Driver Perception of Crest and Sag Combinations at the Driving Simulator: effects on driver's behaviour

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Francesco Bella
Department of Sciences of Civil Engineering - Roma TRE University
via Vito Volterra n. 62 - 00146 Rome
Phone +39-6-55.17.34.16; fax +39-6-55.17.34.41
E-mail: bella@uniroma3.it

Synopsis

Several researches have pointed out that optical illusions may occur when the horizontal curve is combined with a vertical curve. Crest and sag combinations can cause a significant different driver's behaviour compared to the behaviour adopted on the horizontal curves on flat grade. In particular the literature reports the hypothesis that horizontal curves appear sharper or flatter when overlapping with crest o sag vertical curves, respectively. This hypothesis was validated from studies on the visual perception of the road through the use of computer animation techniques. On the basis of these researches models were proposed to estimate the horizontal radius perceived on the combined curve as a function of the actual horizontal radius to evaluate the operating speed through 2-D predicting models.

A drawback of computer animation techniques though is that they are limited and not interactive. Interactive driving simulation systems, on the contrary, have high potentials for the analysis of the effects of the combined alignment.

An experimental survey at the driving simulator of CRISS (Interuniversitary Research Center on Road Safety) was carried out in order to assess the driver's behaviour on crest and sag combinations, compared to the behaviour on horizontal curve with the same radius but on flat grade. Two road alignments for the experiment were designed according to the technical Italian guidelines on the coordination of horizontal curves overlapping with vertical curves. One alignment had a flat longitudinal grade, the other had three crest combinations and three sag combinations but with the same horizontal alignment. The vertical grade on the approach tangent of each combined curve was flat in order to avoid the influence of the grade on driver's behaviour. 35 drivers carried out two driving sessions at the simulator (one for each road alignment) during which the local speeds and the local lateral placement were recorded.

On the crest combinations the result of statistical analysis of the speeds was entirely consistent with the hypothesis of perception on crest combinations: at beginning of the circular curve on the reference curves the speeds are greater than those on the correspondent crest combinations. Furthermore the outcomes of the unilateral Z-test showed that the differences between the speeds on reference curves and those on crest combinations tend to decrease as the curve radius increases. Also the influence of the crest vertical curve on the trajectory was clear: the mean deviations from the ideal trajectory at the beginning of the circular curve with radii medium and great were significantly higher on the crest combinations than the mean deviations recorded on the reference curves.

On the sag combinations the speeds were not significantly higher (at 5% significance level) than those on the correspondent reference curves. Such result does not seem to strengthen the hypothesis of perception on sag combinations and suggests that the models to estimate the horizontal radius perceived on the sag combinations as a function of the actual horizontal radius to evaluate the operating speed through 2-D predicting models are inappropriate. No significant effect of the sag vertical curve was observed on the trajectory.

Driver Perception of Crest and Sag Combinations at the Driving Simulator: effects on driver's behaviour

It is well-known that the information the road provides to the driver is essential for him in order to modulate the driving control parameters and avoid risky behaviour (Saad, 2002) (Theeuwes, 1995). Also it is known that most of the information required by the driver during the driving task is perceived visually and that a relevant quote of accident occurs in curve and is due to the erroneous perception of the features of the alignment (Cartes, 2002).

Furthermore, several researches have pointed out that the occurrence of erroneous perception increases as the complexity of the alignment increases and that erroneous perception could be significantly relevant in the conditions of horizontal curves overlapped with sag vertical curves or with crest vertical curves. (Smith and Lamm, 1994) (Mori et al, 1995) (Wooldridge et al, 2000) (Bidulka et al, 2002). In particular Smith, and Lamm hypothesized that an overlapping crest curve may cause the horizontal curve to look sharper while a sag curve may cause the horizontal curve to look flatter than it actually is (perception hypothesis). Then the driver may adopt a lower or higher speed, respectively, than the design speed on which driving dynamic calculations are based. Therefore the erroneous perception of the horizontal curve may be particularly hazardous for the sag combination where the drivers may perceive a sharp curve as a flat one.

The hypothesis of Smith and Lamm was based on the result of the study carried out in Germany at the beginning of 1970's and on the bases of one study on the accident locations (Smith and Lamm, 1994). This study, in particular, was carried out on three sag combinations and one crest combination, and established that the accident rate at the sag vertical curves was higher than the average accident rate over the entire lengths of the observed state routes. It ascertained also that excessive speed was the most frequent cause of accidents. On the crest combination, on the contrary, the accident rate was less than the average accident rate. However it is important to notice that the accidents were few and the authors pointed out that the results were not statistically valid and recommended more studies on the driver's perception. Later, the perception hypothesis was studied with methods based on the drawing of the perspective of the road and, more recently, it was validated from studies on the visual perception of the road through the use of computer animation techniques (Hassan and Sayed, 2002) (Bidulka et al, 2002).

These studies made use of specific software to draw perspective views of the road and create short sequences simulating the view of the driver during the driving. Computer animations of horizontal curves overlapping with crest vertical curves or with sag vertical curves (test curves) and of horizontal curves with the same radius but overlapping with flat grade (reference curves) were prepared. The horizontal radius ranged from 300 m to 700 m. The vertical radius of the crest combinations was of 10000 m and the vertical radius of the sag combinations was of 5000 m. Each test curve and the correspondent reference curve were showed on a computer monitor simultaneously to a sample of drivers. Each driver was asked if the computer animation of the reference curve appeared "same sharp" as, "less sharp" than, or "sharper" than the computer animation of the test curve. The statistical analysis of the responses of the drivers confirmed the hypothesis of Smith and Lamm.

During a subsequent experiment (Hassan et al, 2002) the still images of each test curve and of three reference curves, each with different radius, were showed on a computer screen at the same time to a sample of drivers. Each driver was asked to determine the reference curve that had a curvature closest to that of the test curve. On the basis of the responses of the drivers, models were set to estimate the horizontal radius perceived on the combined curves as a function of the actual radius. The perceived horizontal radius was proposed to determine the operating speed for evaluating design consistency of the alignment through 2-D predicting models (model based on features of the horizontal alignment only). This implies accepting the hypothesis that to a different perception of the horizontal radius corresponds a different speed adopted by the driver. It must be said that this assumption was never verified by an experiment and that the drawing methods and the technique based on the use of computer animation are limited as they evaluate the driver's perception of the road features in conditions far from the actual driving ones.

Furthermore these techniques are non interactive and do not allow to evaluate the driver's reaction to its perception of the road scenario. The driving simulators are believed to be the most accurate method in order to study the drivers' perception (Lamm et al, 1999) (Zakowska, 1999).

Driving simulation in virtual reality is an interactive method and, besides allowing a realistic simulation of the road scenario in a dynamic perspective, allows to evaluate the effect on driving caused by the perception of the road as it is possible to record the driver's reactions at the visual perception.

Therefore, an experimental survey using the interactive driving simulator of Interuniversitary Research Center for Road Safety (CRISS) was carried out in order to verify, on the basis of the speeds and the trajectories adopted by the driver, whether :

- the horizontal curve overlapping with crest vertical curves (called crest combinations) induce the driver to a significantly different behaviour than he would adopt on flat horizontal with same radius (called reference curves), consistently to the perception hypothesis (perception of a shorter horizontal radius than actually is;
- the horizontal curves overlapping with sag vertical curves (called sag combinations) induce the driver to a significantly different behaviour than he would adopt on flat horizontal curves with same radius (called reference curves), consistently to the perception hypothesis (percepiton of horizontal radius greater than it actually is).

Two road alignments were designed to this purpose, one with flat longitudinal grade, the other with crest and sag combinations, but with the same horizontal alignment. Subsequently, they were implemented at driving simulator. Thus 35 drivers carried out two driving sessions (one for each road alignment) during which the local speeds and local lateral placements were recorded. At a second stage, based on the data registered on the crest and sag combinations and on the correspondent reference curves, several parameters were determined to evaluate if the driver's behaviour on the horizontal curves was influenced by the overlapping vertical curves.

