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Operational and Safety Effects of Transition Curves in Highway Design - a Driving Simulator Study

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Abstract

Keywords: geometric road design, transition curves, safety, speed, simulation.

The critical point in rural road safety and road design is evaluation of perceptual properties of road curves. This research project deals with geometrical aspects of horizontal curves design that enhance road safety and it covers experimental studies of driver's perception, using CRISS simulator. Experimental research goal is to test and to evaluate the effect of geometric road parameters (width and number of driving lanes, curvatures, transition curves, etc.) and road environment characteristics (visibility related) on drivers behavior expressed by the speed adopted indicators which are related to driving safety.

The main objective of this work was to test the effect of rural road design parameters, especially horizontal curves geometry, on driver's behaviour directly related to road safety. The detailed objectives related to driving behaviour on curves, were:

1. To test the effect of curve radius on driving behaviour and risk perception,
2. To investigate the effectiveness of spiral transition curves (clothoids),
3. To evaluate the road visibility effect on driver's behaviour (differences in risk perception on curves without and with restricted visibility),
4. To test the effects of road category (different design speed and cross- section parameters) on driver's behaviour in adopting driving speed and trajectory.

A driving simulator experiment was designed, where four independent variables (cross-section and horizontal curve geometric parameters) were manipulated. The laboratory experiment, pilot studies and the main experimental works were conducted at driving simulation laboratory of The Italian Interuniversity Research Centre of Road Safety, CRISS. Analysis presented in the paper are focusing on relations between experimental variables and driver's behavior related to driving speed and other advanced behavioral indicators connected to driving trajectory, speed choice, risk perception and curve geometry.

The results obtained demonstrate the effectiveness of clothoids as transition curves in road paths in terms of road safety. The variable effects of road visibility on driver's behavior under different geometrical conditions and road curve scenario are shown. The general results show that the advanced techniques of visualization and simulation of road space can disclose the relationships between design road parameters and behavioral aspects important to create safer road infrastructure.

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INTRODUCTION

To achieve higher quality in geometric road design as well as to reduce overall time and person-hours in the design process, new tools and techniques are being implemented. In the geometric road design process it is indispensable to test the road view of projected construction from the driver's eye position *(1), (2), (3)*. The nature of geometric road design comes from the spatial, and dynamic character of the road. The road appears to drivers as a spatial and moving view. This moving road view is the most important information source that affects driver perception and behavior *(4), (5).*

The critical point in rural road safety and road design is evaluation of perceptual properties of road curves. Accidents are more likely to occur on horizontal curves than on straight segments of roadway because of increased demands placed on both driver and vehicle. Over 50 percent of accidents on rural roads in Poland involve single-vehicle crashes on curves. The causes of the abnormally high frequency of such accidents are not yet fully understood, although it is claimed that perceptual factors play a significant role *(6), (7), (8).* Shinar *(7)* concludes, that engineering-based solutions to increase safety will remain relatively ineffective unless they take into account all the potential effects on behavior and should be user-centered. The process of curve perception, as described by Zakowska in 1999 *(8)*, is complex and requires research in interdisciplinary nature with respect to the broad list of interrelated effects of the road, road environment, exterior factors such as light, weather conditions, driver's psychological responses, and much more. Previous research and literature review let authors to draw several conclusions *(8), (9), (10)* which are still valid in this field of research. Modern computer-based methods of visualization were claimed to be developed without effective procedures for their evaluation. To date there has been little systematic empirical research comparing driving behavior on curves of different design parameters.

Driving simulation based approach seems to be very promising to consider once in a time all the different variables that play different roles in the road safety processes *(11), (12),* which is well documented in CRISS studies results *(13) – (19).* In particular Bella *(12), (20)* demonstrated relative validation of simulator under different road scenario and he found that the best correspondence of simulated and real data occurs where the road imposes to drivers strict maneuvers (work zones and small curve radii). Moreover the researches *(18), (21) – (23)* demonstrated effectiveness of simulation for evaluation of road design consistency in terms of speed and acceleration adopted and other experimental indicators.

Other studies *(13), (14), (19)* verified the big potentials of virtual reality simulation in evaluating driver's behavior under different geometric and traffic conditions. Simulation approach takes into account human factors. In this context it is recommended to generate an environment virtually and to test driver's behavior in simulators studies.

RESEARCH OBJECTIVES

The main objective of the research presented in this paper was to investigate driver's behaviour and the perception of road curves, which is directly related to road safety. In particular, two groups of objectives are recognised. The first group deals with validation of method used in scenario organisation (see points 1 and 2 below) and the second group is related to analysis of the effects of road design parameters on driving behaviour connected to speed choice and risk perception (points 3,4,5 and 6). The objectives related to validation of experimental method, conducted as the first part of this research were:

5. To test the influence of the sequence of driving scenario on driver's behaviour;
6. To test the influence of the previous geometric elements of the scenario on driver's behaviour.

Elimination of influence of the sequence of presented curves and influence of one element on another element perception is important not only for validation of designed method, but also for all other results. It is crucial to demonstrate that driver's behaviour is influenced only by the geometric element he is approaching to.

The second group of detailed objectives, related to driving behaviour on curves, were:

7. To test the effect of curve radius on driving behaviour and risk perception;
8. To investigate the effectiveness of clothoid as a transition curve;
9. To evaluate the road visibility effect on driver's behaviour (differences in risk perception on curves without and with restricted visibility);
10. To test the effects of road category (different designed speed and cross- section parameters) on driver's behaviour in adopting driving speed and trajectory.

