INFLUENCE OF HIGHWAY 3D COORDINATION ON DRIVERS' PERCEPTION OF HORIZONTAL CURVATURE AND AVAILABLE SIGHT DISTANCE

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ABSTRACT

Drivers' road perception is an important human factor of comfort and safety on driving. Available sight distance of crest vertical curves superimposed on horizontal curves can be geometrically optimised by applying 3D coordination criteria. However, drivers could not perceive available sight distance improvements.

Two approaches were used to investigate the effect of geometrical optimised design on perceived sharpness and visibility of isolated crest vertical curves overlapped with horizontal curves. A survey-based approach was used to evaluate subjective perception of 100 drivers. Three-dimensional renderings were displayed to subjects; who were asked to rank the curves by sharpness and sight distance. Moreover, 50 of those drivers previously participated on a driving simulation experiment involving the same curves, so objective driving data were collected too.

Drivers' survey results indicate that driver curve perception depends on algebraic difference of grades while coordination of vertical and horizontal curves does not appear to affect this perception. On the other hand, the operating speeds on different curves were not statistically different from each other. Surprisingly, the operating speeds on a flat curve tended to be lower than on the vertical crest curves superimposed on the same radius horizontal curve. The likely causes of these results are discussed in the paper.

1   INTRODUCTION

Drivers' road perception is an important human factor of comfort and safety on driving. Sufficient sight distance allows drivers receiving visual information crucial for safety to accommodate their driving to both road conditions and perceived margin of safety. So, geometric design should provide enough sight distance to safely perform the manoeuvres.

Modern roads are often designed curvilinear to adapt the roadway to the terrain and to minimize both total amount of earthwork and environmental impact. Consequently, current design practice leads to designing horizontal and vertical curves that frequently overlap each other. Geometric design guidelines, such as the Green Book [1] or the Spanish design standard [2], specify that both vertical and horizontal alignments should not be designed independently. Moreover, available sight distance (ASD) of crest vertical curves superimposed on horizontal curves can be geometrically optimised by applying 3D coordination criteria [3 - 6]. One coordination criterion is the ratio between the crest curve parameter and the horizontal curve radius (Kv/R); which is recommended to be the inverse of the superelevation rate (e) on the superimposed circular curve (%) [2]. Some research [4 - 6] concluded that the optimal proportion of Kv/R was generally within the interval [0.05, 0.15] per cent grade. On the other hand, there was only a weak impact of the offset between the horizontal curve midpoint and vertical curve vertex on ASD [6].

Driver perception of the horizontal curvature on the combination of horizontal and vertical curves has also been studied by other authors [7 - 12]. The initial hypothesis set by Smith and Lamm [7] is that crest vertical curves combined with horizontal curves look sharper than the same horizontal curve placed on a flat road segment; whilst the sag combination looks flatter. This effect has been studied using static and dynamic computer-generated three-dimensional renderings [8 - 11]. It was concluded that the probability of erroneous curve perception depended on: type of vertical curve (crest or sag); horizontal radius; crest curve parameter; and, travelling direction. Furthermore, static and dynamic rendering presented the same results. Nevertheless, road perception determined through a survey may be questioned as not always being reflective of the actual perception at the time of approaching the curve while driving.

Another measure of perception of the curve by a driver is drivers' free-flow speeds and their percentiles that are believed to be affected by the curve perception (sharp curves discourage high speeds). Unfortunately, field measurements can be expensive, dangerous, and most

importantly, they do not provide sufficient repeatability.

Driving simulators are a flexible tool for research and eliminate the necessity of field measurements and have been widely used to evaluate driver perception [12 - 18]. Specifically, Bella [18] used a driving simulator to analyse the effect of driver's perception of combined curves on speed and lateral placement. To isolate the impact of the vertical profile on driver perception and preferred speed, the experimental road included a sequence of similar horizontal curves placed on various vertical crest curves. The speeds selected by 35 drivers on the vertical curves were found lower than those on the reference flat grade curve. Thus, the findings of the research confirmed the research hypothesis that crest curves make the horizontal curves look sharper. However, the curves of the previous studies were not geometrically optimised to improve their ASD. Consequently, further research is needed to better understand drivers' perception of three-dimensional optimised curves.

