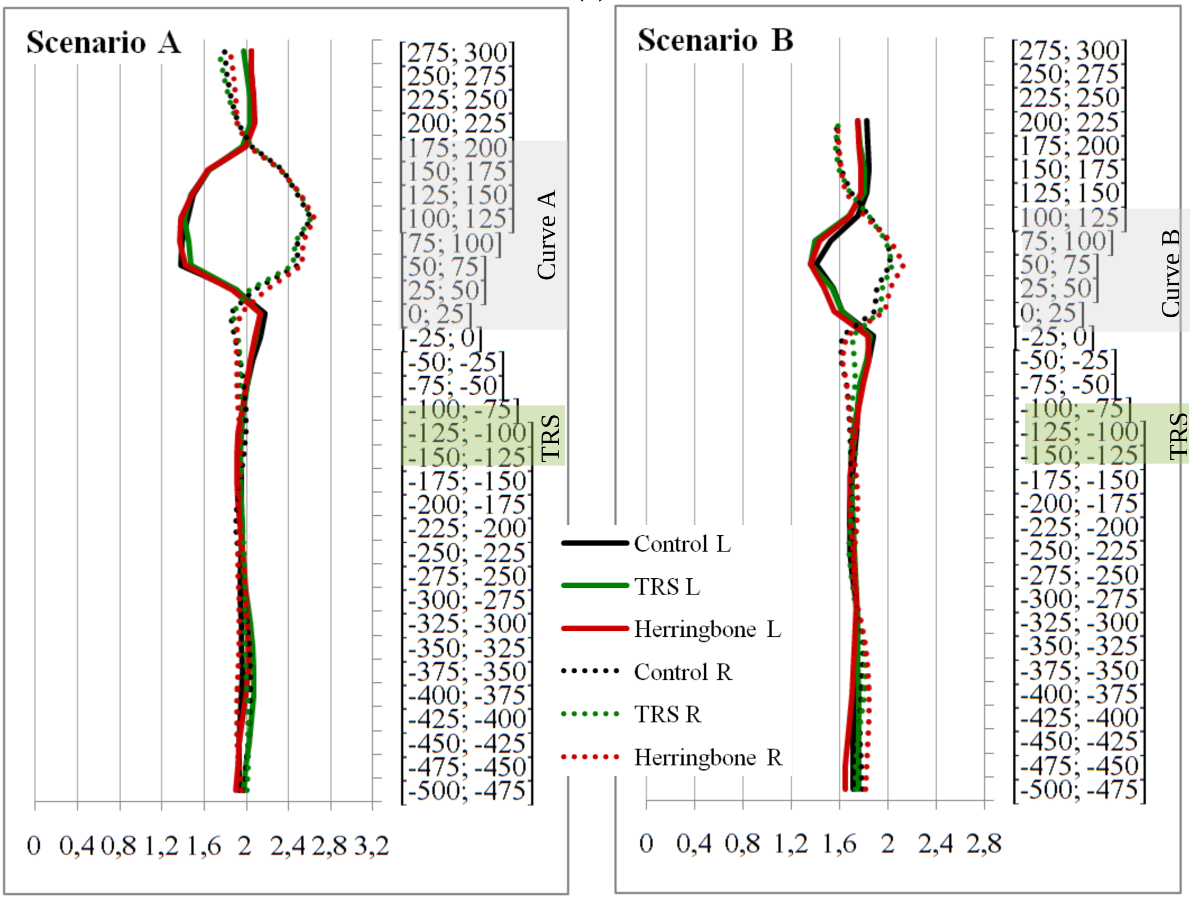
Panel 3b is meant to give further insight into how mean LP evolves for the three conditions throughout both left and right curves at the two test locations under study. It basically shows that the different conditions did not influence mean LP.

SDLP

The plots for SDLP (see FIGURE 4) illustrate that, at both locations and in each of the three conditions, SDLP remained at a constantly low level along the 400m of straight road in advance of the curve. At both locations, two peaks could be established within the curve. A first peak was situated shortly after curve entry at location A and nearby curve entry at location B. A second peak was located between curve middle and curve end at both locations. Interestingly, peaks at location A were higher than at location B. Around the curve middle SDLP decreased again but stayed above values recorded along the straight road section in advance of the curve. Once exited the curve SDLP tended to decrease again. As can be derived from the plots, there were no large differences between the three conditions.