THE EXPERIMENT

A multifactorial experiment was designed to test the effect of horizontal curves geometric parameters and rural roads environment characteristics on drivers perception.

FIGURE 1 Driving simulator at CRISS.

Apparatus
Driving simulations have been performed at the driving simulator system at laboratory of the Italian Interuniversity Research Centre of Road Safety, CRISS (Figure 1). The complete model has been validated extensively *(16).*

The hardware is composed of four networked computers and three hardware interfaces. One computer generates the images, two computers provide the driver with the lateral view and another one processes the motion equations. The hardware interfaces are the steering systems, the pedals and the automatic/manual gear.

The simulator allows modeling the road in accordance with the traditional roads engineering constraints. It is installed inside a real vehicle to have the best feeling of reality during the experiments.

Method
Thirty one drivers were tested in laboratory conditions of the CRISS driving simulator. Each subject was driving three sections of virtual roads representing three roads categories. All scenarios were composed of twenty horizontal curves divided by straight sections, organized in random sequence. The outcomes of driving in virtual reality environment were stored in the driving simulator system, then validated and analyzed.

Dependent Variables
Driving speed was the main variable evaluated, in forms of average speed on curve, approaching speed at the section where curve with constant curvature begins and speed in the middle of curve. The other variables were dispersion of trajectory (DT) and pathologic discomfort indicator (PD).

Dispersion of Trajectory (DT)
This advanced indicator has been identified to quantify the dispersion of driver's trajectory on curve (t_v) with respect to his average trajectory (t_a). The higher the indicator, the more difficulties the driver has experienced in the perception of the road geometry and consequently on his driving exercise. The area between driver's local trajectory and driver's average trajectory on the curve represents the Dispersion of Trajectory as it is shown in figure 2 and computed with formula (1):

$$DT = \int_{s=0}^{s=L} \left| t_v(s) - t_a \right| ds \tag{1}$$

where $t_v(s)$ is the local trajectory of driver (driver's lateral lane position with respect to the roadway dividing line), t_a is the average driver's lateral lane position on the curve and L is the length of the curve. Then the indicator has been divided by the length of the curve L to allow the comparison between different curves.

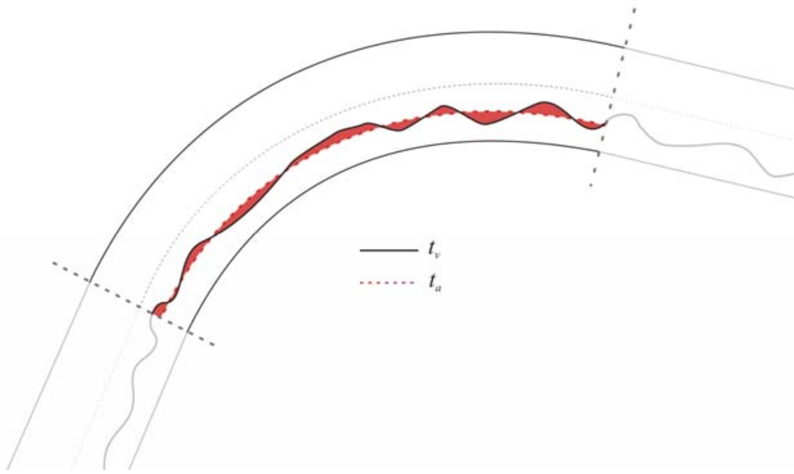

FIGURE 2 Dispersion of Trajectory.

Pathologic Discomfort (PD)

This indicator has been already presented and discussed in previous papers *(13), (15), (18),* where it has been correlated with road accident rate with high value of correlation factors. Moreover the indicator has been computed and correlated with accident rate in on site investigations driving an instrumented car *(24)*. The main theoretical assumption is: a subject driving on a self-explaining road assumes a correct and safe trajectory and the local transversal accelerations depend only on the curvature of road geometry. If the driver corrects the vehicle's trajectory more than what road curvature imposes, the road is not self-explaining and, consequently, it can be unsafe. If the local transversal accelerations do not depend only on the actual road curvature, they are biased by the driver's corrections of trajectory.

The local instantaneous variability of transversal acceleration shows clearly the corrections of trajectory that the driver assumes (figure 3) and this could be so labeled as a discomfort index. This repeated local oscillations represent a violation to driver expectancy. Authors have used formula (2) to compute PD for each curve (constant curvature) of each scenario:

$$PD = \int_{s=0}^{s=L} \left| a_t(s)^{\text{pat}} \right| ds \approx \sum_{j=0}^{N} \left| \left(a_{tj} - \frac{v_j^{\;2}}{\rho_j} \right) \right| \tag{2}$$

where a_{tj} is driver's transversal acceleration (simulation output), v_j is the average speed of the driver on curve, ρ_j and L are the radius and the length of the curve, respectively. PD corresponds to the area between the diagram of driver's transversal acceleration and the diagram of theoretical transversal acceleration.

PD has been divided for the length of the curve L to allow the comparison between different curves.