Before the detailed description of the experiment, in order to better explain the contribution of this research to the theme of the perception of combined curves, the current knowledge on the matter is synthesised in figure 1, also indicating the aim of the study.

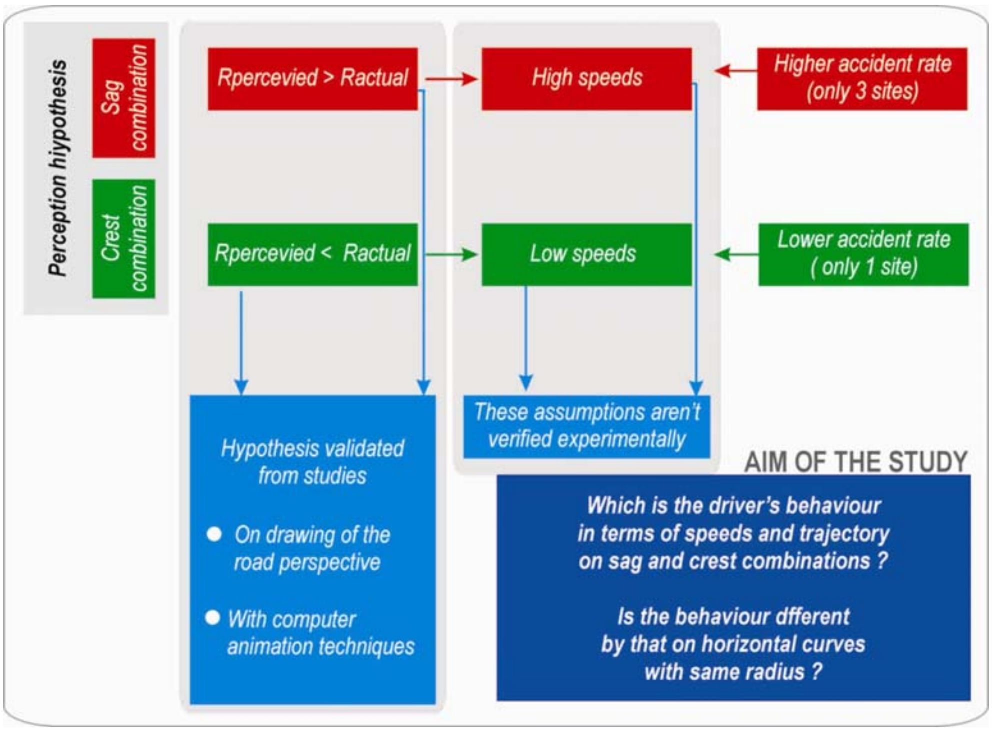

Figure 1: Background knowledge on the perception hypothesis and aim of the study

THE COMBINED CURVES AND THE REFERENCE CURVES

Two two-lane rural roads, with the same horizontal alignment and with only a different profile, were designed. One was flat (called reference alignment), while the other had a longitudinal grades different to zero (called combined alignment). The reference alignment was used as a reference through which the effects of combined curves on the other road alignment could be assessed. According the Italian design guide (Ministry of infrastructures and Transports, 2001) for rural roads (type C1), the cross section was wide 10.50 m (lane width 3.75 m and shoulder width 1.50 m).
For the purposes of this research 3 crest combinations and 3 sag combinations were designed on the combined alignment with the following features:

- the vertical curves were overlapped with horizontal curves so the vertices of the two curves coincided and their length was the same order of magnitude, as required by Italian design guide about the coordination of horizontal alignment and profile;

- to eliminate the influence of the longitudinal grade and the curvature of the element preceding the combined curves on the driver's behaviour, all the combined curves were designed with flat and long approach tangent (length ranged from 600 m to 1400 m).

The three crest combinations had a departure tangent with longitudinal grade – 3%. The horizontal radius was of 252 m, 437 m and 600 m and the deflection angle was of 77°, 65° and 57°. The radii of vertical curves were, respectively, of 16000 m, 20500 m and 26700 m. They were greater than those used by previous researches (Hassan and Sayed, 2002) (Bidulka et al, 2002). The sight distance was of about 380m, 430m, and 480m, respectively. These sight distances were longer than double stopping sight distance but a little shorter than the passing sight distance calculated according to Italian guidelines. The correspondent reference curves had the same features of the horizontal curves of the crest combinations.

The three sag combinations had a departure tangent with longitudinal grade + 4%. The horizontal radius was of 252 m, 437 m and 600 m and the deflection angle was of 77° 65° and 57°. The radii of vertical curve were, respectively, of 12000 m, 16500 m and 20000 m. The correspondent reference curves had the same features of the horizontal curves of the sag combinations.

The geometric parameters of the crest combinations and sag combinations are shown in table 1. Figure 2 shows the schemes of the surveyed crest combinations and sag combinations.

Tab 1: The Geometric Features of the Combined Curves

	N	Horizontal curve						Vertical curve				
		R	L_c	L_{cl}	L_{circ}	$L_{a.t.}$	γ	R_v	L_v	i_a	i_d	Δi
Crest	1	252	480	140	200	600	77°	16000	480	0	-3	3
	2	437	660	180	300	1200	65°	20000	600	0	-3	3
	3	600	800	200	400	1400	57°	26700	800	0	-3	3
Sag	1	252	480	140	200	600	77°	12000	480	0	4	4
	2	437	660	180	300	1200	65°	16500	660	0	4	4
	3	600	800	200	400	1400	57°	20000	800	0	4	4

R = radius of horizontal curve
L_c = length of horizontal curve in m (Lcl+Lcirc+Lcl)
L_{cl} = length of clothoids in m
L_{circ} = length of circular curve in m
$L_{a.t.}$ = length of approach tangent in m
γ = deflection angle

R_v = radius of vertical curve in m
L_v = length of vertical curve in m
i_a = approach grade in percent
i_d = departure grade in percent

