# DRIVING SIMULATION FOR DESIGN CONSISTENCY

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**ABSTRACT.**

Drivers' speeds were recorded on 32 tangent-curve-tangent configurations of four two-lane rural roads implemented in the CRISS (Inter-University Research Center for Road Safety) driving simulator. 147 driving tests were used for the analysis in order to verify if: a) the midpoint of the tangent and the midpoint of the curve are the most appropriate locations for speed data collection to evaluate the speed differential through the subtraction of operating speed on two locations; b) the speed differential obtained by the subtraction of the maximum operating speed on the last 200 m of the tangent and the minimum operating speed on the curve is significantly different from the 85$^{th}$-percentile of the distribution of maximum speed reduction experienced by each driver. The results were the following. The maximum operating speed on the last 200 m of the tangent ($V_{85max\_200}$) is higher than the operating speed at the midpoint of the tangent. The operating speed in the midpoint of the curve overestimates the minimum operating speed on curve ($V_{85min,c}$). A relationship between the point along the curve where the minimum operating speed is achieved and the geometric features of the tangent-curve transition was defined. Speed differential obtained using $V_{85max\_200}$ and $V_{85min,c}$ tends to underestimate the amount of speed reduction experienced by the drivers. Predicting models of the maximum operating speed on the last 200 m of the tangent, of the minimum operating speed on curve and of the 85$^{th}$-percentile of the distribution of maximum speed reduction experienced by each driver were developed.

## INTRODUCTION

It is widely recognized that design consistency verification is particularly effective in the improvement of road safety. In accordance with the numerous definitions in scientific literature, it's aimed at avoiding road alignment configurations which might surprise drivers and lead to anomalous behaviour.

In literature there are various criteria to evaluate design consistency. They are based on the analysis of alignment indices or on the quantification of the mental workloads of drivers as well as on the analysis of operating speed. The most commonly used criteria are based on operating speed ($V_{85}$), considered as the expressive parameter of the driver's behaviour and defined as that speed below which 85% of passenger cars operate under free flow conditions. In particular the quantitative safety criteria developed by Lamm et al. (1) (2) for the evaluation of design are usually used. As is well known, these criteria provide the evaluation of design on three levels (good, fair and poor) with regards to the difference between design speed ($V_d$) and the operating speed ($V_{85}$) on each element of the alignment (Criterion I) and between the $V_{85}$ of successive elements (Criterion II). A third safety criterion (Criterion III) is based on vehicle stability on horizontal curves.

In order to avoid surprising events, it's considered very important to limit the speed reduction (or speed differential) by drivers between successive elements of the alignment (3). According to a traditional approach the speed differential is quantified as the difference between the operating speeds on tangent and successive curve. The steps of this process are the following:

- estimation of the operating speed ($V_{85}$) at a significant location of the approach tangent;
- estimation of the operating speed ($V_{85}$) at the midpoint of the circular curve;
- calculation of the speed differential as difference between $V_{85}$ on tangent and curve.

This process is characterized by several criticalities such as:

- estimation of the operating speed on tangent and identification of the proper location along the tangent where to collect speed data;
- assumption of constant operating speed on curve; it is assumed equal to that measured at the midpoint of the circular curve;
- estimation of the speed reduction experienced by the individual drivers on tangent-curve transition.

Concerning the prediction of operating speed on tangents of two-lane rural roads a satisfactory model has yet to be developed (4). Several average values of the observed 85$^{th}$ percentile speed are recommended in literature. Lamm and Choueiri (5) suggested 94.7 km/h, Krammes et al. (6) 97,9 km/h, Fitzpatrick et al (3) used the value of 100 km/h although several data showed that higher speeds may be observed on tangent. The most recent average values of operating speed for independent tangent (longer than 200 m) and non-independent tangent are respectively 103 km/h and 95.8 km/h (7). Also concerning the location along the tangent where to collect the speed data there is a wide range. The measures are performed or at the midpoint of the tangent (8) or at locations 100 m (7) or 200 m before the beginning of the curve (9) or also at several locations of the last section of 200 m of tangent approaching the curve (9) (10). These last choices of locations where to collect speed data derive from the result of a research (3) that showed that the speed along the approach tangent does not start dropping until a point closer than 200 m to the point of curvature. Obviously the assumption of an average value of operating speed on tangent or the location where to collect speed data in order to obtain the operating speed, may have significant effects on calculation of the speed differential in the tangent-curve transition.