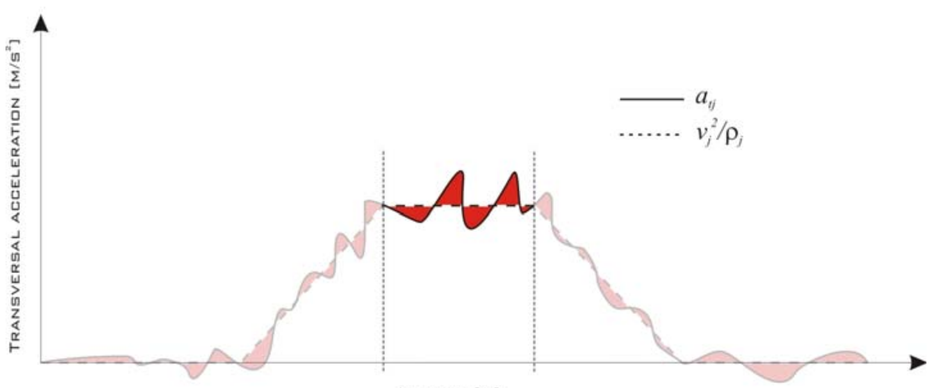

FIGURE 3 Pathologic Discomfort.

Independent Variables

Curve geometric parameters, cross-section parameters of different road categories and road environment characteristics were manipulated in the experiment.

The following levels of independent variables were introduced:

- Three levels of road category reflecting the design standards in Poland, namely: classes Z, G and S. These three categories are associated with the design speed, the function of the road and the cross-section geometry, as follows:
  A. **Z class** (Vd=50km/h), 2 x 2.75m, gravel shoulders, central line painted, no edge lines painted;
  B. **G class**: (Vd=70km/h) 2 x 3.25m + 2 x 1.50 paved shoulders, central and edge lines painted;
  C. **S class**: (Vd=100km/h) 2 x (2 x 3.50m + 2m paved shoulder + 0.5m inside emergency) divided with the central greenery lane of 2-3m.
- Three levels of curve radius (300m, 500m and 1000m);
- Two curve directions (left and right);
- Two levels of transition curve (with and without clothoids);
- Two levels of curve visibility restriction in an effect of steep side slopes along the road at curves (good unrestricted visibility and poor, restricted visibility of inner edge of curve).

Participants

Thirty one participants (twenty six men and five women; mean age of 25 years old, range 21-29 years) were recruited as volunteers from the Department of Sciences of Civil Engineering at the University Roma Tre via direct contact.

All participants had a valid Italian driving licence and had, on average, been driving for 5.9 years (range 3–10 years). The participants reported having driven, on average, 13050 km in the preceding year (range 1000–25000 km). Only four subjects experienced driving an instrumented car and four subject experienced light simulation sickness symptoms like headache during the simulations.

Scenario

Three different scenarios (A, B and C types) were designed and implemented in virtual reality environment (Figure 4), representing three categories of roads (A for class Z and design speed 50 km/h, B for class G and design speed 70 km/h, C for class S and design speed 100 km/h). Each scenario was composed of twenty horizontal curves (R = 300, 500, 1000 meters) and twenty one straight segments. The first straight was 1000 meters long to allow the driver to reach a significant approaching speed in the first curve. The other twenty road straights were of different length: road of higher category had longer straight sections than the lower category roads (300 meters in scenario A, 400 meters in scenario B and 500 meters in scenario C). Those straight sections between two consecutive curves have the aim of preventing driver's behavior through curve being biased by the previous geometric elements of the road.

The geometry of each scenario has been mirrored into another scenario. So finally scenario A was subdivided into A1 and A2 and the same for scenario B and C. Table 1 presents the curves sequence and characteristics for scenarios of type 1 and 2, respectively.

A: scenario representing Z class road | B: scenario representing G class road | C: scenario representing S class road

FIGURE 4 Examples of scenarios (A, B and C) of the three road categories investigated in experiment.

TABLE 1 Characteristics of Horizontal Curves Used in Scenarios A, B, C

Curve characteristics				***scenario A1, B1, C1***		***scenario A2, B2, C2***	
Length [m]	*Radius [m]*	*Visibility*	*Clothoid*	*curve code number*	*turn*	*curve code number*	*turn*
393	500	yes	yes	***1***	right	***1***	left
237	300	yes	yes	***2***	left	***2***	right
524	1000	no	no	***3***	right	***3***	left
237	300	no	yes	***4***	right	***4***	left
262	500	yes	no	***5***	left	***5***	right
524	1000	yes	no	***6***	left	***6***	right
393	500	no	yes	***7***	right	***7***	left
157	300	no	no	***8***	left	***8***	right
393	500	yes	yes	***9***	left	***9***	right
157	300	yes	no	***10***	right	***10***	right
157	300	yes	no	***11***	left	***11***	right
524	1000	yes	no	***12***	right	***12***	left
262	500	no	no	***13***	right	***13***	left
237	300	no	yes	***14***	left	***14***	right
393	500	no	yes	***15***	left	***15***	right
262	500	yes	no	***16***	right	***16***	left
237	300	yes	yes	***17***	right	***17***	left
262	500	no	no	***18***	left	***18***	right
157	300	no	no	***19***	right	***19***	left
524	1000	no	no	***20***	left	***20***	right

Procedure

According to the strict procedure of simulation experiments *(14), (16)*, participants were required to complete a familiarization training of at least 10 min driving the simulator vehicle. The experimental drive lasted 60 min in total (3 simulations) per driver. The same subject drove three scenarios.

Between each scenario participants were allowed a short break. This break was intended both to diminish as much as possible the fatigue effect of each driving period and to fill in the questionnaire. Results of the answers to the questionnaire (driver's perception of road legibility, fluency, visibility, safety and aesthetics) correlated with simulation data will be published in a forthcoming paper.

Subjects were required to drive in the centre of the right lane. Subjects could see their speed on the speedometer visualized on the screen and were free to choose the velocity they prefer, according to what the road scenario suggested them. In this experimental design the driver was alone (in his direction) along the simulation path, while on the opposite direction there was a significant traffic flow.