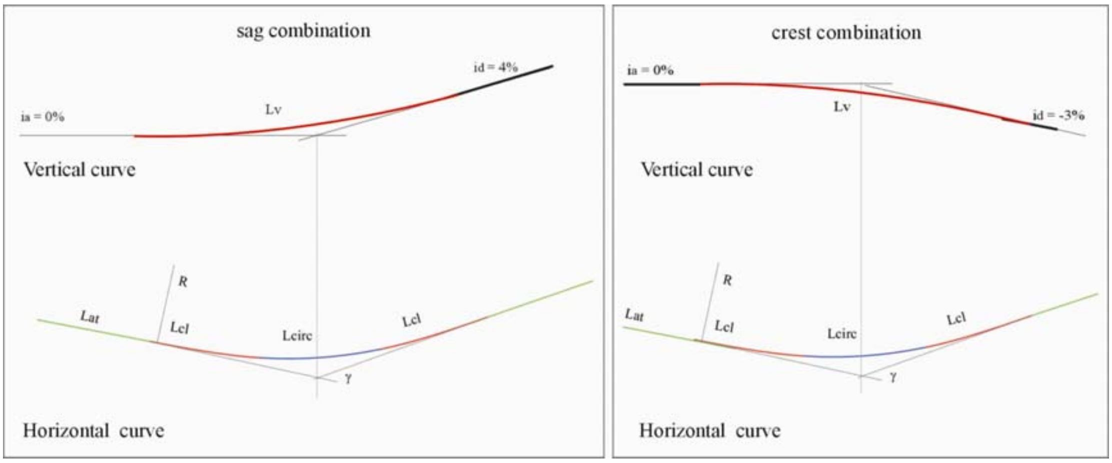

Figure 2: The scheme of crest and sag combinations

THE EXPERIMENTATION AT DRIVING SIMULATOR

The simulation system of CRISS is widely described in several previous researches (Bella, 2005a) (Bella, 2005b) (Bella, 2005c) (Bella, 2005d) and we will omit here a further description. We only emphasize that it is an interactive static base driving simulator. It includes a complete vehicle dynamics model based on the computer simulation Vehicle Dynamics Analysis Non Linear and adapted to run in real time (VDANL/RT). Complete model has been validated extensively (Allen et al. 1998).
The system allows to represent the infrastructure's scenario, the traffic conditions, the configurations of horizontal and vertical alignments, the cross section's features, and to simulate the friction between tires and road surface and the vehicle's physical and mechanical characteristics.
The hardware is composed by four networked computers and three hardware interfaces. One computer processes the motion equations the others generates the images. The hardware interfaces are the steering system, the pedals and the gear lever and in order to create a driving environment similar to the actual one, they are installed on a real vehicle. The road scenario is projected onto three big screens: one in the centre in front of the vehicle and two lateral ones angled at 60° with respect to the plane of the central screen. This set up provides a realistic view of the road and surrounding environment. The scenario is updated dynamically according to the travelling conditions of the vehicle, depending on the actions of the driver on the pedals and the steering wheel. The resolution of the visual scene is 1024x768 pixel and the update rate is 30-60 Hz depending on scene complexity. The system is integrated with a sound system to reproduce the sounds of the engine. It offers a very realistic simulation, recording the intensity of the actions of the drivers on the brake and the accelerator pedals and on the steering wheels, and providing many other parameters describing travelling conditions (vehicle barycentre, relative position with respect to the road axis, local speed and accelerations, steering wheel rotation angle, pitching angle, rolling angle, etc.) at time or space intervals respectively of a fraction of a second or of a meter.
The experimentation was carried out using dry pavement conditions in good state of maintenance and with the free vehicle on its own driving lane. Whereas, on the opposing lane a modest traffic was distributed randomly for the sole purpose of inducing the driver not to invade it. The simulated vehicle was a standard medium class car, both for dimension and for mechanical performance, with an automatic gear. The data recording system acquired all the parameters at spatial intervals of 5 m. 35 drivers were selected to perform driving at the simulator according to the following characteristics: no experience with the driving simulator, at least four years of driving experience and an average annual driven distance on rural roads of at least 2500 km.
The procedure of the drivings can be divided into the following steps: a) communication to the driver about the general modalities of the driving (duration of the driving, use of the steering wheel and pedals, automatic gear, etc.); b) filling in of a form with personal data; c) setting the driver inside the car and adjustment of the driver's seat; d) training at the driving simulator on a specific alignment for approximately 10 minutes; e) carrying out the first driving; f) car vacated by the driver for about 5 minutes in order to re-establish psycho-physical conditions similar to those at the beginning of the test; g) carrying out the second driving on a different road; h) filling in of a questionnaire about the uneasiness perceived during the driving at the simulator in order to eliminate from the sample the drivings carried out in anomalous conditions. The questionnaire consists of 4 questions, each for a kind of uneasiness: nausea, giddiness, weariness, other. Each question could be answered scoring 1 to 4, proportionally to the level of uneasiness experienced: null, light, medium and high. The level "null" for all four kinds of uneasiness is considered the condition of acceptability of the driving. No case of unacceptable driving was observed. All 35 drivings could be used for the purpose of the study.
In order to limit the influence, on the data analysis, of the possible effects induced by the repeated drivings on drivers (habit and tiredness), we chose to alternate the order of the drivings on the two roads. Figure 3 shows an example of the visual representation of the road scenario as seen by the driver during the driving simulation.

Figure 3: The road scenario during the driving simulation

DATA COLLECTION

Within the number of parameters collected by the simulator we processed the local speeds and local lateral placements. The data were recorded at spatial intervals of 5 m.
For each combination of the combined curves, at each measurement site along the horizontal curve (section formed by approach clothoid, circular curve and departure clothoid) the following parameters were determined, on the basis of the local speed and local placement of the barycentre of the vehicle measured from the cross section axis:

- mean speed (V_{50}) and speed of 85th percentile (V_{85})
- difference between V_{85} (ΔV_{85}) and average value of V_{85} on the approach tangent ($V_{85average\_tangent}$)

  $$\Delta V_{85} = V_{85average\_\tan gent} - V_{85}$$

- the mean deviation (St) from the ideal trajectory, assumed to coincide with the driving lane axis (fig. 4)

  $$S_t = \frac{3.75}{2} - lp$$

where 3.75 is the lane width and *lp* is the lateral position recorded by the simulator (measured from the axis of the cross section).
The same parameters were determined for the correspondent reference curves of the reference alignment.

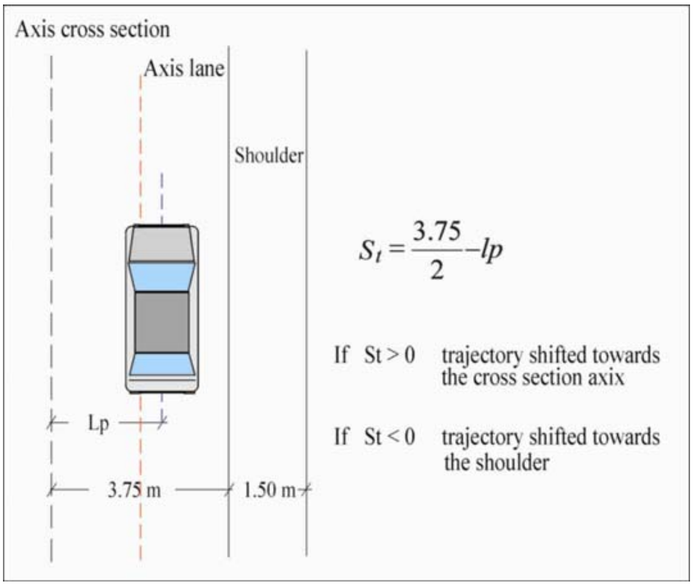

Figure 4: The mean deviation

DATA ANALISYS

The parameters described above recorded on the combined curves were compared to the same ones recorded on the correspondent reference curves in order to point out the influence on the driver's behaviour of crest vertical curves and sag vertical curves overlapped with horizontal curve.
The outcomes of the comparison, related to two types of combined curves (crest combinations and sag combinations), follow.

Crest combinations: mean speed and V_{85}

The analysis of the diagrams of the mean speeds (V_{50}) and of the operating speeds (V_{85}) highlighted that both V_{50} and V_{85} recorded on crest combinations are slower than those recorded on the correspondent reference curves (fig. 5). This is true for the whole section of the horizontal curve (approach clothoid, circular curve and departure clothoid), with any value of the radius.
As the crest combinations were designed with a flat approach tangent they are descending slopes (longitudinal grade ranges from zero on approach tangent to -3% on the departure tangent). The speed recorded along them were slower than those on correspondent reference curves and this supports the hypothesis of the perception of a smaller horizontal radius than it actually is (thus the driver is urged to slow down).
This is confirmed by the statistical analysis performed on the mean values of the speeds recorded on the crest combinations and on the correspondent reference curves at the site of measurement at the beginning of the circular curve.