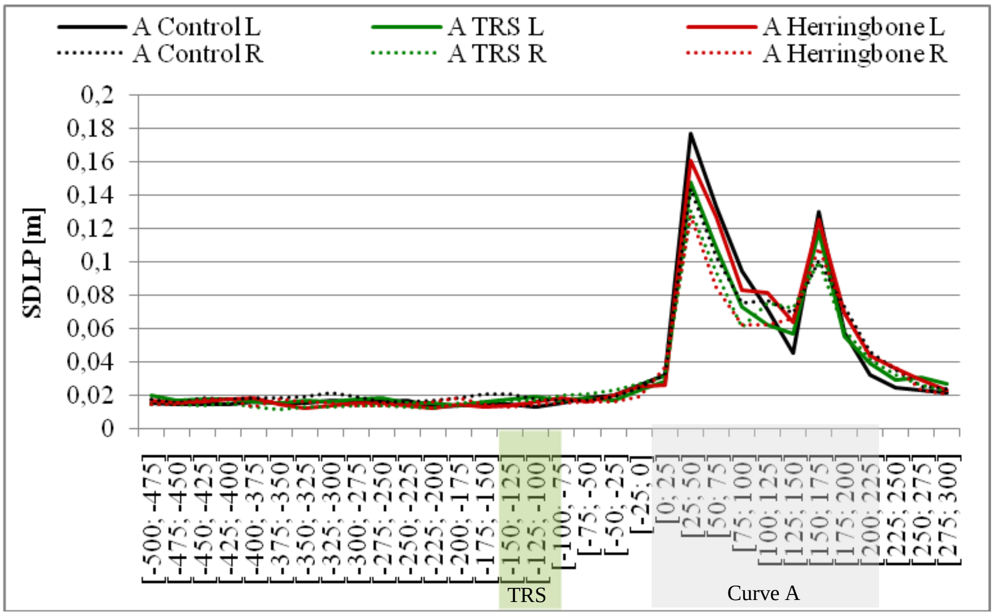


(a)

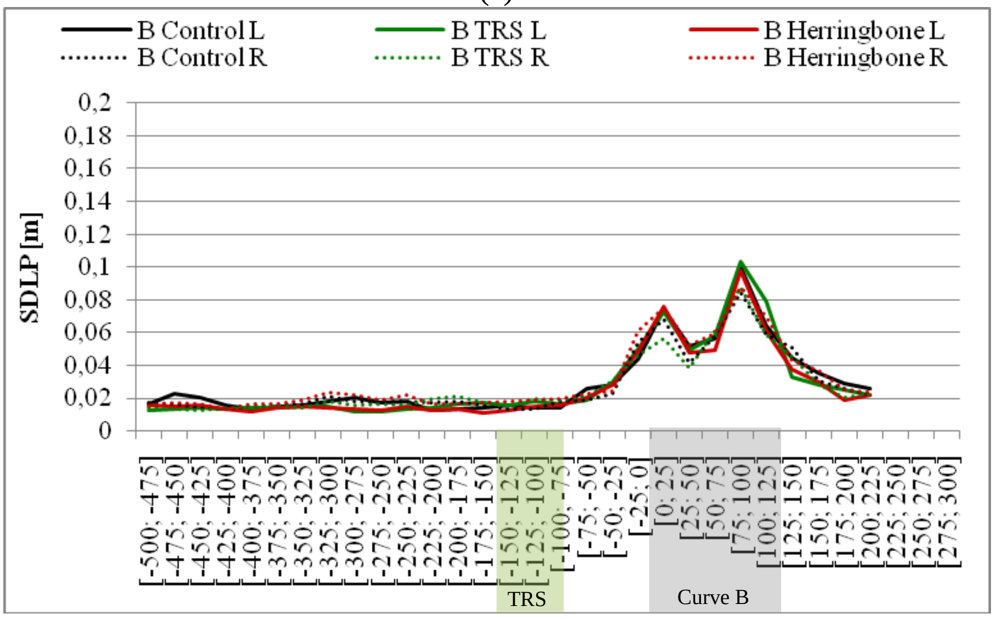


(b)

FIGURE 3 Mean LP and ANOVA statistics for the interaction of (a) Location × Direction × Measurement point and (b) descriptive plot for mean LP



(a)



(b)

FIGURE 4 Descriptive plots of SDLP for (a) location A and (b) location B

5 DISCUSSION

In this study, two real-world curves with strong indications of an existing safety problem were identified and replicated in the simulator. Interestingly, these were two compound curves both (1) situated within a rural two-way road environment, (2) following a long tangent, and (3) characterized by complex geometrical properties. Besides these similarities, the two curves in this study were substantially distinct in terms of (1) speed limit (70kph vs. 90kph), (2) cross-sectional view (different lane widths; with vs. without separate cycle lanes; with vs. without a tree-line nearby edge lines), and (3) horizontal alignment (different length; different curvature structure). These mutual dissimilarities can partially explain why differences in both speed and lateral control could be found between the two curves.