As regards the operating speed on curve, the main operating speed-profile models (they provide the graphic representation of $V_{85}$ along the road alignment) available in scientific literature are in agreement in holding that the operating speed on curve can be considered constant (2) (10). This assumption was considered acceptable although field data illustrated that the speeds vary throughout the curve (2) (11). Therefore the operating speed is usually determined at the midpoint of the circular curve. It's implicitly considered representative of the driver's behaviour on the whole curve and is used for the evaluation of the speed differential according to the traditional approach. However further more recent studies (12) (9) highlighted that the assumption of constant speed on curve doesn't correspond to the real driver behaviour and it may compromise the proper computation of the speed differential. More specifically McFadden and Elefteriadou (9) observe that in order to quantify the speed differential, the midpoint of the horizontal curve and the midpoint of the approach tangent may not be the appropriate locations for data collection. Therefore they recommend researches that identify where the drivers reach the maximum speed on the approach tangent and the minimum speed on the horizontal curve.

Concerning the speed differential, Hirsh (13) argued that the value calculated through a simple subtraction of $V_{85}$ at two locations would underestimate the amount of speed reduction experienced by the individual drivers. Subsequently some researches (9) (14) confirmed Hirsh's hypothesis. In particular McFadden and Elefteriadou (9) suggested a new parameter (85MSR) based on analyzing the speed profile of individual vehicles. 85MSR was determined as the $85^{th}$ percentile of the distribution of maximum speed reduction experienced by each driver. The speed profile of each driver was obtained on the basis of speed measurements at 9 locations of the section constituted by the last 200 m of the approach tangent and by the successive curve. Then the speed reduction experienced by each driver was obtained from the difference between the maximum speed on the last 200 meters of the approach tangent and the minimum speed on the curve. Also Misaghi and Hassan (7) developed an innovative parameter ($\Delta_{85}V$) based on the analysis of the reduction of speed by a single driver. $\Delta_{85}V$ was defined as the differential speed not exceeded by 85% of the drivers traveling under free-flow condition. This parameter was calculated on the basis of the speeds at two locations fixed ahead of time: at the point on the approach tangent approximately 100 m before the beginning of the curved section and at the midpoint of the curve. Subsequently a research (15) showed that the calculation of the speed differential on the basis of the speeds recorded at two locations fixed ahead of time ($\Delta_{85}V$) leads to an underestimation of the speed differential obtained through the analysis of the speeds collected at 9 locations (85MSR). A such result showed that the estimation of the speed differential is significantly affected by data availability to draw the speed profile of every driver.

Bearing in mind these criticalities and the possibility of recording speed data at very brief spatial intervals along the alignment thanks to the technique of driving simulation in virtual reality, the present study was carried out using the CRISS (Inter-University Research Center for Road Safety) interactive fixed-base driving simulator located at Roma TRE University. The objectives of the study were:

1. to ascertain whether the midpoint of the tangent is the appropriate location for speed data collection in order to evaluate the speed differential or if it's more appropriate to analyse the operating speed on the last 200 m of the tangent to identify the maximum value. In other words: to verify whether the operating speed at the midpoint of the tangent is significantly different from the maximum operating speed on a location of the last 200 m of the approach tangent;
2. to ascertain, analogously to the previous point, whether the midpoint of the curve is the appropriate location for speed data collection in order to evaluate the speed differential or if it's more appropriate to analyze the operating speed on the whole curve to identify the minimum value;
3. to verify if the speed differential obtained by the subtraction of the maximum operating speed on the last 200 m of the tangent and the minimum operating speed on the curve is significantly different from the $85^{th}$ percentile of the distribution of maximum speed reduction experienced by each driver (85MSR);
4. to define predicting models of the main variables (operating speed, speed differential, etc.).

It should be noted that interactive driving simulators are considered useful and reliable tools to study driver behavior induced by road configurations (for exhaustive references see (16). They allow a high degree of realism, low costs for the performance of experiments, easy data collection, the highest safety for test drivers and the possibility of carrying out experiments in controlled conditions. However in order for a driving simulator to be considered an useful research tool, it is very important that the reliability of the measurements recorded during the driving in virtual reality are verified. Concerning this aspect it should be pointed out that a previous validation study revealed the high degree of reliability of the speed measures recorded using the CRISS driving simulator (17) (18). In particular it was demonstrated that the differences between the speeds observed in a real two-lane rural road and those measured on the same road reconstructed in the simulator are statistically non-significant. Only for the alignment configurations which lead to high speeds, such as extremely long tangents (more than 1,100 m), the differences of speeds are statically significant. For these configurations, the higher speeds recorded in simulator appeared to stem from the different risk perception on the simulated road as opposed to that on the real road (18). Considering the outcomes of this previous validation study of CRISS driving simulator, in the present research the speeds adopted by the drivers on configurations of two lane rural roads with tangents long not more than 1,100 m were analyzed.