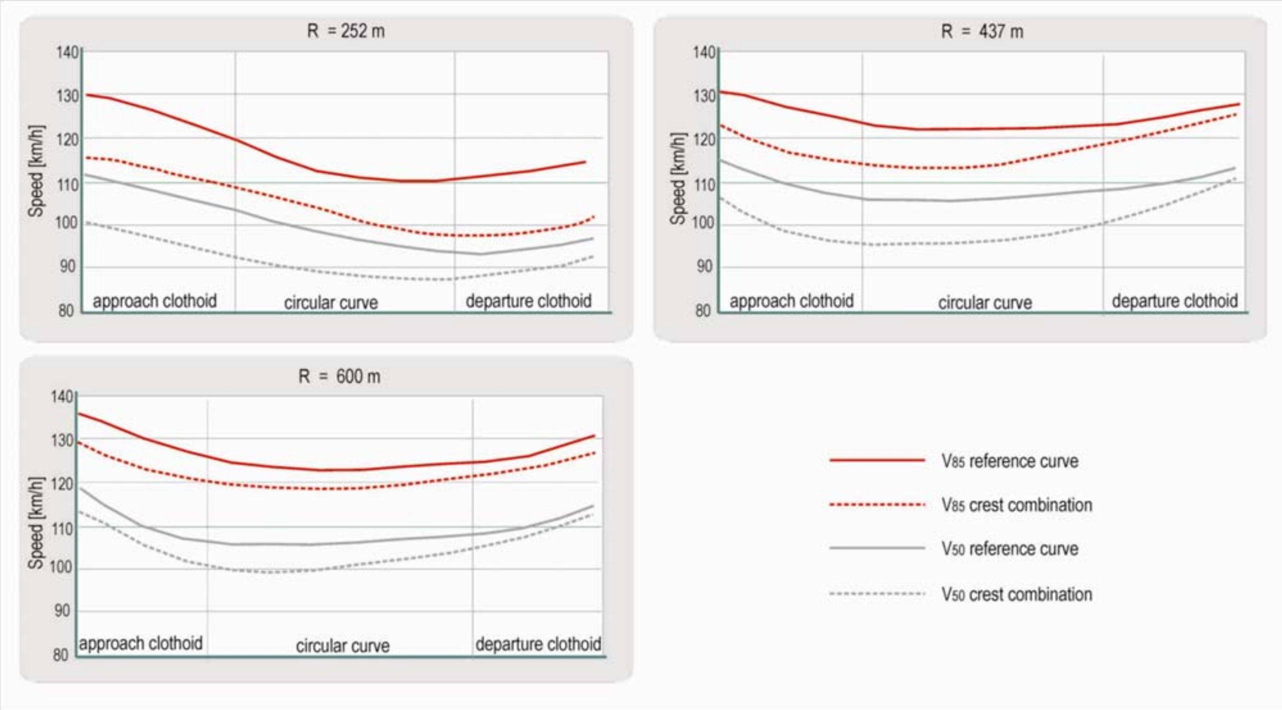

Figure 5: The diagrams of V_{50} and V_{85} on the crest combinations and on the reference curves

A unilateral Z-test, for matched samples was used for the analysis. The test was used to ascertain whether the mean speed of the population of speed recorded at beginning of the circular curve on the reference curve is significantly greater than the mean speed of the population of speed recorded at the same point on the crest combination.

For each crest combination the following hypotheses are formulated:

– null hypothesis H_0: the speeds at beginning of the circular curve on reference curve are less than or equal to speeds on the same point of the correspondent crest combination;
– alternative hypothesis H_1: the speeds at beginning of the circular curve on reference curve are greater than speeds (those) on the same point of the correspondent crest combination.

Such hypotheses can be written as follows:

null hypothesis H_0: $\mu_{ref} \leq \mu_{crest}$

alternative hypothesis H_1: $\mu_{ref\,t} > \mu_{crest}$

Where μ_{ref} and μ_{crest} are, respectively, the mean of the speeds' population on the site "beginning of the circular curve" of the reference curves and the mean of the speeds' population on the site "beginning of the circular curve" of the crest combinations.

The test is run at the level of significance (α) of 5% and at the level of significance of 1%. This means to accept the probability of 5% or 1%, respectively, that an error of type 1 may occur, that is to reject, mistakenly, a true null hypothesis.

Z statistic was calculated according to the following

$$Z = \frac{\bar{d}_{V(ref-crest)}}{\frac{sd_{V(ref-crest)}}{\sqrt{n}}}$$

where the $(\bar{d}_{V(ref-crest)})$ is the average of the speeds' differences between the crest combinations and the reference curves on the site "beginning of the circular curve"; it was calculated through the following functions

$$\bar{d}_{V(ref-crest)} = \frac{1}{n}\sum_{i=1}^{n}\left(V_{(ref)i} - V_{(crest)i}\right)$$

and $(sd_{V(ref-crest)})$ is the standard deviation of the speeds' differences between the crest combinations and the reference curves on the site "beginning of the circular curve".

The calculated Z was compared to the critical values (Z_c) correspondent to the level of significance of 5% ($Z_{c5\%}$ = 1.65) and of 1% ($Z_{c1\%}$ = 2.33).

At the level of significance 5%, if

$Z < Z_{c5\%} = 1.65$ then H_0 is rejected

$Z > Z_{c5\%} = 1.65$ then H_0 cannot be rejected

At the level of significance 1%, if

$Z < Z_{c1\%} = 2.33$ then H_0 is rejected

$Z > Z_{c1\%} = 2.33$ then H_0 cannot be rejected

It is interesting to notice that Z values decrease as the horizontal radius increases and that the null hypothesis must be rejected for the three horizontal radii (tab.2). Particularly for the small and medium radii (252 m and 437 m) the null hypothesis must be rejected also at a level of significance of 1%, whereas for the longest radius (600 m) the null hypothesis must be rejected only at a level of significance of 5%. This verifies the statistical significance of the phenomenon (speeds on the crest combinations are slower than on reference curves) and points out that it tends to decrease as radii increase.

Tab. 2: Result of the Z test on the speeds recorded at the beginning of the circular curve

Crest	$\bar{d}_{V(ref-crest)}$	$sd_{V(ref-crest)}$	n	Z	$Z_{c5\%}$	result of the test (level of significance α = 5%)	$Z_{c1\%}$	result of the test (level of significance α = 1%)
R= 252	11.46	19.27	35	3.52	1.65	H0: rejected	2.33	H0: rejected
R=437	10.50	19.07	35	3,26	1.65	H0: rejected	2.33	H0: rejected
R=600	5.60	19.6	35	1.69	1.65	H0: rejected	2.33	H0: accepetd
null hypothesis		H_0: $\mu_{ref} \leq \mu_{crest}$						
alternative hypothesis		H_1: $\mu_{ref\ t} > \mu_{crest}$						

Further confirmation comes from the analysis of the decreases of the average values of V_{50} ($V_{50average}$) and V_{85} ($V_{85average}$) measured on the approach clothoid, the circular curve and the departure clothoid of the crest combinations compared to the same parameters measured on the correspondent elements of the reference curves (fig.6).