5.1 Driving behavior compared over the two curves

Overall, mean speed was higher at location A than at location B which is probably attributable to the higher speed limit at location A (90kph, location B 70kph). With respect to mean deceleration, drivers not only decelerated till further into the curve at location A, they also reduced their speed more strongly. At its peak nearby curve entry, values for mean deceleration at location A even significantly exceeded the rate of -0.85 m/s² recommended by Lamm and Choueiri (22). Even though others proposed higher acceptable values up to -1.34 and -1.8 m/s² (23, 24), which was more within the range of our results. Contrary to that, for curves at location B, maximum deceleration was reached earlier (i.e., 50m before the curve) and remained below the more stringent value of -0.85 m/s². One good reason for these differences in terms of deceleration might be that, over the different conditions, mean speed nearby curve entry at location A was still at 70kph while at location B it was only at 55kph. Consequently, drivers at location A were forced to bring back their speed more strongly than at location B in order to safely enter the curve. This is reflected in a substantially higher maximum speed reduction between tangent and curve at location A (speed difference = 31.1 kph) when compared to location B (speed difference = 17.7 kph). When considering some of the international design standards as listed up by Lamm, Mailander, & Psarianos (24), these values would indicate poor design quality for location A and fair quality at location B. Anyway, excessive and abrupt deceleration should be avoided both in terms of safety (the risk for skidding accidents would increase drastically, especially under wet conditions) as in terms of maintenance (increased tire friction puts more pressure on the road surface) (17).

With respect to lateral control mean LP was lower at location B than at location A which is not unexpected given a narrower lane width at location B. However, at both locations as well as in both directions, drivers drove closer to the inside road edge nearby the curve middle (cf. paragraph 4.2). This confirms results reported in other studies (21, 27). Results for SDLP clearly showed how this lateral shift towards and then back away from the inside road edge was larger at location A, probably due to the fact that driving lanes were broader at this location, thereby leaving drivers with more free space to move laterally. These results seemingly corroborate the contention that broader road lanes might induce larger variations in lateral control (21, 27, 28). Such increased swerving might of course become dangerous in case there is opposite traffic, under slippery conditions, when facing heavy winds or when there is only limited sight.

5.2 Effect of TRS and HP on driving behavior

The primary objective of this study was to examine the effect of TRS and a backward pointing HP on speed and lateral control in and nearby curves. Both TRS and HP generated significant speed reductions that persisted until reaching the curve end. Yet, compared to the HP, TRS evoked lower speed earlier (166m before the curve vs. at curve entry) and more strongly at curve entry. The results for mean acc/dec corresponded to this finding with the highest deceleration rates at 166 meters before the curve for TRS versus 50m before the curve for HP. Important in terms of safety is that, deceleration until the curve entry was more stable with TRS than with HP. Parameters for lateral control were not significantly affected by TRS or HP.

6 CONCLUSION AND RECOMMENDATIONS

Considering the results for the different behavioral parameters, TRS might be preferred over the backward pointing HP as a speed reducing measure nearby curves. According to the power model for speed and accidents (28), mean speed reductions obtained for TRS in this study (i.e., -5.9 kph at curve entry; -1.8 kph at curve middle; -1.2 kph at curve end) would result in a decrease of 6.4 to 28.7% for fatal accidents and 3.6 to 17.1% for injury accidents, depending on the exact location of accidents along the curve (i.e., entry, middle or end). Despite the favorable implications in terms of traffic safety, Dewar and Olson (18) warn for the potential negative side effects of TRS such as noise, rapid wear, disruption of drainage and reduced tire-road surface friction. It should not be overlooked either that neither of the two markings examined fail to produce any significant effects on parameters for lateral control. Even though this is not the primary function of TRS or HPs, this finding should warrant policy makers not to consider these two road markings as a countermeasure in curves where accidents are mainly due inappropriate lateral control.

7 ACKNOWLEDGEMENTS

Part of this research was funded by the European Regional Development Fund (ERDF). The authors thank Dirk Roox and Marc Geraerts for technical assistance and Jeroen Vercaigne for helping collect data.

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