The sample of drivers was divided into four groups according to the sequence of the driving scenario:

- A1-C2-B1
- B1-C2-A1
- A2-C1-B2
- B2-C1-A2

VALIDATION RESULTS

Validation of the Sample of Drivers

The sample of drivers was formed by 31 participants, as described in subject's part of experimental design chapter . The procedure that has been followed for drivers simulation output validation is the Chauvenet criterion *(25),* based on the driver's average speed of travel. Chauvenet criterion is a strong statistical test used to determine possible outliers and to decide whether or not a bad data point should be discarded. An outlier among residuals is one that is far greater than the rest and lies three or four standard deviations or further from the mean of all the residuals. Four experimental drives were excluded from final analysis, due to biased outputs revealed (one in scenario A, two in scenario B and one in scenario C).

Validation of Simulation

First analysis have been carried out to verify if driver's behaviour has been influenced by the sequence of the scenario or by previous element of the path. This preliminary analysis is important to verify if data are not biased by the experimental procedure.

Moreover, to compare driver's behaviour at specific curve, it had to be verified whether the straight between two consecutive curves allows the driver to erase all the influences of previous curves.

Sequence of Driving Scenario

The influence of the scenario sequence on driving behaviour was tested. The sample of driver was divided into four groups according to the sequence of scenarios simulated. Results summarized in table 2 demonstrate that the sequence has not affected significantly the speed adopted. In case of scenario A the average speed increases 2,2% when driven as the third. For scenario B the difference of 5,5% was observed. Obtained differences were satisfactory, which is an important positive result. As at scenario C drivers experience high speed (on highway), it might be expected that the other two scenarios are influenced if driven as first (before C) or as the third (after C). No significant influence was observed. Moreover, driver's speeds in both scenarios A and B were similar, while drivers adopted higher speed in scenario C that present larger section with two carriageways.

TABLE 2 Results of Validation of Simulation: The Sequence of Driving Scenario

Average speed [km/h]				
Scenario A		*Scenario B*		*Scenario C*
first run	third run	first run	third run	second run
97.42	99.61	95.80	101.05	108.04

Influence of Previous Elements of the Path on Driver's Behaviour along Each Curve

Here different indicators have been evaluated along each curve of the scenario, considering the geometric element with constant curvature. The objective was to understand if drivers behaviour approaching a curve was influenced by the previous curves passed. Straight section between every two consecutive curves was included and two different paths for each scenario were created. A1 and A2 (as well as B1 and B2, and C1 and C2) had the same geometric elements but their paths were perfectly mirrored. So in example in A1 the curve of radius 500 meter, with restricted visibility and without clothoid, turning right, had the number 13 while in A2 it had number 18. In case of A1 (or B1 or C1) and A2 (or B2 or C2) scenarios, curve number 13 had the same characteristics, except of the right (for A1, B1, C1) and left (for A2, B2, C2) turn.

The following indicators were analysed:

1. average speed on the curve (along the constant curvature);
2. approaching speed in the section where the curve (constant curvature) begins;
3. speed in the middle of the curve;
4. pathologic discomfort (PD) on the curve (constant curvature);
5. dispersion of trajectory (DT) on the curve (constant curvature).

The authors prefer here to provide the readers just with the results obtained by the analysis on the average speed on each curve (along the constant curvature) shown in Figure 5. There is no significant difference observed between average speed on mirrored scenarios curves, as shown in Fig.5a for scenarios A1-A2, in Fig.5b for scenarios B1-B2, and in Fig.5c for C1-C2 respectively. Approaching speed and speed in the middle of curves also gave similar, not significant differences.

The same occurs for the analysis on Pathologic Discomfort and Dispersion of Trajectories. These first results, confirmed by all five indicators analyzed, needed two considerations:

1. Driver's behavior on a curve seems to be affected only by the characteristics of the curve, and, is not influenced by previous curves passed as it has been demonstrated by the small differences observed of same indicators measured along the same curve.
2. This is an important first step of the research as it allows the authors to compare driver's behavior on different curves to verify the influence of road geometry and road scenario on driver's perception and behavior.