The objective of this research is to study if and how geometric optimal design applied to isolated three-dimensional curves may affect drivers' perception of crest vertical curves superimposed on horizontal curves using two methodologies: subjective perception evaluations and driving simulations.

2   METHODOLOGY

A survey-based study and a driving simulator experiment were carried out to investigate the effect of geometric optimal design on perceived sharpness and ASD of crest vertical curves overlapped with horizontal curves. The survey research was conducted in four phases: design nine test crest vertical curves and one reference flat curve, all of them overlapping the same horizontal curve, by applying general coordination criteria; develop three-dimensional renderings of the curves and a driver questionnaire; display the renderings to subjects and carry the survey; and, statistically analyse the data to obtain the results. On the other hand, a study segment of 7.4 km was designed including the nine test curves and the reference curve. Then, the driving simulation scenario was created by converting the study road into a representation compatible with the driving simulator. 50 subjects participated on the simulations and the developed speeds were analysed. Finally, subjective and objective results were compared; and, drivers' characteristics were tested if they influence on the results.

3 SUBJECTIVE PERCEPTION EVALUATION

3.1 Test curves design

The road segment used on the study was designed by applying the Spanish Road Geometric Design standard for two-lane rural highways [2]. Only 3D coordination criteria were studied [6]. Consequently, all test curves presented the same horizontal radius (265 m) determined from the assumed design speed of 80 km/h. The test curves were generated varying: ratio between vertical crest curve parameter and horizontal radius (Kv/R); and, algebraic difference of vertical grades (A). Kv/R values were: 0.000 per cent of grade (curve 3); 0.075 per cent of grade (curves 2, 9); 0.100 per cent of grade (curves 6, 8); 0.150 per cent of grade (curves 5, 7, 10); and, 0.200 per cent of grade (curves 1, 4). The algebraic differences on grades were: 0 % (curve 3); 2 % (curves 4, 7); 4 % (curves 1, 6, 9, 10); and, 6 % (curves 2, 5, 8). Consequently, curve 3 was the reference flat curve and the optimised curves corresponded to curves 2, 7 and 10; as they present longer ASD for the same A. Test curves design parameters are shown in Table 1.

Table 1: Test curves design parameters

Curve Id	Radius R (m)	Deflection angle Ω (º)	Algebraic grade difference A (%)	Vertical crest curve parameter Kv (m/%)	Kv/R ($\%^{-1}$)	Vertical curve length L_V (m)	Horizontal curve length L_H (m)	Available stopping sight distance $ASSD$ (m)
1	265	35	4	-53.00	0.200	212	211	120
2	265	30	6	-19.87	0.075	119	192	110
3	265	31	0	0	0	0	196	Unlimited
4	265	29	2	-53.00	0.200	106	185	197
5	265	42	6	-39.75	0.150	238	238	118
6	265	29	4	-26.50	0.100	106	185	114
7	265	25	2	-39.75	0.150	80	171	198
8	265	23	6	-26.50	0.100	160	160	109
9	265	25	4	-19.87	0.075	80	171	113
10	265	23	4	-39.75	0.150	159	167	174

The other geometric components of the studied road were: two traffic lanes; symmetrical spiral curves with a parameter of 132 m; symmetrical vertical curves; symmetrical tangential vertical grades; vertex of vertical curves coincided with the midpoint of horizontal curve; 10-meter cross-section: 3.5 m lane width and 1.5 shoulder width; and, fill slope 4 to 1.

3.2 Three-dimensional renderings development

The 3D renderings were developed with the commercial road geometric design software Clip by

entering the curves' geometry. Afterwards, still images were obtained with the 3D Clip's feature. According to the Spanish Road Geometric Design standard, 8 % superelevation was assumed [2]. Road environment, background, lighting, and pavement texture remained the same in all test curves.