Finally it is appropriate to highlight that driving simulator appears to be an effective tool to analyze the speed of the driver thanks to, besides the reliability of the measures, also its some important characteristics such as the easy data collection and the possibility of carrying out experiments in controlled conditions. The importance of such characteristics becomes even more evident if we consider the characteristics of field studies. As a matter of fact, field studies are characterized by complexities entailed in collecting field data (which need to be carried out while ensuring that the presence of research personnel and instruments do not affect measurements, leading to anomalous driver behavior) as well as by the difficulties encountered in making the measurements under controlled environmental and traffic conditions (7) (19) . More specifically, the impossibility in most of the research carried out in the field of conducting controlled experiments (in which causal factors are held constant) is underscored among the main factors affecting research quality (20).

## METHOD

### Test alignments

For the aims of the study, four road alignments of two-lane rural roads used in previous researches carried out at the CRISS Simulation Laboratory were considered. One of these (alignment 1) was the reconstruction in virtual reality of an Italian real two-lane rural road; it was 10 km long with longitudinal grades less than 6%. The other three alignments were designed according to the recent Italian guidelines on road design (2001); they were flat. Two of these (alignment 2 and 3) were more than 30 km long, while the last alignment (alignment 4) was almost 40 km long. The cross-section was 10.50 m wide for the all the road alignments. Lane and shoulder widths were 3.75 m and 1.50 m respectively. Thirty-two configurations made up of the tangent-curve-tangent transition were selected according to the results of previous validation study of CRISS driving simulator (18). These configurations are characterized by tangents whose length ranges from 118 m to 1108 m, by a radius of the circular curves ranging from 200 m to 588 m and a longitudinal grade ranging from -3% to +4.70%. The geometric parameters of each configuration are shown in table 1.

**TABLE 1 Geometric Features of the Studied configurations**

| Configuration | Approach Tangent | | Horizontal Curve | | | | | | | Departure Tangent | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $L_{at}$ | i | CCRs | $L_{cl}$ | $L_c$ | $L_{circ}$ | R | γ | ΔR | $L_{dt}$ | i |
| 1 | 744.90 | 4.70 | 182.28 | 48.77 | 306.55 | 209.45 | 294 | 47 | -37.71 | 370.47 | 4.70 |
| 2 | 620.83 | 4.70 | 221.16 | 28.69 | 334.58 | 276.79 | 263 | 71 | 93.98 | 492.20 | 4.70 |
| 3 | 304.65 | 0.00 | 183.05 | 135.96 | 483.25 | 211.09 | 250 | 77 | 184.78 | 303.52 | 0.00 |
| 4 | 1004.99 | 0.00 | 108.34 | 172.88 | 659.98 | 316.07 | 435 | 65 | 0.00 | 302.64 | 0.00 |
| 5 | 305.28 | 0.00 | 182.91 | 137.03 | 486.52 | 211.97 | 250 | 77 | 338.24 | 302.70 | 0.00 |
| 6 | 304.46 | 0.00 | 108.34 | 172.56 | 659.4 | 315.81 | 435 | 65 | -184.78 | 806.52 | 0.00 |
| 7 | 302.19 | 0.00 | 182.88 | 136.55 | 484.02 | 210.78 | 250 | 77 | 0.00 | 302.66 | 0.00 |
| 8 | 301.52 | 0.00 | 183.00 | 136.9 | 484.02 | 211.24 | 250 | 77 | 0.00 | 307.70 | 0.00 |
| 9 | 307.70 | 0.00 | 82.22 | 191.65 | 796.22 | 412.8 | 588 | 57 | -338.24 | 801.18 | 0.00 |
| 10 | 154.79 | 0.00 | 151.21 | 126.04 | 606.4 | 353.26 | 333 | 80 | 101.45 | 258.40 | 0.00 |
| 11 | 609.79 | 0.00 | 108.42 | 200.95 | 628.46 | 227.24 | 400 | 60 | 314.29 | 255.44 | 0.00 |
| 12 | 290.38 | 0.00 | 150.26 | 82.42 | 387.04 | 221.6 | 333 | 50 | 435.90 | 591.15 | 0.00 |
| 13 | 255.99 | 0.00 | 75.25 | 143.25 | 467.18 | 182.13 | 588 | 30 | 181.00 | 255.40 | 0.00 |
| 14 | 290.82 | -3.00 | 150.60 | 80.49 | 383.42 | 220.89 | 333 | 50 | 435.90 | 591.14 | -3.00 |
| 15 | 370.47 | 4.70 | 161.34 | 28.34 | 298.49 | 241.52 | 357 | 39 | -63.03 | 620.83 | 4.70 |
| 16 | 217.19 | 4.70 | 194.01 | 26.99 | 355.57 | 300.77 | 303 | 66 | 96.97 | 1107.57 | 4.70 |
| 17 | 161.07 | 1.70 | 200.50 | 28.06 | 377.95 | 321.84 | 294 | 72 | -56.02 | 231.62 | 1.70 |
| 18 | 117.51 | 2.60 | 217.58 | 28.33 | 89.87 | 32.92 | 200 | 24 | 300.00 | 343.29 | 2.60 |
| 19 | 607.16 | 0.00 | 108.61 | 170.88 | 663.32 | 320.15 | 435 | 65 | 0.00 | 304.65 | 0.00 |
| 20 | 303.52 | 0.00 | 108.29 | 172.49 | 662 | 316.63 | 435 | 65 | -184.78 | 1004.99 | 0.00 |
| 21 | 302.64 | 0.00 | 183.10 | 137.02 | 485.24 | 212.15 | 250 | 77 | 184.78 | 305.18 | 0.00 |
| 22 | 305.44 | 0.00 | 182.89 | 136.9 | 486.09 | 211.73 | 250 | 77 | 338.24 | 303.47 | 0.00 |
| 23 | 305.18 | 0.00 | 183.04 | 136.29 | 484.54 | 211.63 | 250 | 77 | 338.24 | 304.46 | 0.00 |
| 24 | 806.52 | 0.00 | 108.29 | 172.84 | 660.7 | 316 | 435 | 65 | 0.00 | 806.76 | 0.00 |
| 25 | 303.27 | 0.00 | 182.78 | 136.7 | 483.85 | 210.33 | 250 | 77 | 184.78 | 302.19 | 0.00 |
| 26 | 302.66 | 0.00 | 182.72 | 137.26 | 483.91 | 210.13 | 250 | 77 | 0.00 | 301.52 | 0.00 |
| 27 | 254.85 | 0.00 | 75.09 | 141.76 | 463.63 | 179.33 | 588 | 30 | -188.24 | 254.29 | 0.00 |
| 28 | 591.15 | 0.00 | 150.36 | 82.13 | 386.75 | 221.86 | 333 | 50 | 0.00 | 289.98 | 0.00 |
| 29 | 256.47 | 0.00 | 108.45 | 200.55 | 629.06 | 227.7 | 400 | 60 | 188.24 | 609.20 | 0.00 |
| 30 | 258.06 | 0.00 | 151.29 | 126.14 | 606.86 | 354.04 | 333 | 80 | 380.95 | 155.31 | 0.00 |
| 31 | 155.04 | 0.00 | 106.36 | 147.06 | 535.8 | 242.17 | 435 | 50 | 65.22 | 401.97 | 0.00 |
| 32 | 257.32 | 3.00 | 151.29 | 125.87 | 605.97 | 353.51 | 333 | 80 | 380.95 | 155.23 | 3.00 |

