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SCHOOL FOR TRANSPORTATION SCIENCES
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Master's thesis

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Thesis presented in fulfillment of the requirements for the degree of Master of Transportation Sciences

Universiteit Hasselt | Campus Hasselt | Martelarenlaan 42 | BE-3500 Hasselt
Universiteit Hasselt | Campus Diepenbeek | Agoralaan Gebouw D | BE-3590 Diepenbeek

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THE IMPACT OF PERCEPTUAL COUNTERMEASURES ON DRIVING BEHAVIOUR IN RURAL-URBAN TRANSITION ROAD SEGMENTS: A DRIVING SIMULATOR STUDY

Qinaat Hussain
Hasselt University – Transportation Research Institute (IMOB)
Agoralaan, 3590 Diepenbeek, Belgium
Tel: +32 (0) 466 04 46 86 E-mail: qinaat.hussain@student.uhasselt.be

Ali Pirdavani*
Hasselt University – Faculty of Engineering Technology &
Hasselt University – Transportation Research Institute (IMOB)
Agoralaan, 3590 Diepenbeek, Belgium
Tel: +32 (0) 11 29 21 83 Fax: +32 (0) 11 26 91 99 Email: ali.pirdavani@uhasselt.be

Caroline Ariën
Hasselt University – Transportation Research Institute (IMOB)
Agoralaan, 3590 Diepenbeek, Belgium
Tel: +32(0)11 26 91 35; Fax: +32(0)11 26 91 99; Email: caroline.arien@uhasselt.be

Tom Brijs
Hasselt University – Transportation Research Institute (IMOB)
Agoralaan, 3590 Diepenbeek, Belgium
Tel: +32 (0) 11 26 91 55 Fax: +32 (0) 11 26 91 99 Email: tom.brijs@uhasselt.be

* Corresponding author

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ABSTRACT

This driving simulator study investigated the impact of perceptual countermeasures on driving behavior by creating perceptual effects via pavement markings. Two different marking schemes (i.e. Optical Circles and Optical Bars) were tested separately for road transitions between rural and urban areas where the speed limit reduces from 70 kph to 50 kph. The tested treatments were intended to achieve combined perceptual effects (i.e. increase drivers' attention, perceptual speed and perceptual road narrowing effect) independently. Data were analyzed for 44 participants (30 men and 14 female). The study results showed that the speed was reduced significantly for the both road marking treatments, however, the Optical Circle scenario in which circles with increasing size were implemented was the most effective solution. Moreover, variations in acceleration/deceleration and lateral position were not found to be significant due to treatments. This indicates that drivers did not decelerate or evade vehicles unsafely when confronting the road markings. The obtained results recommend Optical Circles to policy makers for further evaluation as a low-cost speed management tool.

Key Findings:

- Bigger size and solid (i.e. filled) polygons can be used to increase drivers' attention in a better way than smaller size polygons
- Optical circles can help drivers appropriately reduce speed at road transitions
- Combined perceptual effects (i.e. perceptual speed, drivers' attention and road narrowing illusion) can be achieved using Optical Circles instead of using combined expensive countermeasures such as, combination of markings, roadside fence and gantries

Keywords: Perceptual measures; Driving simulator; Urban area; Driving behavior; Road safety; Optical circles

1. INTRODUCTION

Many journeys include transitions from a road stretch where speed limit drops from higher values to lower values. These transition road segments (i.e. rural to urban) are more complex for drivers because of a combination of changes in the road environment and a sudden speed change (i.e. 70 kph to 50 kph in Flanders) (Ariën et al., 2013; Galante et al., 2010) with often an inadequate adaption to the speed limits (Cao et al., 2015; Hallmark et al., 2007). As speed influences both the probability of a crash and its severity (Aarts & van Schagen, 2006; De Pauw et al., 2014; De Pelsmacker & Janssens, 2007; Elvik, 2009; Heydari et al., 2014; Soole et al., 2013; Wu et al., 2013), these transitions could be considered as higher accidents prone zones. Furthermore, logistic models describing the relationship between impact speed and pedestrian fatality risk show that the risk increases or decreases very rapidly for any smaller change in the impact speed after 50 kph (Anderson et al., 1997; Ashton, 1980; Davis, 2001; Oh, Kang, & Kim, 2008; Pasanen, 1992). Therefore, appropriate speed management at rural to urban transitions between 70 kph and 50 kph is essential.