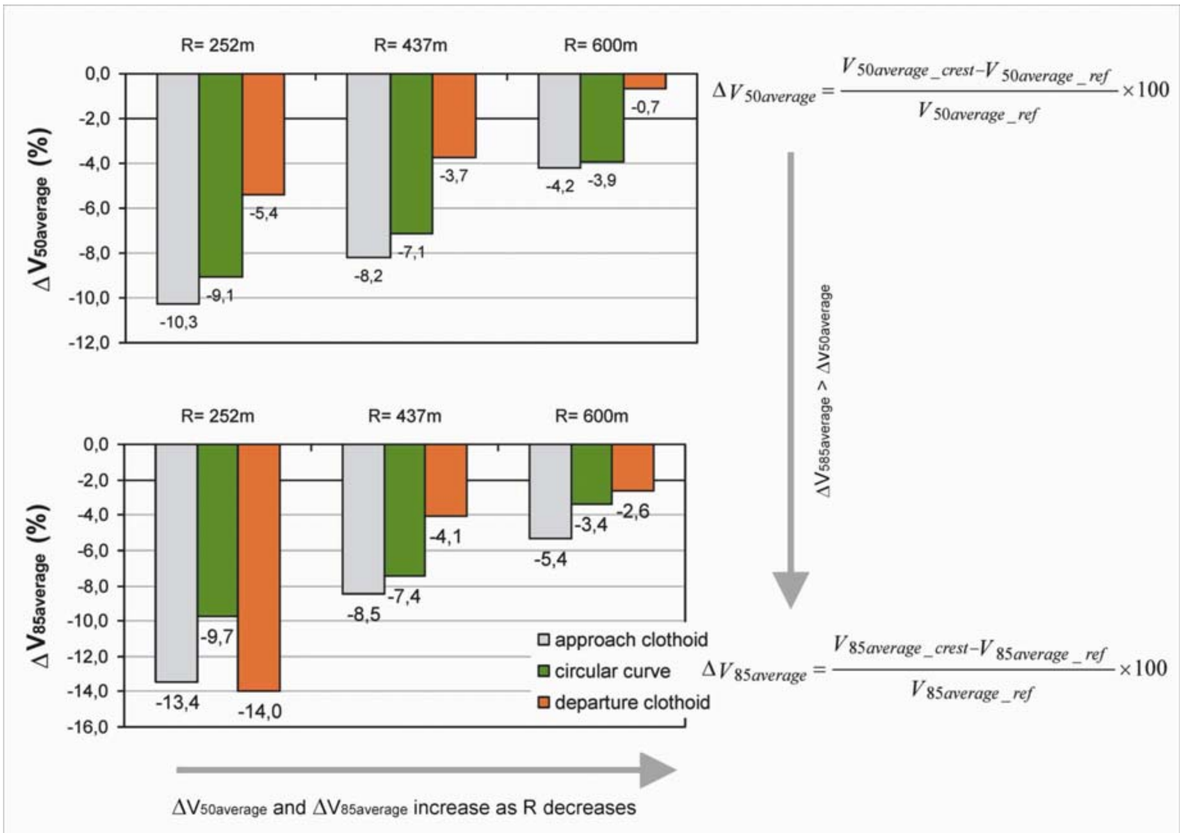

Figure 6: Percentage decreases of $V_{50average}$ and $V_{85average}$ on horizontal elements of the crest combinations

The comparison between the percentage decreases of $V_{50average}$ and $V_{85average}$ obtained on the horizontal elements of the crest combinations shows that the speed reduction decreases as the radii increase. In fact, both the percentage decreases of $V_{50average}$ and $V_{85average}$ are smaller as the radius increases.

Furthermore, the comparison between the percentage decreases of $V_{50average}$ and $V_{85average}$ obtained on the same horizontal element of a crest combination shows that the effect of the speed reduction is more evident for faster drivers than for average ones (the percentage decreases of $V_{85average}$ are greater than those of $V_{50average}$).

Crest combinations: ΔV_{85} compared to the average value of V_{85} on the approach tangent

The behaviour described above is basically confirmed if we calculate the reduction (ΔV_{85}) of V_{85} on the horizontal curve compared to the average value of V_{85} on the approach tangent ($V_{85average\_tangent}$) and compare such reductions obtained both on crest combinations and on correspondent reference curves (fig.7).

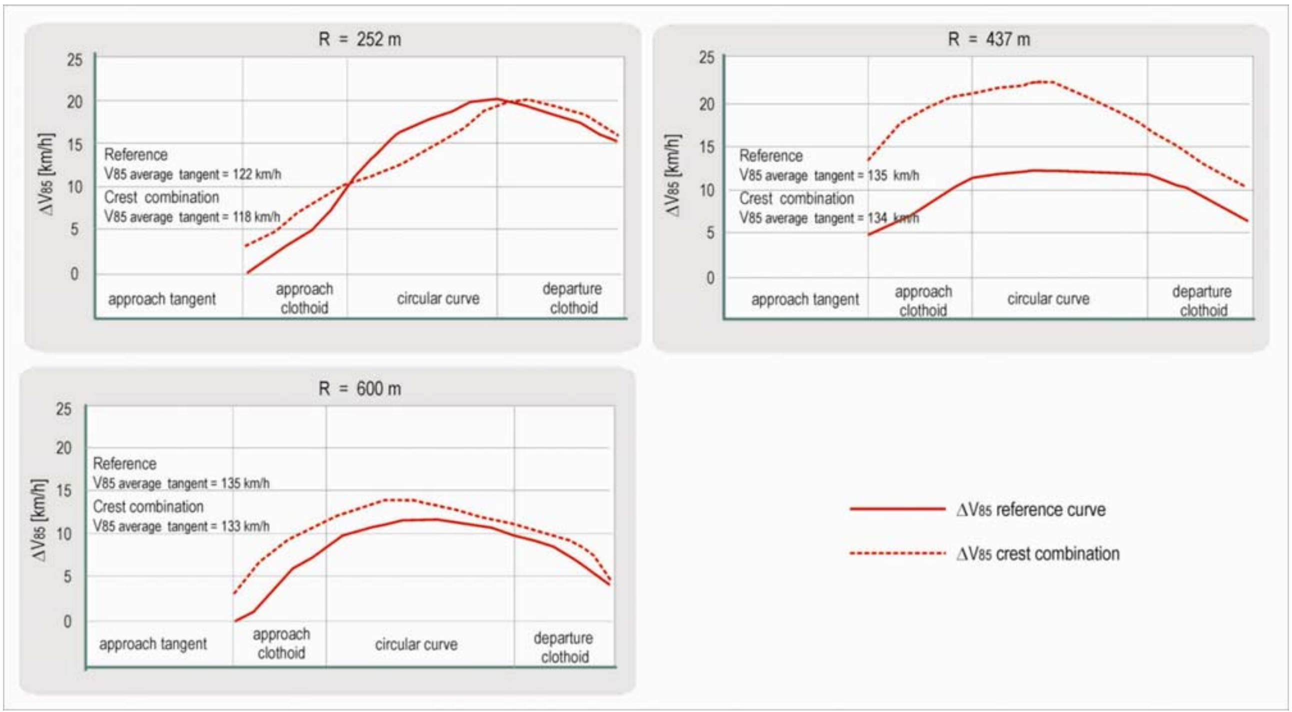

Figure 7: ΔV_{85} compared to the average values of V_{85} on the approach tangents

On the approach clothoids of the crest combinations ΔV_{85} is greater than the correspondent value on the reference curves. Besides $V_{85average\ tangent}$ on the approach tangent of each crest combination is smaller then $V_{85average\ tangent}$ on the correspondent approach tangent of the reference curve for an amount equals to 4 km/h, on R=252 m, 1 km/h on R=437 m, 2 km/h on R=600m.
This means that the driver, not only drives along the approach tangents of the crest combinations at lower $V_{85average\ tangent}$ than those on the correspondent tangents of the reference curves, but also that he decreases his V_{85} on the approach clothoids of the crest combinations more than he does on the approach clothoids of the reference curves. This matches completely with the hypothesis of the perception of a smaller horizontal radius than it actually is on the crest combination.

Crest combinations: lateral placement

To study driver's behaviour concerning the trajectory adopted to drive along the crest combinations and the reference curves the mean deviation (S_t) of the lateral placement of the vehicle's barycentre was determined, as compared to the ideal trajectory, assumed to coincide with the driving lane's axis. The diagrams of this parameter on the three crest combinations and correspondent reference curves are shown in figure 8.