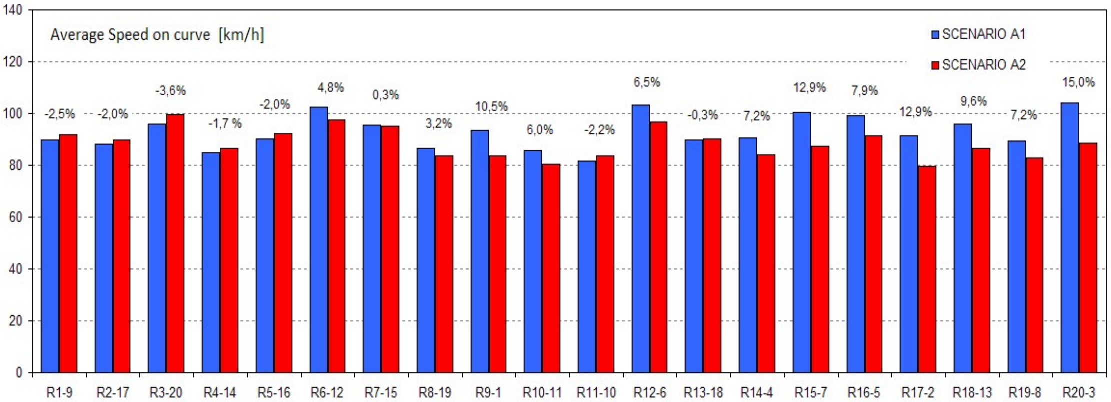

FIGURE 5a

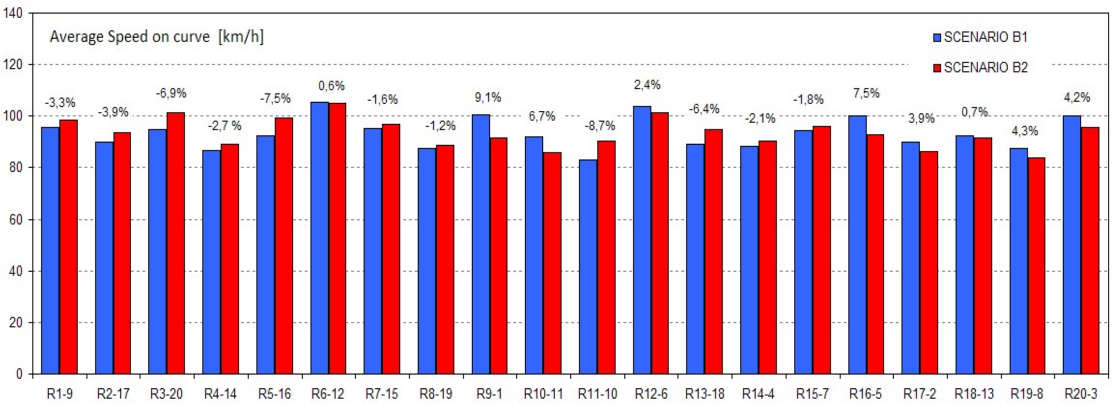

FIGURE 5b

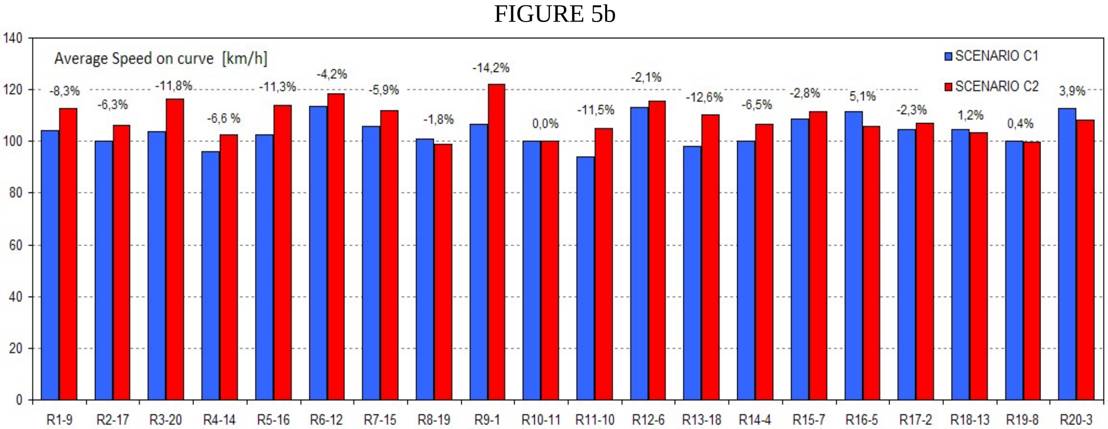

FIGURE 5c

FIGURE 5 Comparison of average speed on curves of the same characteristics, but mirrored, for scenarios (a) A1-A2, (b) B1-B2, (c) C1-C2.

After the above verifications, all indicators for each curve were compared and analysed for each scenario. Results are illustrated in figure 6 and in table 3. The value of the indicator for each curve in each scenario has been assumed as the average of values of i.e. scenario A1 and A2 for that curve. It is interesting to note that in scenario C all the indicators reach the higher value for most of the curves.