Different types of approaches have been used to manage driving speed on roads. Perceptual countermeasures could be one of the best possible solutions to adequately reduce driving speed and increase road safety at transitions as tested by previous researchers. In this study, we focus more specifically on optical pavement markings of which various types exist. Optical speed bars OSB with reduced spacing in travelling direction (Galante et al., 2010; Gates et al., 2008; Godley et al., 2000; Hallmark et al., 2013; Montella et al., 2011) were used to increase drivers' perceptual speed; while dragon teeth markings (Montella et al., 2015; Montella et al., 2011), peripheral transverse bars (Galante et al., 2010; Montella et al., 2011) and herringbone pattern (Arien et al., 2016; Charlton, 2007) were used for producing road narrowing effect. To achieve combined perceptual effects of increasing drivers' attention, increasing perceptual speed and creating road narrowing effect, researchers tested combinations of different treatments.

Galante et al. (2010) conducted a driving simulator study in which two alternative scenarios with integrative traffic calming devices were implemented to investigate drivers' speed behavior in a section of rural highway crossing a small urban community. The first alternative scenario was composed of six different approaches. Transverse rumble strips TRS and OSB were used to increase drivers' perceived speed. Two treatments (i.e. peripheral transverse bars and roadside fence) were installed immediately after the TRS to give road narrowing illusion while colored brick strip and gantry were placed at the transition to increase drivers' attention while entering to the urban area. Both cluster analysis and statistical tests show that the speed reducing effect was significant along the urban community.

Montella et al. (2011) used combination of different treatments including physical road narrowing approach to evaluate driving behavior in their driving simulator study. TRS and OSB were used for the potential impact on perceptual speed while peripheral transverse bars and dragon teeth markings were used based on the principle of visually narrowing the road. To increase further attention of the drivers, intersection area was painted by a strip of red color surface with printed bituminous concrete appearing as brick pavers. The study revealed that combined treatments were significantly more effective than any single treatment. The study strongly recommended the combined treatments for real world implementations.

Another study investigated combined effect of warning signs, delineation treatments and perceptual measures at curves on rural highway (Montella et al., 2015). Curves warning sign was used with TRS, colored TRS, dragon teeth markings and colored median island in different scenarios to increase drivers' perceptual speed, attention and road narrowing effect. The results show that presence of treatments helped drivers detect the curve earlier and appropriately reduce their speed.

In the current study, we aim to achieve combined perceptual effects (i.e. increase drivers' attention, perceptual speed and perceptual road narrowing effect) by implementing a single treatment using a driving simulator. To achieve combined perceptual effects, we introduced Optical Circles 'OC' with increasing diameters (Figure 1b) based on the concept of forced perspective illusion and compared with modified form of the commonly used speed bars (i.e. Optical Bars 'OB' with increasing widths and decreasing spacing displayed in Figure 1a). To the best of our knowledge, circle markings have never used for this purpose while speed bars are commonly used with fixed width and decreasing spacing.

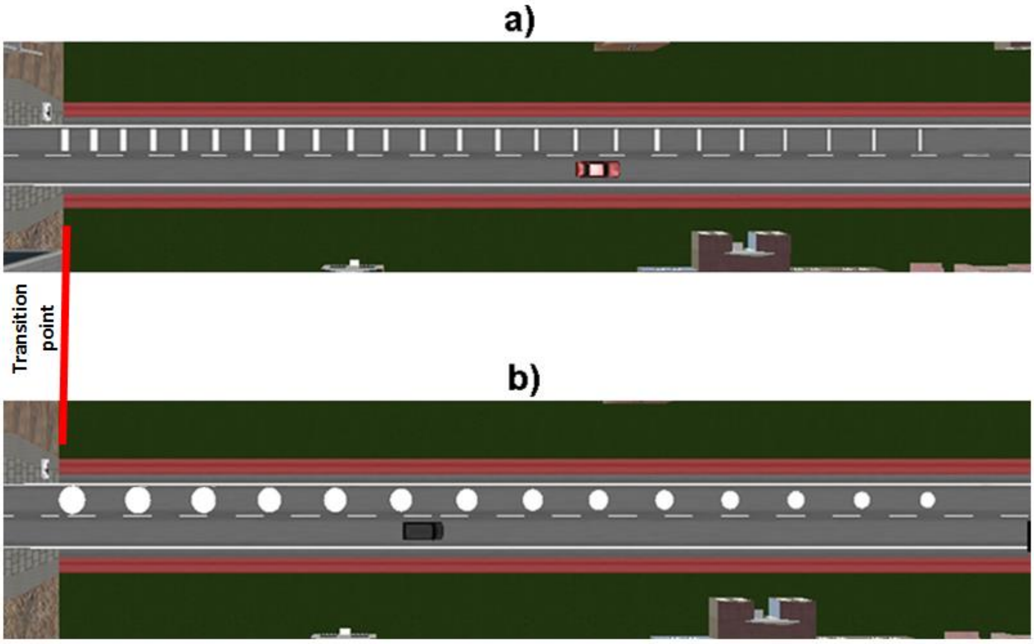

FIGURE 1: Top view of the treatments' segments (Traffic direction on marking side: right to left): a) Optical bars; b) Optical circles.