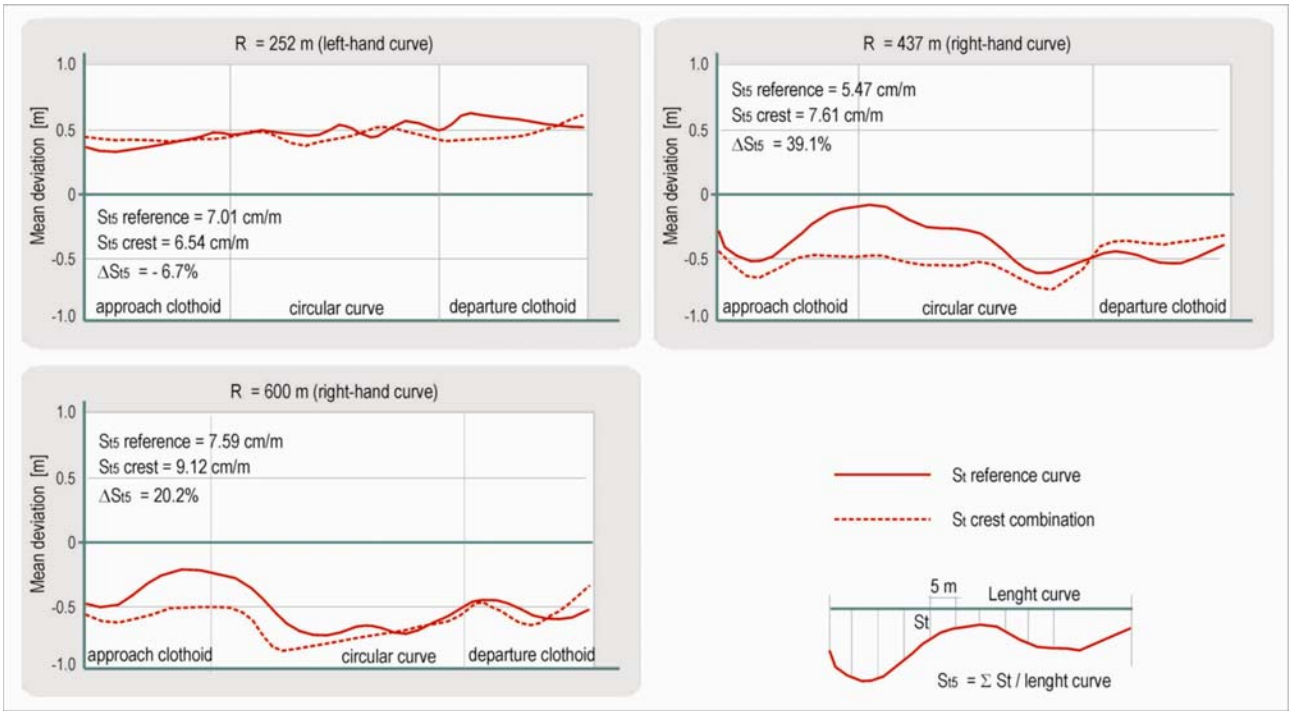

Figure 8: The diagrams of the deviations on the crest combinations and on the reference curves

The diagrams allow to determine the driver's tendency, already reported on literature, to "cut" the horizontal curve. This is true both for left-hand curves and right-hand curves.
It can be noticed that the curve with little radius (252 m) is a left-hand one and shows positive values of deviation along the whole curve. These values indicate a mean trajectory shifted towards the road axis. On the contrary, the curves with medium and big radius (437 m and 600 m, respectively) are both right-handed and show negative values of deviation, indicating a mean trajectory shifted towards the shoulder.

In order to evaluate the effects of the crest vertical curve on the mean trajectory the parameter S_{t5}, was considered. It corresponds to the sum of the deviations measured along the curve (at 5 m intervals) divided by the whole curve's length. The values obtained for both the reference curves and the crest combinations are collected in fig. 8.
It is interesting to notice that on the right-hand curves the values of S_{t5}:

- increase as the radius increases both on the reference curves and on the crest combinations. This shows a tendency to "cut" the horizontal curves, moving towards the shoulder, which increases as the radius increases;
- are greater on the crest combinations than those on the correspondent reference curves. This means that the driver adopts on the crest combinations trajectory more shifted from the ideal one than he does on the correspondent reference curves.
  It is also interesting to observe that the percentage increases of S_{t5} compared to the values on the reference curves, are smaller on crest combination with longest radius (600 m) than on the crest combination with medium radius (437 m). This is explained, probably, by the quite high values (7.59 cm/m) recorded on the reference curve with big radius.

As for the mean speeds, a Z-test was performed for matched samples on the mean values of the deviation recorded on the crest combinations and on the correspondent reference curves at the site of measurement “beginning of the circular curve”.
The outcomes showed that the mean deviations on the crest combinations are significantly higher than the mean deviations recorded on the reference curves, both at level of significance of 5% and of 1% (tab. 3) .

Tab. 3: Result of the Z test on the deviations recorded at the beginning of the circular curve

Crest	$\overline{d}_{St(ref-crest)}$	$sd_{St(ref-crest)}$	n	Z	$Z_{c5\%}$	result of the test (level of significance α = 5%)	$Z_{c1\%}$	result of the test (level of significance α = 1%)
R=437	0.40	0.55	35	4.30	1.65	H0: rejected	2.33	H0: rejected
R=600	0.26	0.65	35	2.37	1.65	H0: rejected	2.33	H0: rejecetd

null hypothesis H_0: $\mu_{st\ ref} \le \mu_{st\ crest}$
alternative hypothesis H_1: $\mu_{st\ ref} > \mu_{st\ crest}$

Where μ_{ref} and μ_{crest} are respectively the mean of the deviations' population on the site "beginning of the circular curve" of the reference curves and the mean of the placements' population on the site "beginning of the circular curve" of the crest combinations.

On the right-hand curves, therefore, the effect on the trajectory of the overlapping crest vertical curve with the horizontal curve is an increase of the mean deviation which marks the driver's tendency to drive along the horizontal curve moving closer to the shoulder than he usually does on the correspondent reference curve.

On the left-hand curve (radius of 252 m), on the contrary, the value of S_{t5} on the crest combination, is slightly lower than on the reference curve. This shows the absence of significant effects on the trajectory caused by the overlapping crest vertical curve with horizontal curve.

Sag combinations: mean speed and V_{85}

The analysis of the diagrams of V_{50} and V_{85} recorded on the sag combinations and on the correspondent reference curves highlights that in the final part of the horizontal curves the V_{50} and the V_{85} are greater on the reference curve than on the sag combinations (fig. 9). This seems to depend on the fact that the final part of the sag combinations is an upward slope. In fact the approach tangent of the sag combinations is flat and the departure tangent has a grade of + 4%.