$L_{at.}$ = length of approach tangent in m

$L_{dt.}$ = length of departure tangent in m

$L_c$ = length of horizontal curve in m ($L_{cl}$+$L_{circ}$+$L_{cl}$)

$L_{circ}$ = length of circular curve in m

$L_{cl}$ = length of clothoids in m

R = radius of curve in m

γ = deflection angle

i = longitudinal grade in %

ΔR = difference between the radius of the previous configuration and that of the actual configuration

CCRs = Curvature Change Rate of the curve in gon/km

$$CCRs = \frac{63{,}700 \times (L_{cl}/\mathrm{R} + \mathrm{L}_{cr}/\mathrm{R})}{L_c}$$

## CRISS Driving Simulator

The CRISS simulation system is an interactive fixed-base driving simulator. It includes a complete vehicle dynamics model based on the Non Linear Vehicle Dynamics Analysis computer simulation. The model has been adapted to run in real time and it has been validated extensively (21). The hardware consists of four networked computers and three interfaces. One computer processes the motion equations while the others generate the images. The hardware interfaces include a steering wheel, pedals and a gearshift lever. They are mounted on a real vehicle in order to create a very realistic driving environment. The driving scene is projected onto three screens, one in front of the vehicle and two on each side. The usual field of view is 135°. The system is also equipped with a sound system reproducing the sounds of the engine. The whole system offers a very realistic simulation and it allows us to record many parameters related to travelling conditions of the vehicle at time or space intervals of a fraction of a second or a fraction of a meter. Figure 1 shows the desk for the construction and implementation of the scenarios in the simulator as well as a phase of a driving.