Perspective view of the road was taken 33 meters before the curve; which corresponds with a travel time of 1.5 seconds to the beginning of the curve of a vehicle traveling at the design speed (80 km/h). This time corresponds well with the preview times between one and two seconds used by Land and Lee [19]. Height and lateral position of a driver's point of view were set consistently with previous research: 1.05 m above the road surface and 1.45 m to the right of the road centreline, respectively [8 - 10].

3.3   *Presentation and data collection*

According to previous research, only 3D still images of the road were used [8 - 10]. Drivers were asked to fill a questionnaire and to rank 10 curves. To facilitate comparison among curves, two curves were viewed simultaneously: one on an extended image (674 pixels tall and 885 pixels wide) and one on a thumbnail (225 pixels tall and 306 pixels wide) (Figure 1).The list of curves could be sorted by using arrow buttons on the right of the curve's name.
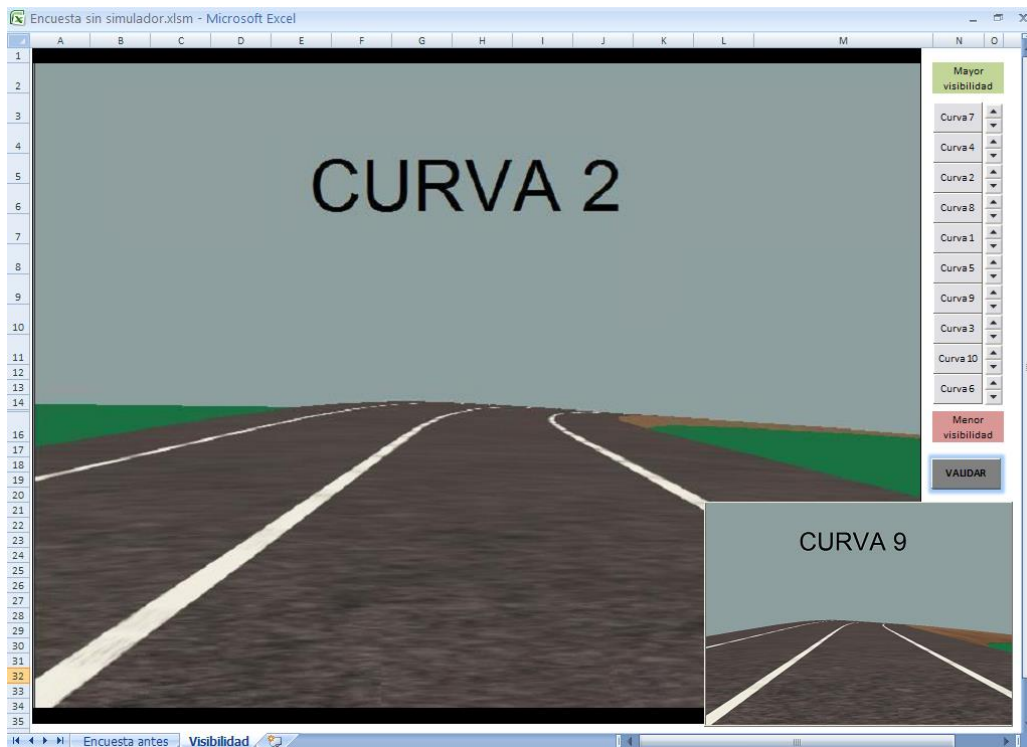

Fig. 1   Screenshot of one curve to be ranked

Drivers were asked to sort ten curves on order of decreasing sharpness (sharpest at the top, flattest at the bottom). Then, drivers sorted other ten curves on order of decreasing ASD (longest ASD at the top, shortest at the bottom). To further reduce or even eliminate dependence on both rankings, test curves had different labels on both lists. Moreover, the initial sequence of curves was randomized for each driver and sorting.