2. OBJECTIVES AND RESEARCH QUESTIONS

This driving simulator research investigates the impact of perceptual countermeasures on driving behavior by creating combined perceptual effects by means of pavement markings at road transitions between rural and urban areas whereof the speed limit reduces from 70 kph to 50 kph. The main research questions addressed in this research are as follows:

- To what extent can Optical Circles (increasing diameter and constant central to central distance in travel direction) reduce the speed of drivers for transition road segments?
- To what extent can Optical Bars (decreasing spacing and increasing width apart in travel direction) reduce the speed of drivers for transition road segments?
- Which technique is more effective in increasing the alertness of drivers by providing optical illusion?
- Which technique is more effective in reducing driving speed at road transition sections?

3. METHODOLOGY

3.1. Participants

Fifty subjects with a valid driving license participated in the study. Six participants were excluded: two were affected by simulation sickness and four participants were identified as extreme outliers. Thus, 44 participants (30 men vs. 14 female) remained in the sample (mean age: 28.06 years, SD age: 8.09 years, mean driving experience: 6.65 years, and SD driving experience: 8.16 years).

3.2. Apparatus

The experiment was conducted using the driving simulator at the Transportation Research Institute (IMOB) of Hasselt University. The simulator consisted of two main components: (a) the driving unit – a real car (fixed-base) equipped with speedometer, force-feedback steering wheel, pedals, indicators, gearbox and (b) a large 180° seamless curved screen with three projectors. The components are interfaced with STISIM Drive® 3 which offers high speed graphics and sound processing (Figure 2).

FIGURE 2: Driving simulator: Transportation Research Institute (IMOB), Hasselt University.

3.3. Scenarios design

Three different rural (70 kph) to urban (50 kph) transition sections were designed using STISIM Drive® interface. The reference transition section was an untreated control scenario, while the other two transition sections were designed with the proposed countermeasures (i.e. OC scenario and OB scenario). The transition sections where alternated with filler pieces, which were meant to create some variation while driving as shown in Figure 3. To provide drivers with appropriate time within painted marking segment, the length of marking segments (i.e. 100 m) was calculated for 6 seconds of driving time. This is the approximate space and time drivers require to decrease their speed from 70 kph to 50 kph.

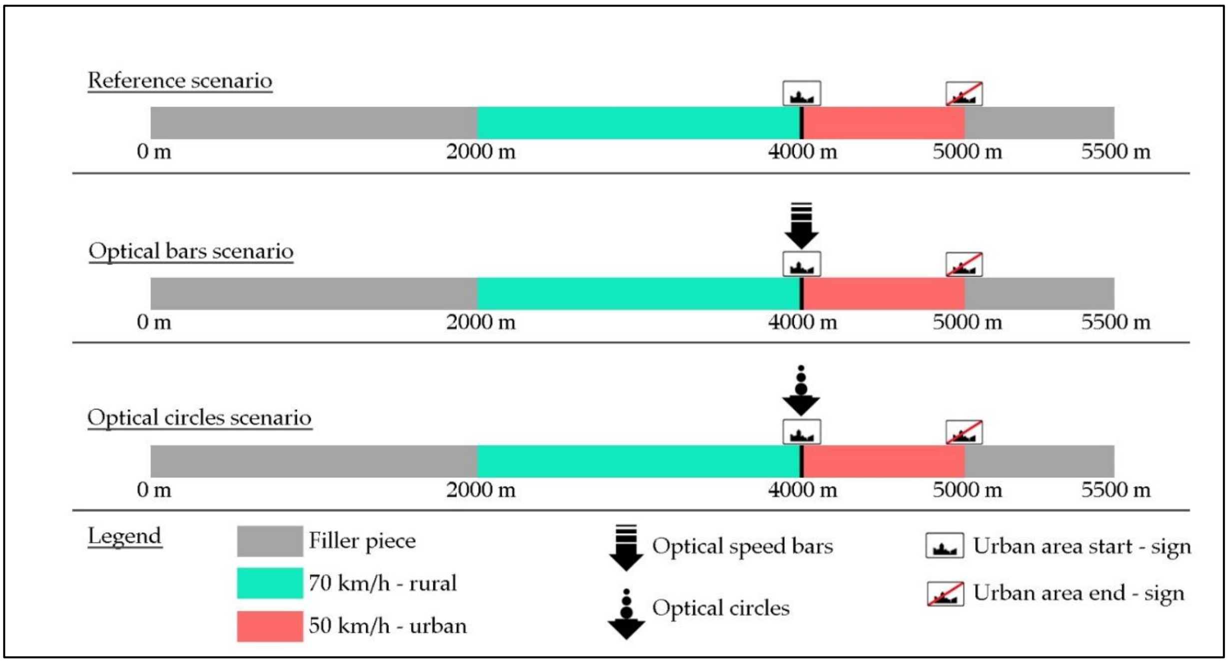

FIGURE 3: Scenarios overview: Reference, OB and OC scenarios.