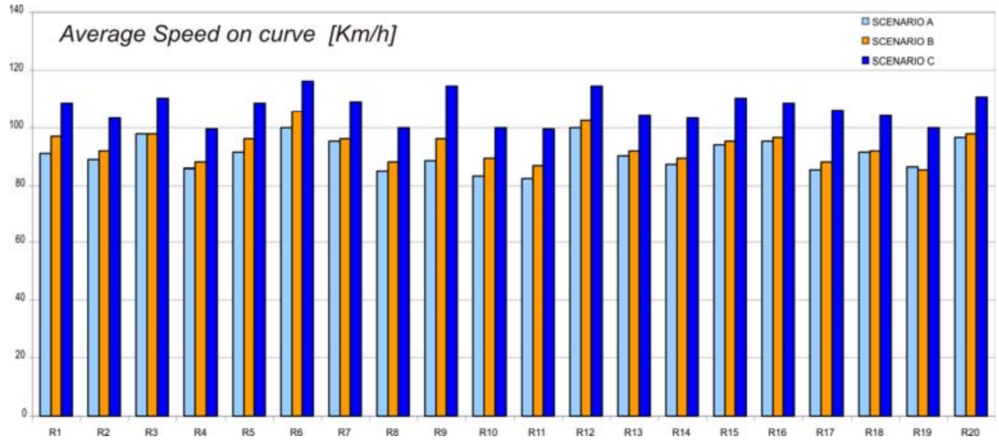

FIGURE 6a

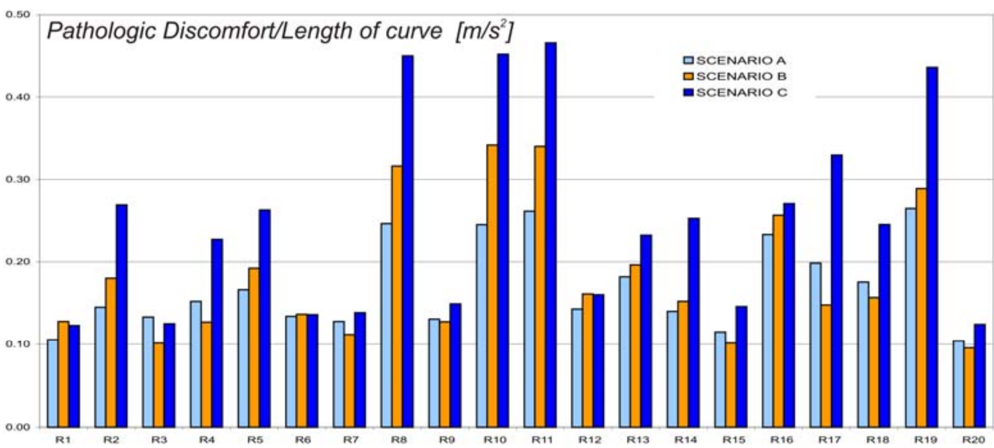

FIGURE 6b

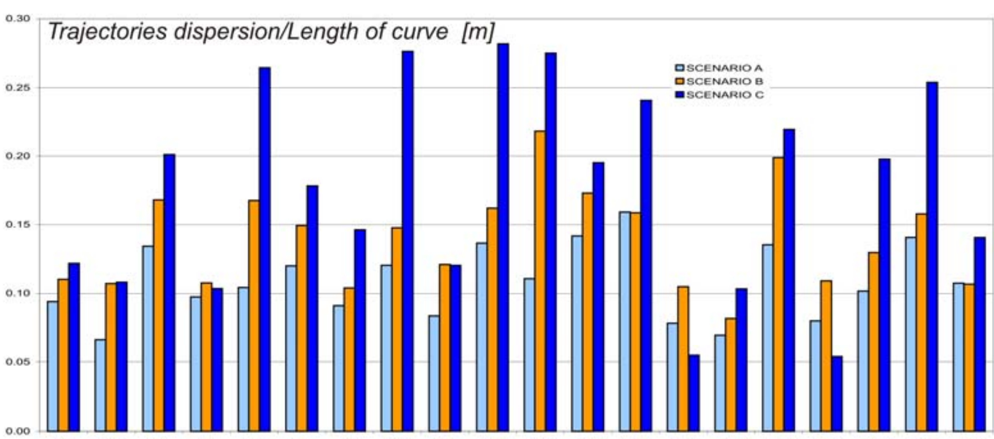

FIGURE 6c

FIGURE 6 Comparison of indicators at the same curves but for different scenarios (a) Average Speed on curve, (b) Pathologic Discomfort, (c) Trajectory Dispersion.

TABLE 3 Values of Indicators for each Curve in each Scenario (*Sa* is the average speed on curve)

Curve	***Scenario A***			***Scenario B***			***Scenario C***		
	Sa [km/h]	**PD/L [m/s^2]**	**DT/L [m]**	**Sa [km/h]**	**PD/L [m/s^2]**	**DT/L [m]**	**Sa [km/h]**	**PD/L [m/s^2]**	**DT/L [m]**
R1	90.88	0.105	0.094	97.06	0.127	0.110	108.53	0.122	0.122
R2	88.86	0.145	0.066	91.76	0.180	0.107	103.10	0.269	0.108
R3	97.76	0.133	0.134	97.96	0.101	0.168	110.10	0.125	0.201
R4	85.80	0.152	0.097	87.99	0.127	0.108	99.40	0.227	0.104
R5	91.30	0.166	0.104	95.86	0.192	0.168	108.23	0.263	0.264
R6	99.87	0.134	0.120	105.29	0.136	0.149	116.05	0.136	0.178
R7	95.39	0.127	0.091	96.17	0.111	0.104	108.89	0.138	0.146
R8	85.02	0.247	0.120	88.01	0.316	0.148	99.92	0.450	0.276
R9	88.37	0.130	0.084	96.05	0.127	0.121	114.40	0.149	0.120
R10	83.06	0.245	0.137	89.02	0.342	0.162	99.99	0.452	0.282
R11	82.58	0.262	0.111	86.76	0.340	0.218	99.54	0.466	0.275
R12	99.99	0.142	0.142	102.39	0.161	0.173	114.40	0.160	0.195
R13	90.02	0.182	0.159	91.85	0.196	0.159	104.09	0.232	0.241
R14	87.27	0.140	0.078	89.29	0.152	0.105	103.22	0.253	0.055
R15	93.78	0.114	0.070	95.34	0.101	0.082	110.06	0.146	0.103
R16	95.35	0.233	0.135	96.43	0.257	0.199	108.61	0.271	0.219
R17	85.41	0.198	0.080	88.07	0.148	0.109	105.71	0.329	0.054
R18	91.17	0.175	0.102	91.94	0.157	0.130	104.01	0.245	0.198
R19	86.10	0.265	0.141	85.53	0.289	0.158	99.72	0.436	0.254
R20	96.45	0.104	0.107	97.91	0.096	0.107	110.66	0.124	0.141

RESULTS ON DRIVING BEHAVIOUR AND RISK PERCEPTION

The Effect of Clothoid Existence on Driver's Behaviour

The analysis of clothoid effects have been developed only for curves of radius R = 300 m and R = 500 m, because it was decided not to include curves R = 1000 m with clothoids in the simulation scenario to not make the run too long. All three indicators (average speed, PD and DT) were calculated based on the element of each curve with constant radius, in order to allow the comparison of indicators between the same curves geometry, but with and without clothoids. Results are shown in Figure 7, where the error bars denotes the 90% confidence level.