Two presentation methods were used. On the first presentation method, 50 drivers completed the questionnaire after the driving simulator experiment. It should be noted that the curves were presented on a different order, background and pavement texture than the displayed on the simulation experiments. On the second method, the same survey was posted on a web page. Consequently, a control group of 50 participants also ranked the curves. The control group gender and age distribution was similar to the driving simulation experiments and it was consistent with Spanish licensed drivers' population.

Drivers were asked to provide personal characteristics including: gender; age; use of corrective eye lenses; and, total distance driven per year. These characteristics will be referred on the remainder of this paper as: gender; age; eyeglasses; and, driving experience.

4 SIMULATION EXPERIMENTS

4.1 Study road design

The road segment used on the study was designed by using the nine test curves and the reference curve (Table 1). Consequently, the simulated study road was composed of the sequence of ten same-radius horizontal curves separated with tangents sufficiently long and adequate for the design speed. On the tangents between two horizontal curves, a sag curve was placed. The algebraic difference on grades of sag combinations was fixed by the crest combinations. The total length of the road was 7.4 km and a cul-de-sac was added at the end of the road to allow making a U-turn and drive the road in the reverse direction.

4.2 Driving simulator

Once the study road segment was designed by the design software, it was converted to a format compatible with the dynamic driving simulator of the Design and Manufacturing Institute (IDF) at the Universitat Politècnica de València.

The IDF's driving simulator is mounted on a movable platform with six degrees of freedom and it is capable of reproducing vehicle movements in immersive driving conditions created with a

180° widescreen installed in a dedicated room. Urban, rural and motorway scenarios can be recreated in various weather conditions. A vehicle is reproduced by a modular car chassis equipped with realistic car controls, as shown in Figure 2. It collects the vehicle movement on the road, the behaviour of the driver and the reaction time under different driving events. The generated log file includes data that represent the use of the gear shift, the pedals and the steering wheel by the subject and also data that describe the forces and torques acting on the vehicle and the vehicle's displacements.

Fig. 2   Dynamic driving simulator

4.3   *Simulation experiments*

Fifty drivers participated in the driving simulator experiments. Two participants were excused from completing the experiment because of simulator sickness discomfort. The initial sample was consistent with Spanish drivers' demographic profile on age distribution (five-year intervals) and gender ratio. The age of the remaining 21 women and 27 men was ranging from 20 to 73 years. The average age was 38.1 and the standard deviation was 12.9. The age distribution of the selected drivers was representative of the licensed drivers in Spain divided on five-year intervals.

Each experiment in the driving simulator started with explaining a driver how to operate the steering wheel and the pedals, the manual gear shift and other controls. After this introduction, participants filled a form to provide personal information and driving data such as driving experience, distance driven per year, rural or urban driving, etc. Then, drivers were asked to

take the seat inside the car and it was adjusted. Next, the training session in the driving simulator was executed on another rural road for approximately five minutes. Drivers were asked about possible sickness symptoms at the end of the training session. Then, participants drove on the study road (Figure 3) which typically took ten to fifteen minutes.

Fig. 3   Simulation experiment

After driving the study road-, drivers filled a second questionnaire about the driving experience, i.e. trip duration, mean speed, road conditions and the scenario. Finally, they ranked the curves on sharpness and ASD.

4.4   Data reduction

The driving simulator stored the data generated during the driving session in a log file. The time stamp and the X, Y, Z coordinates of the centre of the simulated car were saved at the frequency of 20 times per second. These data were used to estimate the vehicle's path, speed, and acceleration rates. To do so, an initial preparation of the data files was required. An algorithm developed for another research was used to calculate the forward and return paths, the speed profile, and the deceleration rates [20]. Then, the operating speed profiles were calculated as the 85th percentile of the speed distribution at each point.

5   RESULTS AND ANALYSIS

5.1   *Subjective perception evaluation*

A score system was developed to analyse drivers' perception of the nine test curves and the reference flat grade curve, for both road presentation methods. One to ten points were assigned to each curve depending on the position given from each participant: the higher points, the less favourable the perception was. Consequently, curves with higher score were considered sharper and with shorter ASD. The results are shown in Table 2.