a) Optical circles scenario and speed reduction mechanism

For OC scenario, circle's diameter is increased by 0.1 m in the travelling direction, starting from the diameter of 1.7 m while ending with 3.0 m. The center to center distance between the adjacent circles was kept similar (i.e. 7.5 m) for the whole marking segment thus circle to circle spacing was reducing due to increase in diameter. The increasing sizes of the circles can produce forced perspective illusion as the visual angle and spacing will change for every next circle (Endler et al. 2010; Kirsti, 2007). According to (Ross & Plug, 1998) false perception of the distance can be produced based on the sizes of the objects. The bigger sizes of the circles can be perceived nearer, which can lead to increase drivers' perceptual speed while approaching the transition zone. The spacing between circles and roadside reduced from 0.9 m to 0.25 m as the size of the circles increased as shown in Figure 1b. This phenomenon can produce road narrowing illusion and according to Godley et al. (2004) this can increase drivers' perceptual speed. Circles were filled with white color (i.e. solid) to increase drivers' attention appropriately.

Why circles?

As a common practice, when vehicle is passing on the polygons with increasing sizes it produces slightly negative effect on the illusion as it takes slightly more time while passing on the bigger sizes. Circles were chosen for this study based on some hypotheses implying that any other possible polygon might produce comparably more negative effect on the illusion. After circle, square was the best alternative but because of more filled area (Figure 4a), squares with increasing sizes may produce slightly more negative effect for passing vehicles as well as lesser road narrowing effect. Ellipse with major at y-axis (Figure 4b) will produce more negative impact on illusion because of greater ratio of solid area in travelling direction, while ellipse with major at x-axis (Figure 4c) will reach roadsides with comparably smaller sizes than circles and, therefore, will produce lesser effect of forced perspective illusion. Triangles are used to warn motorists of an impending junction ahead in the most cases and can create confusions.

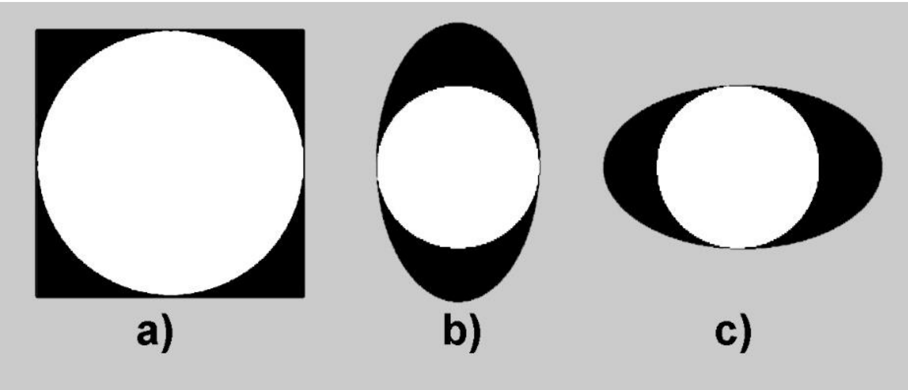

FIGURE 4: Alternative to circle: a) square; b) ellipse with major at y-axis; c) ellipse with major at x-axis.

b) Optical bars scenario and speed reduction mechanism

OB were placed along 100 m stretch of road with reduced spacing from 5 m to 3 m based on the concept of 4 bars per second used by Galante et al. (2010), if the drivers reduce their speed from 70 kph to 50 kph along the stretch. The width of every next bar was increased by 2 cm (i.e. started with width of 0.2 m and ended with 0.66 m) as shown in Figure 1a. The main objective of implementing these bars was creating illusion by reducing the spacing between consecutive bars and increasing their width. Increasing width can intensify the spacing reduction slightly as well as can create slight forced perspective illusion. The drivers face more bars every next second as they approach to transition zone and, hence, perceptual speed is increased.

3.4. Driving scenarios

The three scenarios (i.e. reference, OC and OB) were combined randomly to form a single driving run with the length of 16.5 km. Each participant drives each run two times, implying that (s)he confronted each scenario two times randomly. Weather conditions were sunny and dry and there was only traffic present in the opposite direction.

3.5. Procedure

Each participant was tested individually with the following four steps:

1. Each participant was asked to sign an informed consent form, fill in a pre-questionnaire consisting of sociodemographic questions along with some driving experience related questions.
2. Participants were introduced to the driving simulator and were given a practice trial to get familiar with it.
3. Drivers were instructed to 'drive as you normally do, follow the traffic rules and continue driving until you are instructed to stop'. Each participant undertook two driving runs with a short break in between.
4. After the experimental session is completed, each participant was asked to complete a post-test questionnaire. The questionnaire included feedback/thoughts about the driving experience, about the driving simulator itself and the countermeasures applied in the scenarios.