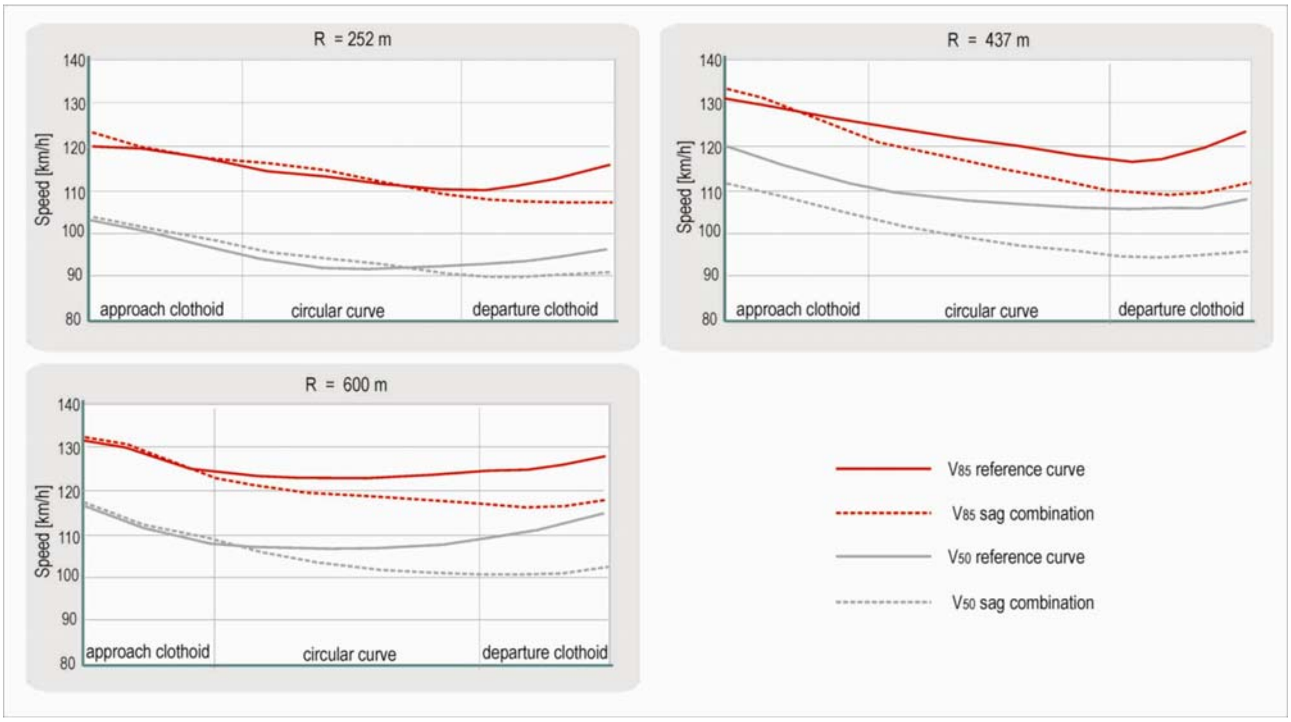

Figure 9: The diagrams of V_{50} and V_{85} on the sag combinations and on the reference curves

Taking this into account, the possible effects on driver's speed due to a different perception of the horizontal radius on the sag combination should occur at the beginning of the curves. Here in fact the different speed which could be adopted on the sag combinations with respect to that on the reference curves is not

influenced by the longitudinal grade (the grade is basically null and so the same as on the reference curve) but only by the perception of the horizontal radius.
Accepted the hypothesis that the horizontal radius is perceived as longer on the sag combination, then a greater speed should be recorded on the initial section of the sag combination than on the same section of the reference curve.

The diagrams though do not support this hypothesis. Even though in some point of the approach clothoids of the sag combinations the V_{85} are slightly greater than those on the reference curves, at beginning of circular curve only on the sag combinations with radius of 252 m and 600 m the mean speeds are a little greater than those recorded on correspondent reference curves.
The Z-test for matched samples performed for these points showed that the speeds on the sag combinations are not significantly greater than on the correspondent reference curves. Therefore the results do not support the hypothesis of a perception of the horizontal curve of the sag combination flatter than it actually is.

Sag combinations: ΔV_{85} compared to average value of V_{85} on the approach tangent

Even though the speeds on the initial section of the sag combinations are not significantly greater than on the correspondent section of the reference curves, it seems proper to analyse the decrease (ΔV_{85}) of the V_{85}, compared to the average value of V_{85} on the approach tangent ($V_{85average\_tangent}$), adopted by the driver on the sag combinations and reference curves. The diagrams of ΔV_{85} on the three sag combinations are shown in figure 10.

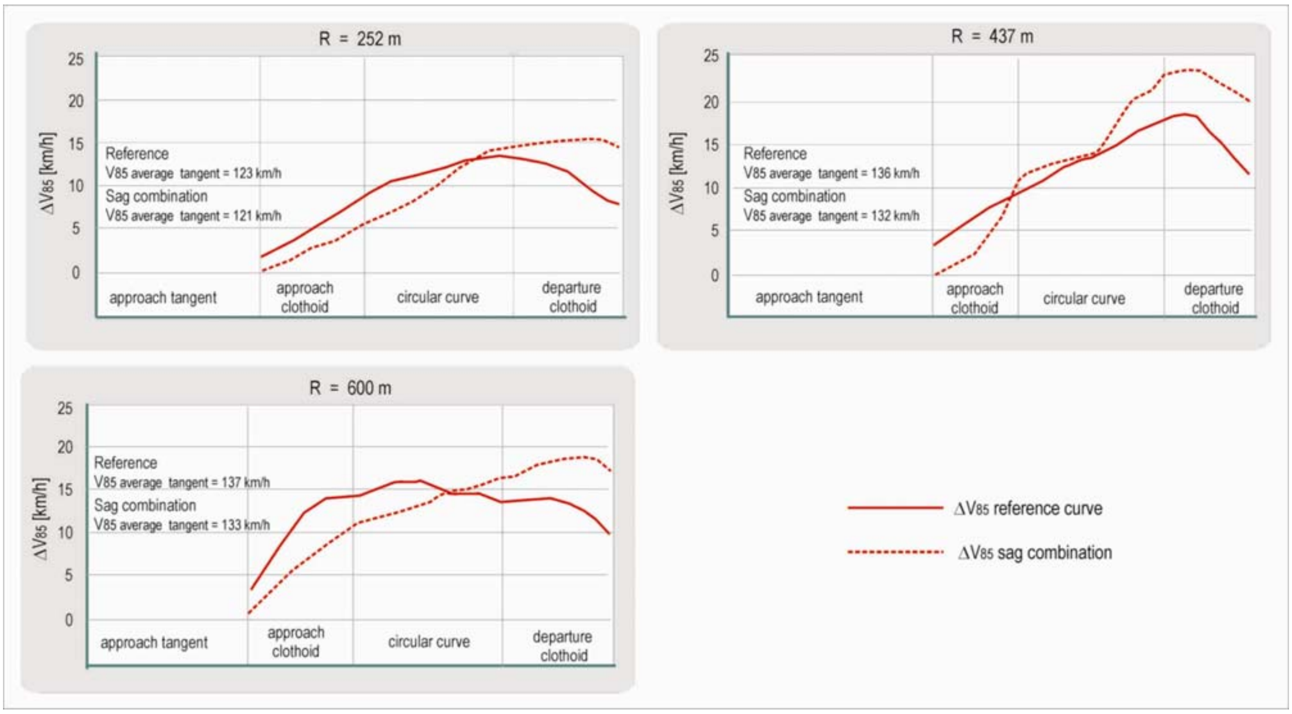

Figure 10: ΔV_{85} compared to average values of V_{85} on the approach tangents

The diagrams show that on the three sag combinations ΔV_{85} calculated for the approach clothoid of the sag combination is smaller than that calculated for the approach clothoid of the reference curve.
This seems to reveal that on the approach clothoids of the sag combinations the driver lowers the operating speed (V_{85}), compared to the average value adopted on the approach tangent ($V_{85average\_tangent}$), less than on the approach clothoids of the reference curves. This seems to be consistent with the hypothesis of the perception of the horizontal radius of the sag combinations greater than it actually is.

Yet it is to be observed that the average speeds on the approach tangents of the sag combinations are slower (about 2 km/h for sag combination with radius 252m, 4 km/h for sag combinations with radius 437 m and radius 600 m) than those on the approach tangents of the reference curves.
This does not allow to exclude the fact that the smaller speed's decrease on the approach clothoids of the sag combinations is caused by the lower speed on the approach tangent rather than by the perception of the horizontal radius greater than it actually is.

Sag combinations: lateral placement

As we did for the crest, to analyse the driver's behaviour in terms of trajectory on sag combinations and on reference curves, the mean deviation S_t was determined. The diagrams on the three sag combinations and on the correspondent reference curves are in figure 11.