Table 2: Subjective perception ranking

Rank	Sharpness				ASD			
	Method 1		Method 2		Method 1		Method 2	
	Curve Id.	Total Score	Curve Id.	Total Score	Curve Id.	Total Score	Curve Id.	Total Score
1	8	408	8	415	8	458	8	472
2	2	354	2	397	2	416	2	424
3	9	291	5	316	9	321	5	333
4	5	289	9	310	5	298	9	332
5	10	275	6	293	6	288	6	312
6	6	269	10	272	10	283	10	243
7	1	226	1	212	1	191	1	179
8	7	198	7	179	7	166	7	165
9	4	186	4	161	4	145	4	127
10	3	144	3	85	3	74	3	53

Curve ranking was almost identical in all categories. Curve sharpness presented less spread of scores than ASD; so, the difference on curve sharpness among curves might be lower or more difficult to detect. Moreover, ASD may play an important role on curvature perception. Presentation method did not influence the order considerably; however, the results were more concentrated after the simulation experiment; so, participants of the control group could be paying more attention to the ranking, as the total time dedicated to the study was shorter.

Based on the results, three groups of curves could be distinguished: curves 8, 2, 9 and 5; curves 10, 6 and 1, and curves 7, 4 and 3. The first group is formed by three curves with A = 6 % and one curve with A = 4 % and kv/R = 0.075 per cent of grade; the last group includes the reference curve (A = 0 %) and two curves with A = 2 %. Therefore, algebraic difference of grades may be a key factor of driver's perception of horizontal curvature and ASD when all curves have the same horizontal radius. Based on the results, the initial hypothesis [7] seemed to be confirmed.

Statistical analysis was performed to demonstrate if curve positions on the ranking were due to

randomness. Firstly, all four data set were tested to be normally distributed. Skewness and Kurtosis results confirmed that the variables followed a normal distribution. So, multiple ANOVA test could be applied. The multiple ANOVA test was used on the sample with the null hypothesis of equal position on the ranking. In Figure 4a, it can be observed that the 95 % confidence interval of the reference curve is overlapped with curves 4 and 7 on sharpness. So, the difference among them can be due to randomness. The remaining curves presented different position than the reference curve. Consequently, crest vertical curves with A higher than 4 % were perceived sharper than the reference curve. On the other hand, ASD of the reference curve is statistically perceived longer than other curves (Figure 4b). Moreover, the curves with higher A were perceived with shorter ASD.
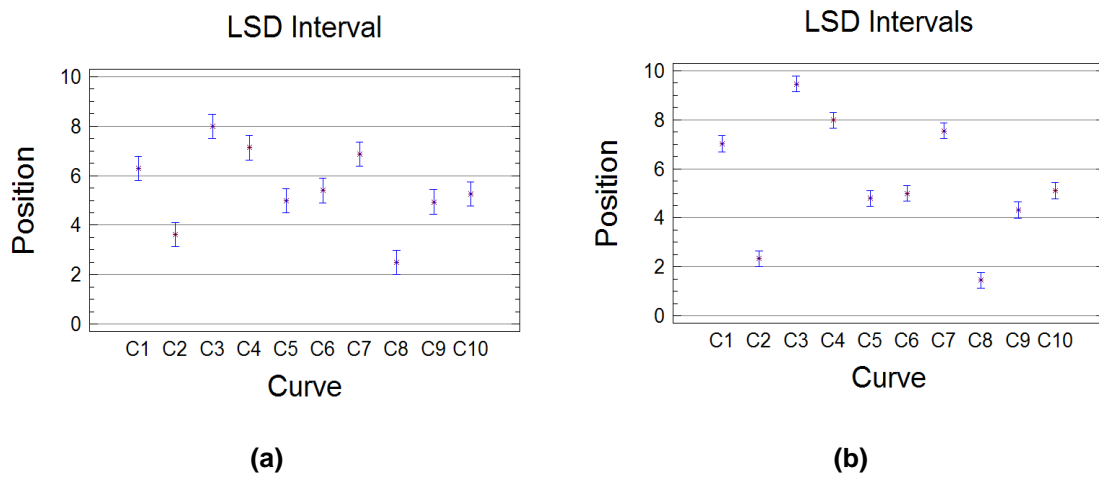