3.6. Data collection and analysis

Data was collected for longitudinal (speed and acceleration) and lateral control (lateral position) using STISIM Drive® Software. Data was converted into every tenth of the meter to achieve high accuracy results.

The entire analysis section is 900 m (500 m before and 400 m after the transition point) long and is divided into 9 equal zones of 100 m. For each zone the mean speed, the standard deviation of acceleration/deceleration (SDAD) and the standard deviation of lateral position (SDLP) were calculated. Standard deviations were chosen for acceleration/deceleration and lateral position in each zone to estimate variations in our dataset. By doing so, we can estimate whether the drivers decelerate and evade vehicles in a safely manner or not.

Outlier analysis was performed for each analysis zone for 48 participants to point out observations that were significantly deviated from the other observations. The analysis was performed separately for each of the 54 possible combinations (i.e. 9 zones x 3 scenarios x 2 runs). Any participant that is identified as an outlier (i.e. drove the analysis section faster than 1.5 interquartile range from the group's mean) in more than 15% of the total zones (i.e. 8 analysis zones) was eliminated from the analysis.

Within-subject design was chosen for experimental method of the current study, as each participant was tested for each scenario twice. According to Huberty & Morris (1989) the typical analysis approach used in the behavioral sciences for multiple outcome variables is either to condcut multiple ANOVA tests or to conduct a multivariate analyses of variance (MANOVA) followed by multiple ANOVAS. For this study MANOVA followed by individual ANOVA tests were conducted on the variables of interest (i.e. mean speed, SDAD and SDLP for 9 zones, 3 scenarios (reference, OC, OB) and 2 driving runs.

4. RESULTS

Table 1 presents the results from the multivariate and univariate analyses. The MANOVA shows significant main effects of the factors Scenario and Zone. Furthermore, the interaction effects of Run x Zone and Scenario x Zone are also significant. This shows that markings as a main effect and two-way interaction effect with Zone were helpful to influence driving behavior. However, to understand the respective effects, we examine the univariate statistics for each dependent variable separately.

TABLE 1: Multivariate and univariate statistics (significant p-values are indicated in bold)

Manova (Wilks' Lambda)				
Variable	*Value*	*F*	*Df*	*p*
Run	0.937	0.915	3.000	0.442
Scenario	0.796	3.385	6.000	**0.004**
Zone	0.029	98.950	24.000	**<.001**
Run x Scenario	0.924	1.127	6.000	0.348
Run x Zone	0.889	1.715	24.000	**0.018**
Scenario x Zone	0.803	3.248	48.000	**<.001**
Run x Scenario x Zone	0.955	0.664	48.000	0.964

Univariate statistics (Greenhouse-Geisser)			
Variable	*F*	*df*	*p*
Mean speed			
Scenario	9.153	1.814	**<.001**
Zone	604.673	3.226	**<.001**
Run	0.487	1.000	0.489
Scenario x Zone	8.397	7.265	**<.001**
Run x Scenario	0.509	1.802	0.584
Run x Zone	4.099	2.976	**0.008**
SDAD			
Scenario	0.084	1.754	0.898
Zone	46.172	3.080	**<.001**
Scenario x Zone	1.048	7.627	0.399
Run x Scenario	1.671	1.978	0.194
Run x Zone	0.911	4.538	0.468
SDLP			
Scenario	0.729	1.979	0.484
Zone	4.693	4.310	**0.001**
Scenario x Zone	0.505	9.246	0.875
Run x Scenario	0.855	1.660	0.411
Run x Zone	0.325	5.478	0.911

4.1. Mean speed

The ANOVA for mean speed shows significant main effects of Scenario and Zone; and the interaction effects of Scenario x Zone and Run x Zone as shown in Table 1. The main effect of Run and the interaction effect of Run x Scenario were insignificant meaning that speed was not significantly changed between two separate driving runs on the three different scenarios.

Figure 5 shows the mean speed values of both driving runs together along each zone and for each scenario separately. It can be seen from the figure, that drivers started to reduce their speed from 400 m before the rural-urban transition point in the OC scenario and after 300 m in the OB scenario. The speed reduction started later in the reference scenario as compared with treated scenarios. Mean speed remains lower for both OB and OC scenarios as compared with the reference scenario up to more than 200 meters after the transition point. Table 2 presents the detailed statistics of mean speed reduction for both treatments comparing with Reference scenario. Mean speed was reduced maximally for OC design on zone 4 (i.e. 5.76 kph) for driving run 1. For both the runs averagely, the highest reduction was noted for OC scenario on zone 4 followed by zone 5. However, for OB scenario the speed was reduced maximally on the pavement markings zone (i.e. zone 5).