Analysis of the average speed at all groups of curves with and without clothoids (Figure 7a) shows the same tendency: curves without clothoids were driven at lower speed, than the same curves with clothoids. This effect is stronger at curves with larger radii, and it increases with the raising road category. It should be caused by a better interpretation of geometries by driver that perceives better the curve when it is preceded by a clothoid and consequently he adopts an higher speed (in reality only, in average, +3%) without significant deceleration before the curve.

The strongest effects of the clothoid existence have been found in a decrease of the Pathologic Discomfort (Figure 7b) and Dispersion of Trajectories (Figure 7c) in the case of curve with clothoids. It occurs for every radius in every road category and confirms that driver's corrections to his trajectory are much lower when the transition curve precedes the circular curve. This effect is higher for the curve with smaller radius (300 m) when the perception of the curve and the geometry are more difficult for the driver. In some cases (see R=300m in figure 7b) the value is quite more than halved. It is an important results that gives reason to the actual road design rules that impose transition curves for all the curves of new road projects.

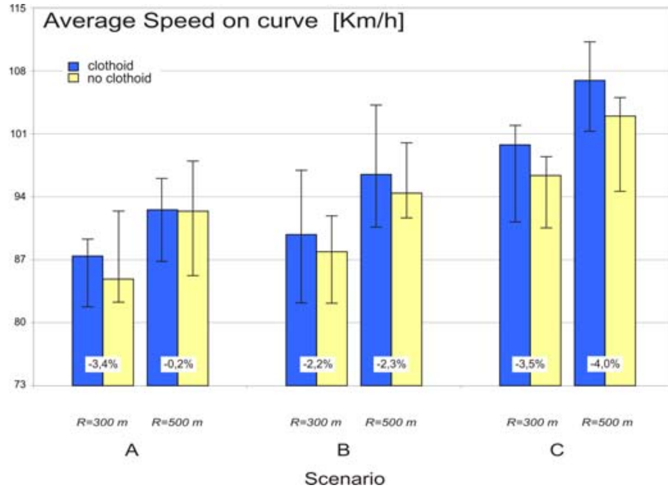

FIGURE 7a

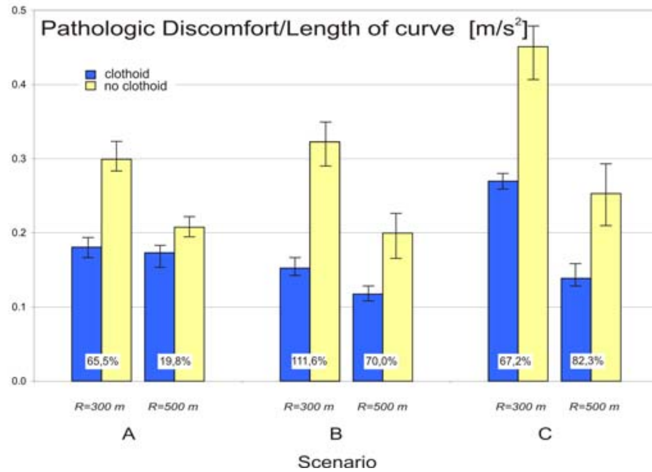

FIGURE 7b

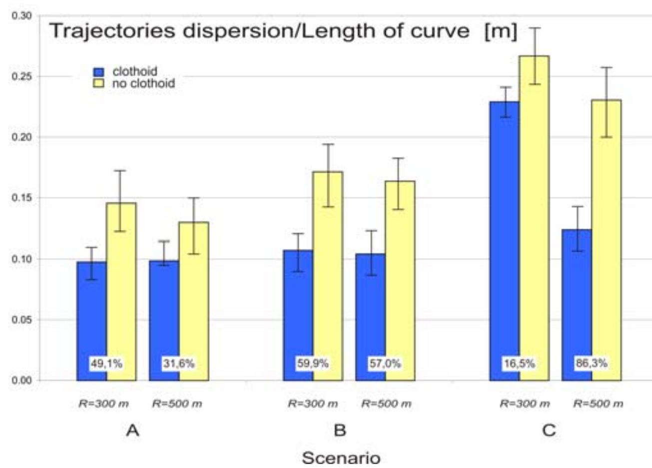

FIGURE 7c

FIGURE 7 Comparison of indicators on 300 m and 500 m radii curves with and without clothoids. (a) Average Speed on curve, (b) Pathologic Discomfort, (c) Trajectory Dispersion.

The Effect of Curve Inner Edge Visibility Restriction on Driver's Behaviour

This analysis covers all three groups of curves with R = 300, 500 and 1000 meters. For each curve of different geometry and different road category two options of road environment were designed. The first environment was built as a flat field without any restrictions to the curve view (Figure 4B), while the second one was built as a steep side slope close to the road edge (Figure 4A and 4C), restricting visibility of the inner edge of the road curve.