Fig. 4   LSD intervals in: (a) sharpness; (b) available sight distance

The statistical analysis supported that algebraic difference on grades was a key factor on driver perception, rather than 3D coordination criteria. Furthermore, the optimised curve with longer actual ASD (curve 1) was considered with shorter ASD and sharper than other curves with 4 % of algebraic difference on grades. Reversely, 3D optimization was perceived on curves with 6 % of algebraic difference on grades, as curve 5 was better considered than curves 8 and 2. Consequently, 3D optimization criteria may only be perceived on crest curves with high difference on grades.

5.2   Objective driving results: operating speed profile

The inspection of the operating speed profiles for the forward and return driving (Fig. 5) reveals a learning curve present during the simulation experiment in spite of the training session. The learning curve is manifested through the growing trend in the maximum speeds on tangents.

This finding forced our research team to remove from consideration speed data on four curves in the forward direction (10, 9, 8, 7 curves) and on two curves in the return direction (1, 2 curves). The initial number of one-way curve cases was reduced from 20 to 14.
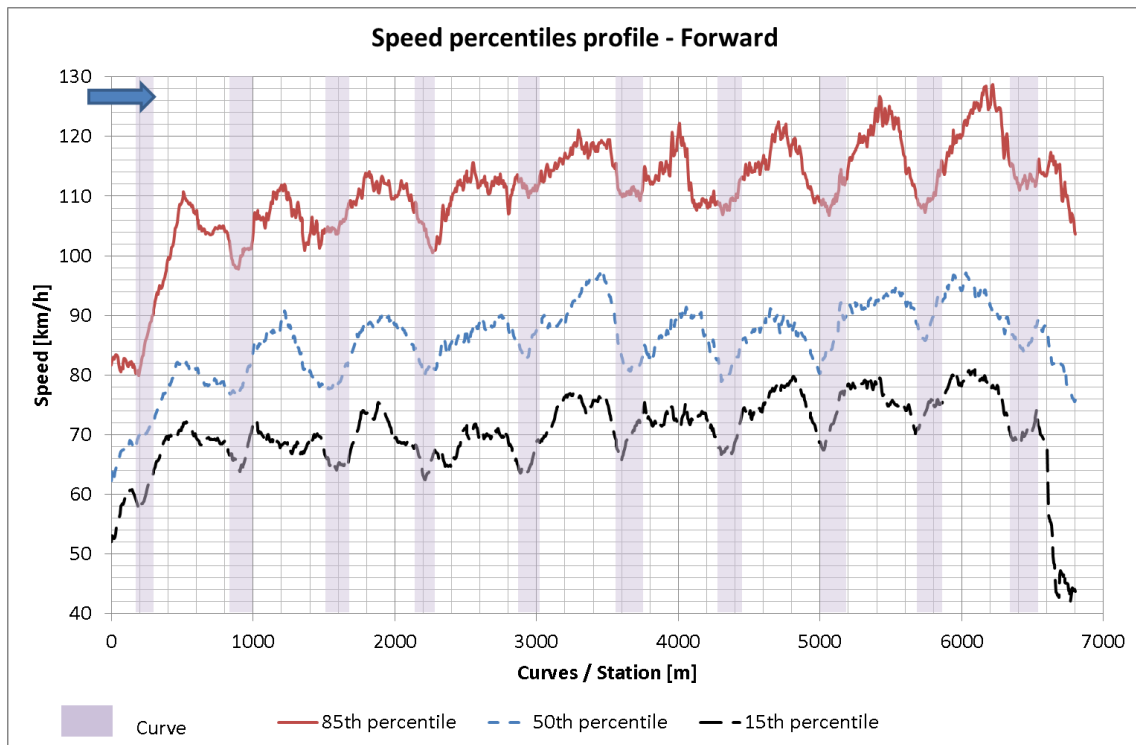
(a)
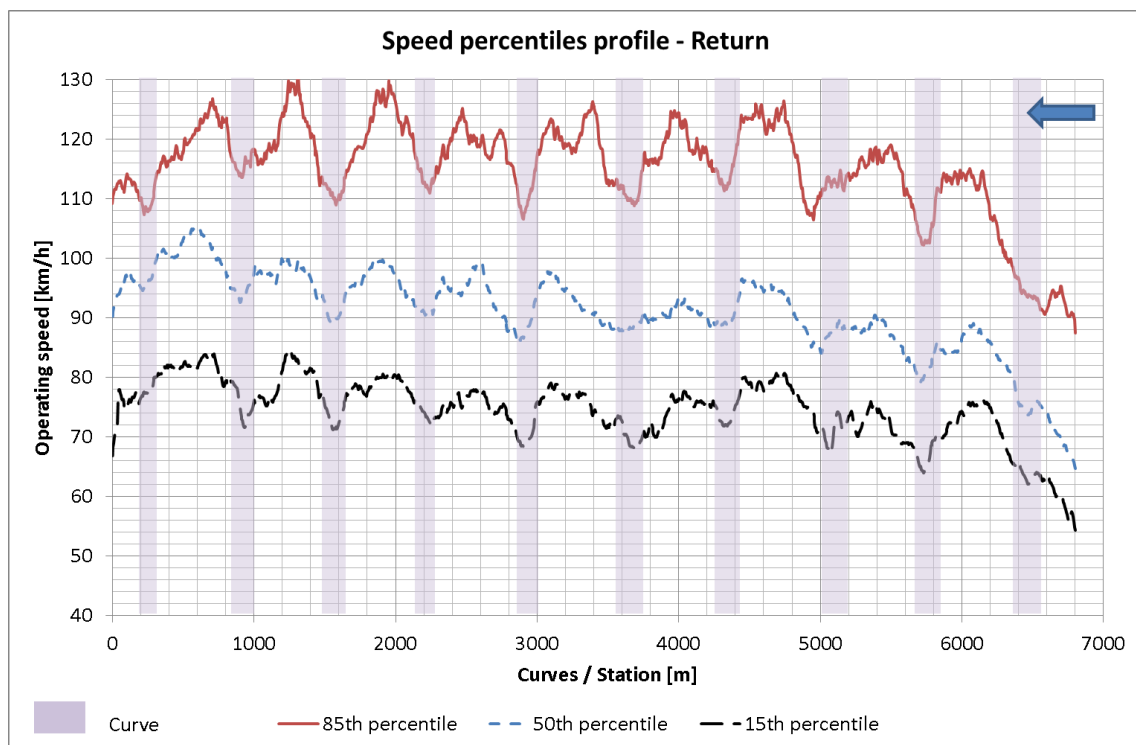
(b)

Fig. 5   Speed percentiles profile: (a) forward; (b) return

The operating speed profile indicates drivers' frequent deceleration inside the horizontal curves except of curve 8, where available sight distance on the approach to the curve is limited. In this specific case, drivers decelerate before entering curve 8 due to the insufficient sight distance and uncertainty about the curve's geometry. After entering the curve and revaluating the curve's geometry many drivers decide to accelerate when still being inside the curve.

The increase trend in speeds along the study road is present in both the 85th percentile speeds and in the 15th percentile speeds although this trend is more pronounced for the more aggressive drivers represented by the 85th percentile. Aggressive drivers tend to drive faster as they get more familiar with the new conditions of the driving simulator and the road scenario.