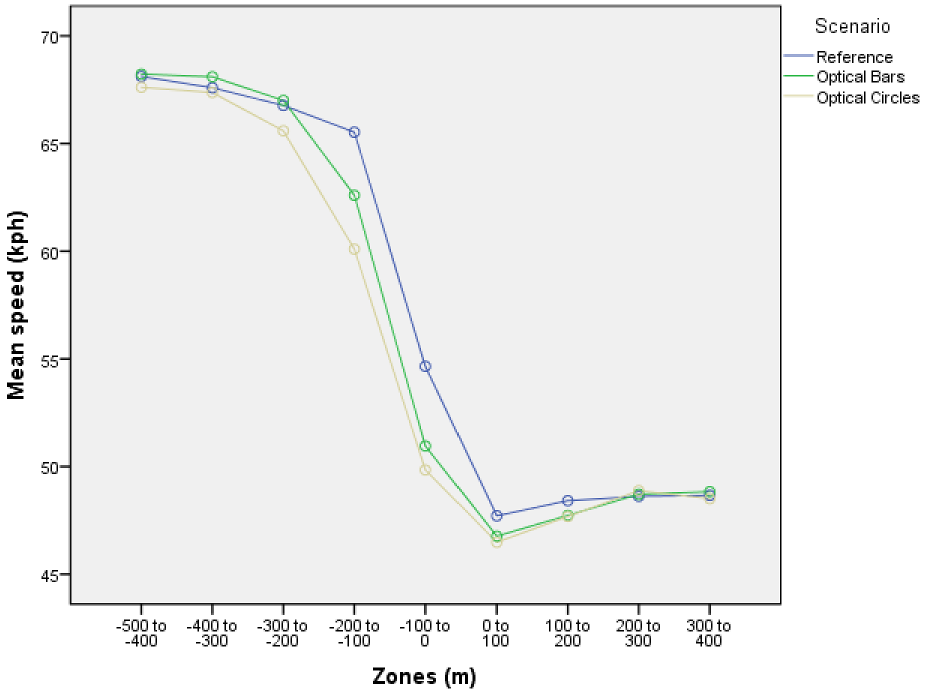

FIGURE 5: Mean speed profiles for Scenarios by separate lines.

TABLE 2: Detailed statistics of mean speed differences over each zone

	Mean speed								
	Zone 1	*Zone 2*	*Zone 3*	*Zone 4*	*Zone 5*	*Zone 6*	*Zone 7*	*Zone 8*	*Zone 9*
Run 1									
Ref-OC	1.11	0.56	1.07	5.76	5.32	1.55	0.57	-0.21	1.28
Ref-OB	0.23	0.04	0.11	2.16	3.80	1.48	0.58	-0.03	0.44
Run 2									
Ref-OC	-0.11	-0.12	1.28	5.10	4.31	0.90	0.89	-0.33	-0.97
Ref-OB	-0.45	-1.06	-0.58	3.69	3.60	0.41	0.78	-0.17	-0.79
Average									
Ref-OC	0.50	0.22	1.18	5.43	4.81	1.23	0.73	-0.27	0.16
Ref-OB	-0.11	-0.51	-0.23	2.93	3.70	0.95	0.68	-0.10	-0.17

4.2. SDAD

Mean acceleration/deceleration cannot assume whether the vehicles decelerate in a safely manner because the values were generated both in positive (i.e. acceleration) and negative (i.e. deceleration) by STISIM Drive® Software and it was zonal analysis. By calculating SDAD for each zone we estimated the variations in the rates at which vehicles were decelerated and further analyzed for all participants and zones by performing ANOVA. The ANOVA for SDAD shows only significant main effect of Zone. Variations in acceleration/deceleration were not significant along the three different scenarios as the main effect Scenario and the interaction effect Scenario x Zone were insignificant. Variation in acceleration/deceleration can be observed in Figure 6. Variations reached to highest point in Zone 5 for untreated scenario (i.e. 0.36 m/s^2) and in zone 4 for OC and OB scenarios (i.e. 0.33 m/s^2 and 0.34 m/s^2 respectively).