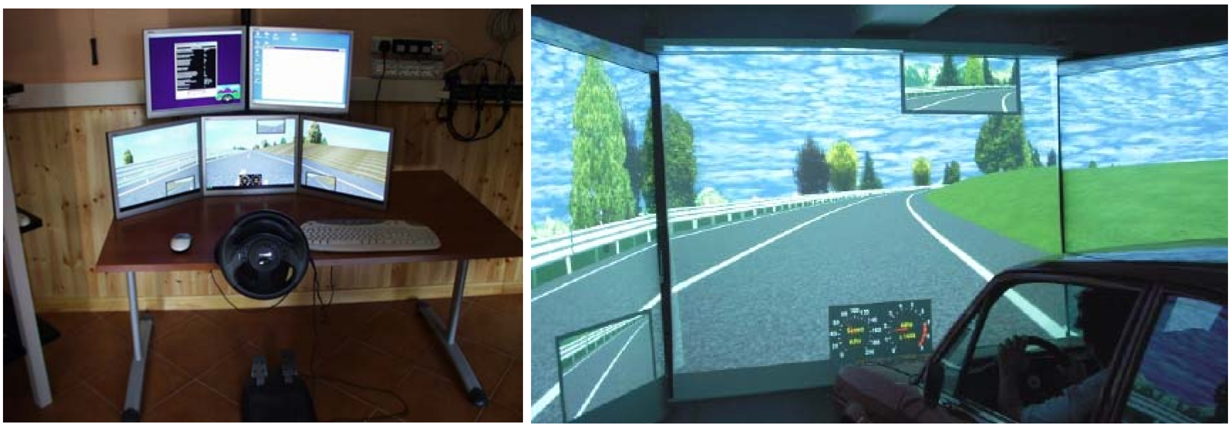

**FIGURE 1 CRISS Driving Simulator:**
**console for implementation of the scenarios and example of driving**

## Procedure

The experimentations were carried out using dry pavement conditions in good state of maintenance, simulating the characteristics of a medium-class car, for both dimensions and mechanical performance, with automatic transmission. In the opposing lane, modest traffic was distributed randomly for the sole purpose of inducing the driver not to invade it. The data recording system was set to acquire all the parameters at spatial intervals of 5 m. The driving procedures were the following: a) communicating to the driver about the duration of the driving and the use of the steering wheel, pedals and automatic gear; b) filling in a form with personal data, years of driving experience, average annual distance driven on rural roads; c) training at the driving simulator on a specific alignment for approximately 10 min; d) driving on the test alignments; e) filling in of an evaluation questionnaire about type (nausea, giddiness, daze, fatigue, other) and entity (null, light, medium, and high) of the discomfort perceived during the driving.

## Participants

Fifty-two drivers drove in the simulator on the road alignment 1, 33 drivers drove on the alignment 2, 32 on the alignment 3 and 35 drivers drove on the alignment 4. The participants, male (60%) and female (40%), ranged in age from 21 to 60 years. They were selected according to the following characteristics: no experience with the driving simulator, at least 3 years of driving experience and an average annual driven distance on rural roads of at least 2500 km. The discomfort was noticed from the outcomes of the questions posed to the drivers after the tests in order to eliminate from the sample driving carried out in anomalous conditions. The null level for all four kinds of discomfort was considered the acceptable condition for driving. Three of the 33 participants that drove on the second alignment and two of the sample selected to perform the driving on the alignment 3 experienced a degree of discomfort that excluded them from the sample. Therefore 147 driving tests were used for the analysis.

**Data Processing**

The local speeds of drivers were collected every five meters on the 32 selected tangent-curve-tangent transitions. Based on the collected speed data, for each configuration the following parameters were determined:

- the maximum operating speed on the last 200 m of the approach tangent ($V_{85max\_200}$);
- the operating speed at the midpoint of the tangent ($V_{85mid,t}$);
- the minimum operating speed on the circular curve ($V_{85min,c}$);
- the operating speed at the midpoint of the circular curve ($V_{85mid,c}$);
- the 85$^{th}$ percentile of the distribution of maximum speed reductions experienced by each driver travelling over the section constituted by the last 200 m of the approach tangent and by the curve (85MSR). For the approach tangents whose length is less than 200 m, the maximum speed recorded on the tangent was considered.

Figure 2 shows a typical studied configuration with locations and sections where the speeds used for the computation of the above mentioned parameters were collected. Table 2 shows the values of each parameter for each configuration.