Figure 8 illustrates the results of this analysis and the error bars denotes the 90% confidence level. With good visibility speed was lower than at curves with restricted visibility only for A road curves of R = 300m and R = 500m. At all other curves the opposite tendency is observed (Figure 8a). This effect is stronger for larger radii of curves. Moreover, drivers experienced a lower pathologic discomfort and trajectory dispersion when driving on curves with restricted visibility, which is shown in Figure 8b and 8c. It was expected to get higher values of indicators for curves with restricted visibility, as a confirmation of unsafe driving conditions. On the contrary, the opposite effect has been observed, as on curves with restricted visibility the lowest values of indicators appeared. This effect can be explained considering that driver's behaviour changes when perceiving hazardous situations, such as restricted visibility. Drivers probably adopted safer behaviour, through driving more carefully and paying more attention to driving exercise. This effect is valid only when no other factors influence driving attitude, such as traffic. It is necessary to stress that in this experimental design the driver was alone (in his direction) along the simulation path. As a consequence, driver had no other cars to overtake and he was conditioned only by visual geometric parameters of road and road environment. The hazardous situation on curves with no visibility occurs usually when driver decides to overtake without enough visibility or in case he has to make an emergency stopping maneuver caused by a sudden obstacle in front of his trajectory. But in such a case he is not alone in the road.

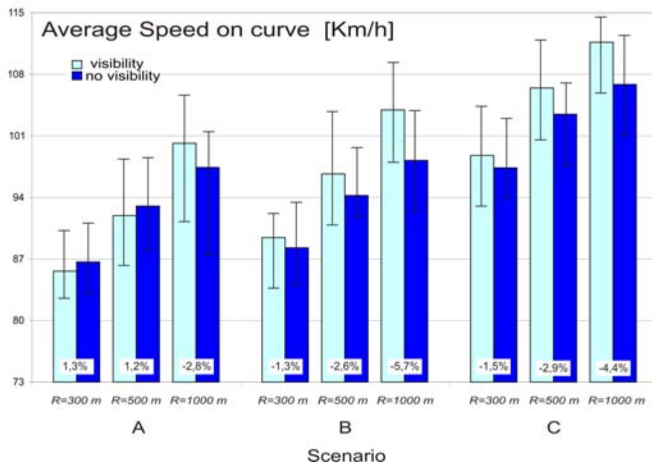

FIGURE 8a

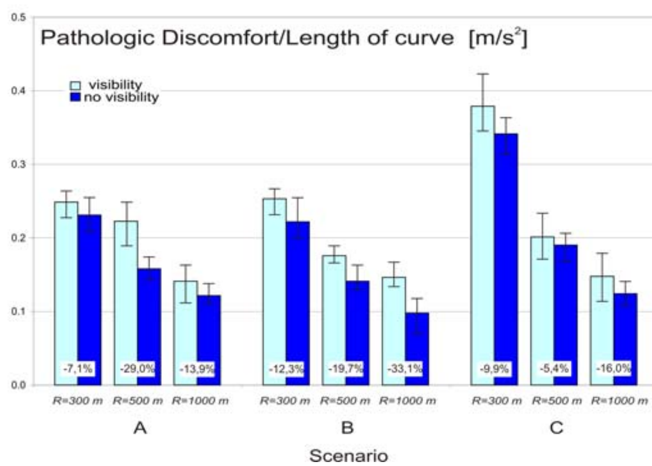

FIGURE 8b

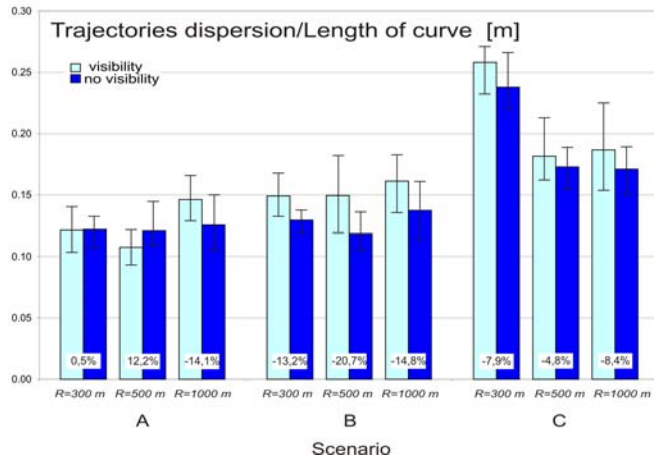

FIGURE 8c

FIGURE 8 Comparison of indicators on 300 m, 500 m and 1000 m radii curves with and without visibility (a) Average Speed, (b) Pathologic Discomfort, (c) Trajectory Dispersion.

CONCLUSIONS

The validation procedure showed that both the method and experimental design are appropriate for studies of relationships between road design parameters and driver's behavior. Driving simulator is an effective tool for evaluation of behavioral aspects, especially those related to driving speed and driving trajectory, of design parameters of roads.

The method used for sample and scenarios validation let to conclude, that it is possible to avoid the biased results and influences of succeeding elements (road curves when separated by straight section) in scenario design.

An important aspect of this simulation method is that it allows a systematic study of relationships between road design parameters and driving behavior.

Regarding road curve perception, three major findings should be stressed:

– the effectiveness of clothoid is recognized, as the results of this experimental study in driving simulator put in light the perceptual and behavioral effects of this transition curves during curve negotiation, presenting safer behavior on curves with clothoids;
– restricted visibility of the inner edge of curves seems to result in safer driving, as the results present lower speed, trajectory dispersion and pathologic discomfort at negotiation of curves with restricted visibility;
– both experimental indicators, pathologic discomfort and trajectory dispersion, show an important relationship between road design parameters and driving behavior on road curves, presenting the increase of risk with road category increase coupled with decreasing curve radius.

The general conclusion of this study results is that advanced techniques of visualization and simulation of road space can disclose the relationships between design road parameters and behavioral aspects important to create safer transportation systems.

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