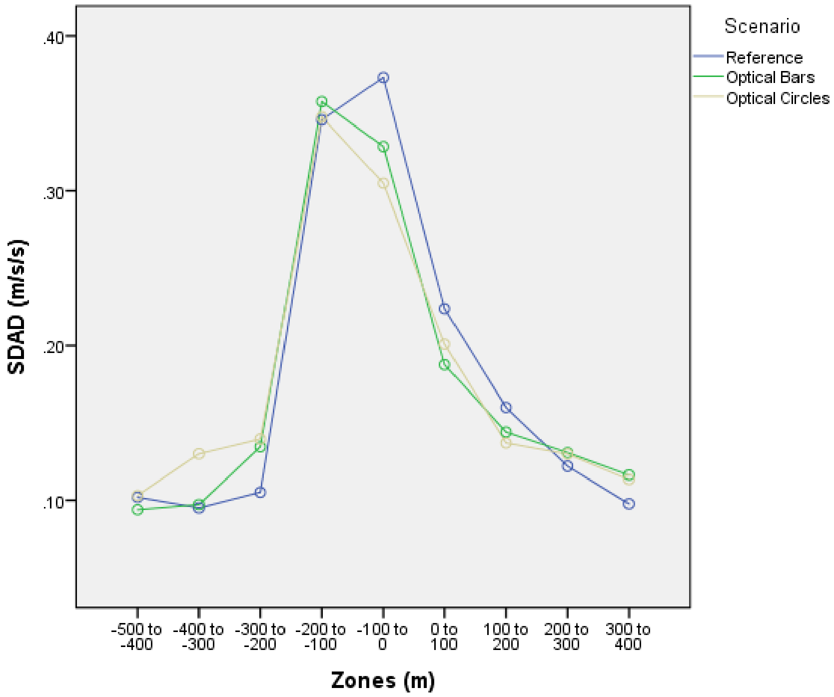

FIGURE 6: SDAD along analysis zones separated by all the three scenarios.

4.3. SDLP

Similar to SDAD, results from ANOVA shows only the main effect Zone was significant for SDLP and other all main and interactions effects were insignificant. The variations in lateral position for all the three scenarios are shown in Figure 7. It can be seen that the highest variation of about 0.11 m was observed for Reference scenario. Variations in the lateral position for OC scenario from zone 4 to zone 6 can be seen considerably lower than other two scenarios.

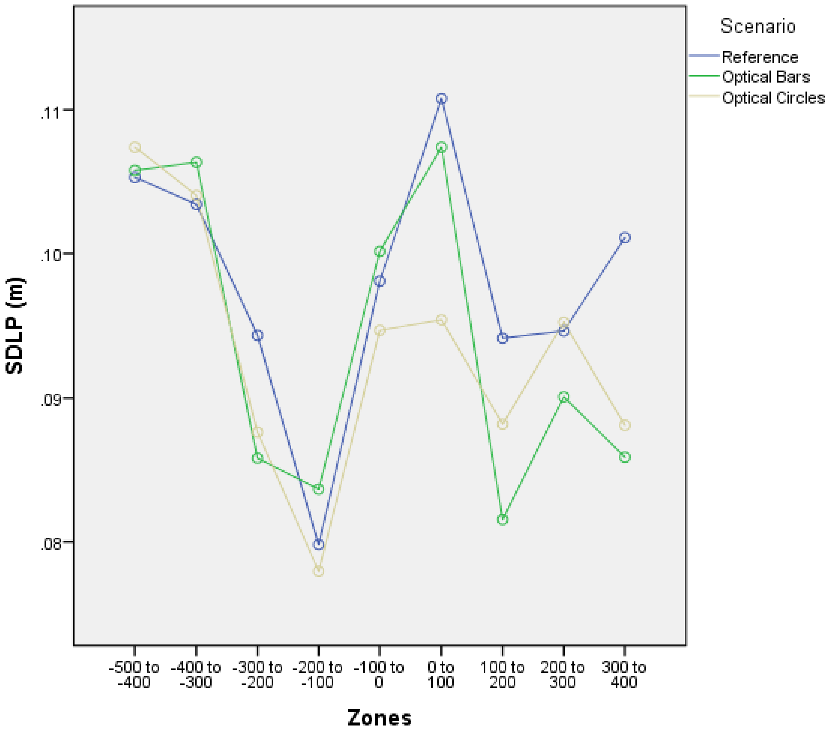

FIGURE 7: SDLP along analysis zones separated by all the three scenarios.

4.4. Alertness/Attention

The results from post-questionnaire are presented in Table 3, for a question 'Did the markings make you more alert while entering to the urban area?' According to participants, both treatments helped them increase their attention while entering the urban area, as 88.5 % answers were with 4+ rating on a 1 to 5 rating scale. OC was, however, more effective in increasing the alertness of drivers.

TABLE 3: Likert scale results for driver's alertness

Did the markings make you more alert while entering to the urban area?				
Treatment type	N	Scale	Mean	St. deviation
OC	43	(Agree = 5; Disagree = 1)	4.488	0.855
OB	44	(Agree = 5; Disagree = 1)	4.227	1.075

5. DISCUSSION

The results from MANOVA showed that both treatments were considerably effective in influencing drivers' behavior. Furthermore, short-term learning effects for the pavement markings were not observed in the study as the results for effect Run X Scenario were insignificant. This phenomenon indicates that these illusive effects may remain to improve road safety in a long term.