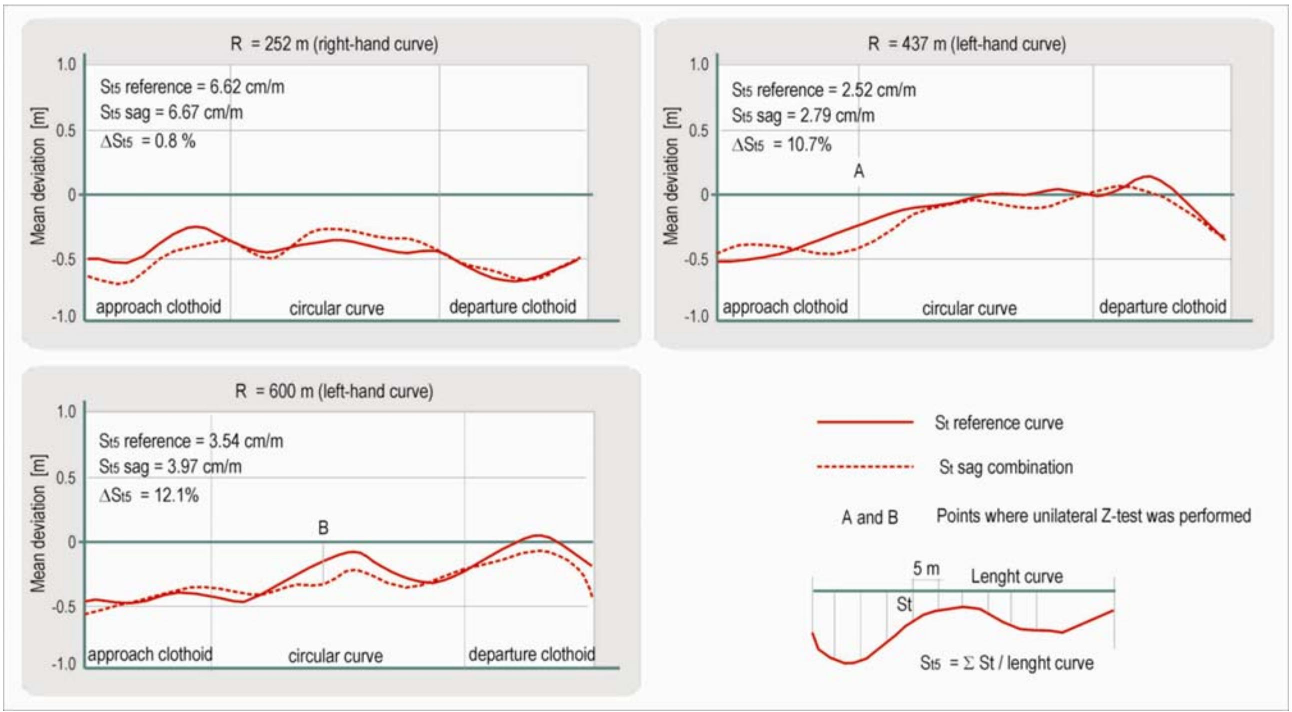

Figure 11: The diagrams of the deviations on the sag combinations and on the reference curves

As for crest, for sag combinations, too, it is clear the tendency of the driver to cut the horizontal curve, both left- and right-hand.
In fact, on the left-hand curves (those with radius 437m and 600m) the driver starts the curve adopting a trajectory shifted towards the shoulder and drives along the curve moving gradually towards the road axis. On the contrary, on the right-hand curve (radius 252 m) the deviation is negative along the curve, revealing a trajectory of the vehicle shifted towards the shoulder.

In this case, as for the crests, in order to evaluate the effects on the mean trajectory of the overlapping sag the parameter S_{t5} was calculated. The values obtained on the sag combinations and on the reference curves are listed in figure 11.

On the left-hand curves the values of S_{t5} for sag combinations are higher than those calculated for the corespondent reference curves. This seems to suggest that the driver adopts on the sag combinations trajectories shifted from the ideal one more than on the correspondent reference curves.
Such an assumption, though, is not confirmed by the statistical analysis performed using a unilateral Z-test for matched samples on the points where the differences between the mean deviations on the sag combinations and those on the reference curves are greater (point A at beginning of the circular curve for radius 437 m, point B on the circular curve for radius 600 m).
At each point the test revealed that the deviations on the sag combinations are not significantly greater (at level of significance of 5%) than the deviations calculated for the correspondent reference curves.
It is so possible to state that the effect of the overlapping sag vertical curves with the surveyed horizontal left-hand curves does not appear to be statistically significant, although the qualitative analysis shows greater deviations from the ideal trajectory on the sag combinations than on the correspondent reference curves.

Finally, on the right-hand curve (radius 252 m) the value of S_{t5} on the sag combination is equal to the value on the reference curve. This means that no effects on the trajectory chosen by the driver were induced by the overlapping sag vertical curve with horizontal curve.

CONCLUSION

The experimentation at the interactive driving simulator of CRISS, carried out in order to verify whether the driver's behaviour on the horizontal curves was influenced by the overlapping vertical curves allowed to determine the following issues.

crest combinatinos

The statistical analysis performed on the speeds recorded at the beginning of the circular curve pointed out that on the reference curves the speeds are greater than those on the correspondent crest combinations.

The outcomes of the unilateral Z-test for matched samples revealed that the differences between the speeds on reference curves and those on crest combinations tend to decrease as the curve radius increases.

Such result is also confirmed by the comparison between the percentage decreases of the $V_{50average}$ and $V_{85average}$ calculated on the horizontal elements of the three crest combinations. In fact both the percentage decreases relative to $V_{50average}$ and to $V_{85average}$ decrease as the radius increases.

Furthermore, comparing the percentage decreases of $V_{50average}$ and $V_{85average}$ for the same element of a crest combination shows that the effect of the reduction of the speed is not only evident observing the V_{50} but even more obvious observing the V_{85} (the percentage decreases of $V_{85average}$ are greater than those of $V_{50average}$).

Finally, the analysis of the variation of the operating speed (ΔV_{85}) on the approach clothoids compared to the average value of V_{85} on the approach tangents ($V_{85average\ tangent}$) showed that the driver lowers the V_{85} on the approach clothoids of the crest combinations more than on the approach clothoids of the reference curves.

Therefore these findings appear to be consistent with the perception hypothesis on crest combinations, that the horizontal radius is perceived as shorter than it actually is.

Concerning the lateral placement, the statistical analysis for the right-hand curves (those with radius medium and great), highlighted that the mean deviations at the beginning of the circular curve on the crests are significantly greater, both for 5% and 1% level of significance, than the mean deviations on the reference curves. This means that the effect of the overlapping of the crest vertical curve with these horizontal curves is to increase the mean deviation. This also means that the driver tends to drive along the horizontal curve moving more toward the shoulder than he does on the correspondent reference curve.

On the left-hand curve (with little radius), on the contrary, no significant effects were observed on the driver's trajectory caused by the overlapping crest vertical curve.

Sag combinations

Even though the operating speeds were slightly greater at the initial section of the sag combinations, they do not come out to be significantly greater (at the level of significance of 5%) than those adopted on the correspondent reference curves.

Such result does not support the perception hypothesis on sag combinations according to which the horizontal radius is perceived greater than it actually is. Such result, consequently, suggests the inadequacy of the models to estimate the perceived horizontal radius on the sag combinations as a function of the actual horizontal radius in order to evaluate the operating speed through 2-D predicting models. Therefore, more properly, the operating speed on the sag combinations should be calculated using a 3-D predicting models to develop on the basis of the speeds actually adopted by the drivers on the sag combinations. Relevant research efforts of many researchers of several Countries are addressing this objective.

Also considering the lateral placement, though the values of S_{t5} observed on the sag combinations are greater than those on the correspondent reference curves, the deviations on the sag combinations are not significantly higher (at the level of significance of 5%) than those recorded on the correspondent reference curves.

Before drawing some general conclusions from this study, especially regarding the outcomes concerning the sag combinations that does not support the perception hypothesis, it is necessary to broaden the sample of combined curves, particularly in terms of longitudinal grade of the departure tangents and of the turning direction (more left and right-hand curves).

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