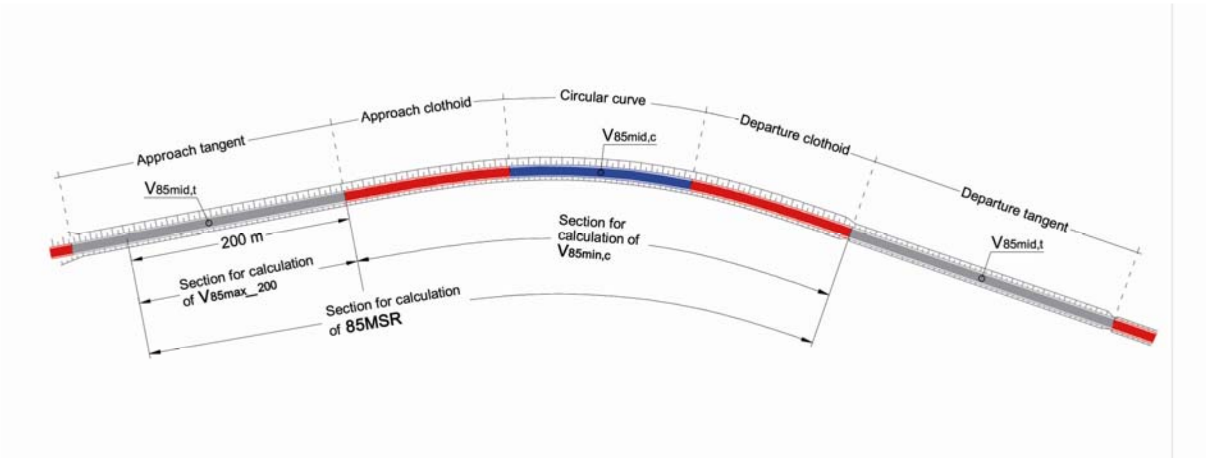


**FIGURE 2 Locations and sections where speed data were collected**

**TABLE 2 $V_{85max\_200}$, $V_{85mid,t}$, $V_{85min,c}$, $V_{85mid,c}$, 85MSR for the 32 Configurations on the Basis of the Speed Collected in Driving Simulator**

| Configuration | Approach Tangent | | Horizontal Curve | | Departure Tangent | 85MSR |
|---|---|---|---|---|---|---|
| | $V_{85max\_200}$ | $V_{85mid,t}$ | $V_{85min,c}$ | $V_{85mid,c}$ | $V_{85mid,t}$ | |
| 1 | 111.19 | 112.75 | 90.17 | 91.35 | 94.93 | 33.12 |
| 2 | 108.19 | 103.14 | 92.69 | 95.82 | 103.43 | 19.49 |
| 3 | 125.23 | 123.55 | 105.74 | 112.24 | 116.93 | 31.62 |
| 4 | 143.08 | 139.00 | 114.43 | 119.15 | 128.57 | 45.86 |
| 5 | 132.86 | 129.99 | 104.66 | 114.33 | 121.36 | 33.80 |
| 6 | 119.20 | 112.80 | 108.64 | 115.14 | 138.42 | 24.07 |
| 7 | 124.72 | 121.96 | 101.71 | 108.91 | 119.30 | 36.28 |
| 8 | 125.55 | 118.97 | 109.11 | 112.34 | 120.70 | 25.12 |
| 9 | 126.26 | 120.70 | 115.47 | 128.35 | 148.86 | 28.84 |
| 10 | 124.37 | 124.00 | 111.29 | 115.64 | 131.75 | 27.55 |
| 11 | 151.16 | 147.52 | 117.95 | 125.22 | 132.76 | 42.22 |
| 12 | 139.77 | 137.65 | 108.31 | 112.81 | 132.07 | 46.13 |
| 13 | 130.66 | 125.76 | 112.41 | 116.44 | 129.87 | 27.38 |
| 14 | 143.65 | 142.91 | 110.52 | 110.62 | 136.73 | 41.75 |
| 15 | 97.19 | 94.93 | 88.82 | 90.00 | 103.14 | 18.33 |
| 16 | 107.95 | 106.59 | 98.50 | 99.57 | 113.63 | 16.82 |
| 17 | 105.01 | 103.20 | 98.04 | 102.38 | 111.78 | 13.27 |
| 18 | 107.87 | 106.05 | 99.18 | 101.59 | 102.37 | 14.46 |
| 19 | 138.95 | 140.73 | 116.22 | 122.89 | 123.55 | 35.98 |
| 20 | 121.54 | 116.93 | 106.85 | 113.26 | 139.00 | 23.79 |
| 21 | 131.12 | 128.57 | 102.01 | 106.24 | 116.68 | 41.45 |
| 22 | 131.87 | 127.95 | 107.71 | 114.50 | 124.44 | 37.34 |
| 23 | 138.19 | 132.71 | 105.50 | 113.49 | 112.80 | 42.69 |
| 24 | 139.35 | 138.42 | 118.73 | 119.14 | 136.67 | 41.46 |
| 25 | 134.44 | 132.72 | 109.61 | 113.01 | 121.96 | 40.49 |
| 26 | 127.76 | 119.30 | 104.41 | 109.43 | 118.97 | 37.78 |
| 27 | 124.61 | 120.14 | 111.32 | 116.29 | 130.97 | 21.45 |
| 28 | 136.31 | 132.07 | 105.95 | 106.95 | 127.94 | 42.73 |
| 29 | 129.90 | 125.16 | 115.03 | 119.23 | 135.34 | 27.23 |
| 30 | 138.74 | 136.14 | 103.78 | 107.54 | 117.12 | 45.29 |
| 31 | 122.34 | 116.50 | 108.83 | 109.55 | 131.83 | 24.13 |
| 32 | 129.26 | 125.63 | 95.82 | 103.83 | 117.65 | 34.87 |

It should be noted that the average operating speed at the midpoint of the independent tangent is equal to 123 km/h (on the non-independent tangent the average operating speed is 114 km/h). This value, although higher than the values of the operating speed obtained on independent tangent in the USA (10) (11) or in Canada (7), is consistent with the values of operating speed (equal to 129.5 km/h by Crisman et al.(22) and to 119 km/h by Cafiso (23)) recorded on tangents of real two-lane rural roads in Italy with characteristics which are similar to those of the alignments which are the object of the present study.