The lowest operating speeds observed inside the test curves were calculated. Interestingly, the operating speeds varied between 105 and 115 km/h while the design speed is only 80 km/h. The 10 km/h difference between the minimum and maximum values of operating speeds may be consider small given the considerable geometrical difference between curves. Curve 4 is the curve with the highest operating speed in right turning direction and curve 3 exhibits the lowest operating speed which is surprising because curve 3 is the reference curve placed on a flat road segment. Furthermore, curve 8 has a limited sight distance and yet the operating speed on this curve is 5 km/h higher than on the reference curve. A multiple ANOVA test was used on operating speed among curves. The results indicated that the speed differences were not statistically significant from each other. It implies that the available sight distance did not influence drivers' behaviour in the simulation experiment and that drivers did not perceive the risk of the curves in the simulated conditions.

5.3   *Comparative analysis*

The driver's perception of the curves is not confirmed with the results obtained in the driving simulator. The considerable difference in the points earned by curves in both the sharpness and sight distance categories is not reflected on the operating speeds. The hypothesis of the same mean speeds on all the curves could not be rejected. Furthermore, the curves with lower position on both rankings (being less favourable perceived by drivers) tend to have higher operating speed. The reference flat grade curve has rather low operating speed despite being considered by the drivers the best one.

Aggregate speeds for each group of the perception evaluation have been calculated. Weighted means according to the ranked points were calculated for both sharpness and sight distance. As

the previous analysis, six curves were removed from the analysis due to the learning curve. An ANOVA test was carried out to determinate if the aggregate speeds are statistically different among the groups. The obtained P-values of the F-statistic indicate that all the aggregate speeds should have equal means and the differences are not statistically significant. Thus, the drivers' performance responses do not accord with the ranked values. It can be explained because during the survey, participants were more focused on observe the differences among curves and they could perceive all of them. However, during the simulation experiments participants were driving and the subtle differences among curves could not be perceived or be considered riskier enough to vary their speeds. Besides, drivers' risk perception may be influenced by the driving simulation experience. The results support Kweon et al. [21] conclusion that objective and subjective (self-reported) measures in the physical environment do not always coincide.

5.4   Effect of driver characteristics

Effect of driver characteristics was also evaluated using ANOVA F-test. The null hypothesis was that drivers' responses did not depend on their gender; age; use of eyeglasses; and, driving experience. Individual responses of all drivers for all curves were included in the test. The obtained p-values of the F-statistic were generally higher than 0.05; so, the null hypothesis should not be rejected in practically all curves and driver characteristics. Therefore, curvature and ASD perception may not be influenced by drivers' characteristics, as previous studies [8, 9].

6   CONCLUSIONS

Despite several efforts were conducted to geometrically optimise available sight distance (ASD), ASD improvements were not tested to be appreciated by drivers' perception. The objective of this study was to analyse the effect of 3D coordination criteria on driver perception of isolated three-dimensional curves using a questionnaire with 3D still images and driving simulation experiments.

The initial hypothesis, that curves with a lower difference of vertical grades are perceived with longer ASD and flatter curvature, was confirmed on the survey. The questionnaire results indicate that drivers' perception of ASD does not correspond with actual ASD, as geometrically optimised curves were generally worse perceived among curves with same difference of vertical grades, except on curves with the highest difference of grades. High dependence of perceived

sharpness on perceived ASD was found. It can be concluded that ASD plays a key role in perceiving horizontal curvature even all test curves presented equal horizontal curvature. No significant differences on the results were detected for the driving simulation group and the control group.

On the other hand, the performance-based analysis showed that operating speeds did not significantly vary across the test curves. This result can be explained with strong differences among drivers, subtle differences among curves or the differences could not be considered riskier enough to change the speed levels. Besides, drivers' risk perception may be influenced by the driving simulation experience. Furthermore, operating speeds were most likely affected by the learning processes still present after the training session and during the experiment. Therefore, the training session should last longer to mitigate or eliminate this undesirable effect. This effect could be further strengthened by the same radius for all the curves. Drivers experienced the same curvature along consecutive curves they were passing along the study road. This might gradually built their expectancy and encourage increasing the speed, whereas reducing the influence of the curves' geometry on the operating speed.

Finally, drivers' characteristics may affect neither perceived horizontal curvature nor perceived ASD.

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