Results for mean speed showed that both treatments were effective in reducing drivers' speed significantly. However, the speed reduction started 300 m before the start of the OC while 200 m before the start of the OB. Speed reduction observed for OC scenario on the zone 4 (100 m stretch before the start of markings), was 2.5 kph lower than observed for OB scenario, for both runs averagely. This was the maximum difference found between the two treatments in corresponding to zones and could be attributed to the bigger sizes of polygons that increase drivers' attention in a better way before they actually reach the markings. The three zones from 200 m before and up to 100 m after the transition point (i.e. zones 4, 5 and 6) can be considered as the most complex sections of the examined road because this is the stretch where road environment scenarios as well as driving speed changes. The lowest speed observed among zone 4 to zone 6, was 52.14 kph for OC scenario compared to 53.44 kph for OB and 55.97 kph for Reference scenarios. According to the logistic model of pedestrian casualty risk in passenger vehicle collision (Kong & Yang, 2010), the risk of pedestrians' fatality for 52.14 kph, 53.44 kph and 55.97 impact speeds, could be 33.73%, 38.37% and 47.95%, respectively. This analysis indicates that about 15 percent of fatality risk could be reduced by implementing optical circles at transition zones.

SDAD was only significant for the variable Zone independent of the other variables. It is probably because the speed dropped from 70 kph to 50 kph and drivers decelerated while entering to urban area. Similarly, SDLP was also only significant for the variable Zone independent of the other variables and could probably because of the changes in road environment and also every zone was of 100 m length. Furthermore, the lowest variations in acceleration/deceleration was found for OC followed by OB along the 200 m stretch before entering to the urban area, which means drivers did not decelerate unsafely because of markings. SDLP values were higher for transition point but still too lower to be considered for further investigations.

Finally, it can be concluded from the participants' arguments and results that attention of the drivers was increased more effectively by both proposed countermeasures. However, OC was ranked higher by the drivers as well as other results were more effective for OC (e.g. speed reduction was higher and variations in SDAD and SDLP were lower than OB before the transition zone). This could be due to the fact that bigger sizes of polygons on the road can attract drivers' attention in a better way.

To finalize the discussion, it is worth to mention that the speed reduction mechanism lasted only for 200 m after the transition zone and did not significantly change afterwards for both treatments. Previous studies on combined countermeasures (Galante et al., 2010; Montella et al., 2011; Montella et al., 2015) noted higher reduction in speed but most probably this was because the speed differences at transitions were higher than our study. Using OC at transitions with higher speed difference (e.g. 100 kph to 50 kph) may help increase drivers' perceptual speed more effectively resulting in greater reduction in speed. However, these circles due to the bigger sizes may create a potential hazard, in particular for motorcyclists. However, using skid resistance materials (e.g. angular materials and silica friction material etc.) can be used to provide adequate skid resistance values similar to common road surfaces (Harlow, 2005).

6. CONCLUSION AND RECOMMENDATIONS

The paper investigated the effect of perceptual countermeasures at rural-urban transitions (i.e. 70 kph to 50 kph) on driving behavior. The study results clearly showed that the speed was reduced significantly for both road marking treatments. The newly introduced OC scenario, in which circle marking with increasing size were implemented, was the most effective solution because it influenced driving behavior by reducing their speed (up to 5.76 kph) and keeping it lower compared to the two other scenarios over the entire course of 500 m (300 m before and 200 m after the transition). The speed reduction profile clearly shows that the driving speed can be decreased more effectively by producing forced perspective illusion with greater size of solid (i.e. filled color) road markings.

Many jurisdictions use TRS to alert the drivers at different areas however, TRS generally produce noise due to their placement and could be perceived negatively by adjacent land owners. OC can be used as an alternative to other expensive (i.e. combined treatments such as roadside fence and gantry for creating road narrowing illusion and increasing drivers' attention, alternatively) and unfriendly (i.e. producing noise for adjacent communities) treatments (e.g. TRS), on the roads with surrounding communities.

In conclusion, the OC scenario is recommended for policy makers as a low-cost speed management tool. Real world implementation of OC will allow practitioners to see the long-term effect by conducting before-after studies.

7. LIMITATIONS AND FUTURE RESEARCH

The study was carried out on limited test persons (i.e. participants) and only presented the short-term effects of the proposed countermeasures on driving behavior. Long-term effects can only be seen after the actual implementation in real world. The study was conducted using a fixed-base driving simulator, which might reduce the degree of realism.

For future research these markings can be tested for different types of the road sections such as curves, intersections and links as well as for transitions with different speeds. Design, size ratios and spacing of polygons can be modified to achieve comparable results. Furthermore, the effects of these markings can be tested over time of successive days of experiment to better reveal the potential learning effects.

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