Also the point ($P_{minV85,c}$) along the horizontal curve where the minimum operating speed is achieved was determined. $P_{minV85,c}$ expresses the distance from the beginning of the curved section divided by the total length of the horizontal curve; therefore it's in percent. Then values more than 50 show that the point is in the 2nd half curve. Table 3 shows for each configuration the value obtained. These values highlight that the minimum speed on the horizontal curve occurs more frequently along the circular curve (in 27 configurations), in particular on the second half (in 16 configurations). More specifically, only in 1 configuration the $P_{minV85,c}$ coincides with the midpoint, and only in 8 configurations the $P_{minV85,c}$ ranges from 45 to 55, therefore indicating that only in the 25% of the studied configurations the minimum value of the operating speed is reached approximately at the midpoint of the circular curve.

**TABLE 3 The points of minimum operating speed on the curves**

| Configuration | R | $L_{cl}$ | $L_{circ}$ | $L_c$ | $P_{minV85,c}$ | Element of the curve |
|---|---|---|---|---|---|---|
| 1 | 294 | 48.77 | 209.45 | 306.55 | 54 | 2nd half circular curve |
| 2 | 263 | 28.69 | 276.79 | 334.58 | 58 | 2nd half circular curve |
| 3 | 250 | 135.96 | 211.09 | 483.25 | 57 | 2nd half circular curve |
| 4 | 435 | 172.88 | 316.07 | 659.98 | 51 | 2nd half circular curve |
| 5 | 250 | 137.03 | 211.97 | 486.52 | 64 | 2nd half circular curve |
| 6 | 435 | 172.56 | 315.81 | 659.40 | 37 | 1st half circular curve |
| 7 | 250 | 136.55 | 210.78 | 484.02 | 59 | 2nd half circular curve |
| 8 | 250 | 136.9 | 211.24 | 484.02 | 58 | 2nd half circular curve |
| 9 | 588 | 191.65 | 412.80 | 796.22 | 20 | approach clothoid |
| 10 | 333 | 126.04 | 353.26 | 606.40 | 41 | 1st half circular curve |
| 11 | 400 | 200.95 | 227.24 | 628.46 | 57 | 2nd half circular curve |
| 12 | 333 | 82.42 | 221.60 | 387.04 | 58 | 2nd half circular curve |
| 13 | 588 | 143.25 | 182.13 | 467.18 | 30 | approach clothoid |
| 14 | 333 | 80.49 | 220.89 | 383.42 | 50 | half-curve |
| 15 | 357 | 28.34 | 241.52 | 298.49 | 37 | 1st half circular curve |
| 16 | 303 | 26.99 | 300.77 | 355.57 | 47 | 1st half circular curve |
| 17 | 294 | 28.06 | 321.84 | 377.95 | 36 | 1st half circular curve |
| 18 | 200 | 28.33 | 32.92 | 89.87 | 75 | departure clothoid |
| 19 | 435 | 170.88 | 320.15 | 663.32 | 60 | 2nd half circular curve |
| 20 | 435 | 172.49 | 316.63 | 662.00 | 37 | 1st half circular curve |
| 21 | 250 | 137.02 | 212.15 | 485.24 | 58 | 2nd half circular curve |
| 22 | 250 | 136.9 | 211.73 | 486.09 | 60 | 2nd half circular curve |
| 23 | 250 | 136.29 | 211.63 | 484.54 | 72 | departure clothoid |
| 24 | 435 | 172.84 | 316.00 | 660.70 | 53 | 2nd half circular curve |
| 25 | 250 | 136.70 | 210.33 | 483.85 | 75 | departure clothoid |
| 26 | 250 | 137.26 | 210.13 | 483.91 | 67 | 2nd half circular curve |
| 27 | 588 | 141.76 | 179.33 | 463.63 | 31 | 1st half circular curve |
| 28 | 333 | 82.13 | 221.86 | 386.75 | 53 | 2nd half circular curve |
| 29 | 400 | 200.55 | 227.70 | 629.06 | 33 | 1st half circular curve |
| 30 | 333 | 126.14 | 354.04 | 606.86 | 49 | 1st half circular curve |
| 31 | 435 | 147.06 | 242.17 | 535.80 | 30 | 1st half circular curve |
| 32 | 333 | 125.87 | 353.51 | 605.97 | 52 | 2nd half circular curve |

R = radius of curve in m

$L_{cl}$ = length of clothoids in m

$L_{circ}$ = length of circular curve in m

$L_c$ = length of horizontal curve in m (Lcl+Lcirc+Lcl)

$P_{minV85,c}$ = point of minimum operating speed on curve in %

## RESULTS AND DISCUSSION

### Appropriate locations for speed data collection on approach tangent and on curve

In order to ascertain the most appropriate locations on tangent and on curve for speed data collection to evaluate the speed differential the following comparative analyses were performed.

*Tangent*

A two-sided t-test for paired samples was carried out in order to verify if the use of $V_{85max\_200}$ or $V_{85mid,t}$ made a difference or not. To this aim the two following hypotheses were formulated:

- null hypothesis $H_0$: the mean values of the two parameters are equal, meaning that it doesn't matter if $V_{85max\_200}$ is used for calculating the operating speed on tangent rather than $V_{85mid,t}$;
- alternative hypothesis $H_1$: the mean value of the two parameters are different

Therefore:

$H_0$: $\overline{V}_{85\max\_200} = \overline{V}_{85mid,t}$

$H_1$: $\overline{V}_{85\max\_200} \neq \overline{V}_{85mid,t}$

The outcome of the test (mean of the paired differences $V_{85max\_200} - V_{85mid,t} = 3.25$; $t = 7.99$; confidence interval: 2.42 – 4.07) imposed to reject the null hypothesis $H_0$. Consequently, at 0.001 level of significance, it was demonstrated that the two parameters are significantly different and lead to different values of the operating speed on tangent. In particular $V_{85max\_200}$ is higher than $V_{85mid,t}$ showing that the maximum speed before decelerating is reached on the last 200 m of the approach tangent. Finally $V_{85max\_200}$ appears to be the most appropriate parameter to evaluate the speed differential through the traditional approach that is based on the simple subtraction of $V_{85}$ on two locations.

*Curve*

Analogously a comparative analysis was performed in order to verify whether $V_{85min,c}$ and $V_{85mid,c}$ are equivalent and so if the minimum speed is reached at the midpoint of the circular curve. Therefore the following two hypotheses were formulated:

$H_0$: $\overline{V}_{85\min,c} = \overline{V}_{85mid,c}$

$H_1$: $\overline{V}_{85\min,c} \neq \overline{V}_{85mid,c}$

The outcome of the test (mean of the paired differences $V_{85mid,c} - V_{85min,c} = 4.61$; $t = 8.91$; confidence interval: 3.55 – 5.66) showed that the null hypothesis is rejected; consequently, at 0.001 level of significance, the two parameters are significantly different. In particular $V_{85mid,c}$ overestimates the minimum speed of the drivers on the curved section. Therefore this last is not achieved at the midpoint of the curve. Then the most appropriate parameter to evaluate the speed differential through the traditional approach appears to be $V_{85min,c}$.

This result led to investigate the point along the horizontal curve where the minimum operating speed is achieved ($P_{minV85,c}$). More specifically if it is possible to define a relationship between $P_{minV85,c}$ and the geometric features of the tangent-curve transition. It was found that a significant correlation exists between $P_{minV85,c}$ and the length of the approach tangent ($L_{at}$), the longitudinal grade (i) as well as the radius of the curve (R). The model that predicts the point of the minimum speed on curve, obtained through the multiple linear regression technique and characterized by a determination coefficient of 0.718, is reported below:

$P_{minV85,c}$ = 83.23 + 0.022 $L_{at}$ - 1.64 i - 0.113 R (1)

$L_{at}$ and R are in meters, i is in %.
The independent variables used in the model are significant at the level of 5%. This result seems coherent; it demonstrates that $P_{minV85,c}$ :

- increases as the length of the approach tangent increases and as the longitudinal grade decreases. Probably because in these conditions (long tangent and low grade) the speed approaching the curve is higher. Consequently the distance from the beginning of the curve to the point where the driver, using a normal deceleration rate, reaches the minimum value is greater;
- and decreases as the radius of the curve increases. Probably because the minimum speed on curve is higher on those curves with a greater radius. In other words it appears reasonable to hypothesize that the driver reduces the speed entering the curve. Once the driver is on the curve, after having realized that the curve isn't particularly demanding (high radius), he doesn't continue to decelerate, so achieving a not low minimum speed at a point not far from the beginning of the curve.

**Operating speed predicting models**

Based on the results mentioned above, the following analysis was carried out to develop predicting models for the estimation of the most appropriate operating speed on tangent ($V_{85max\_200}$) and on curve ($V_{85min,c}$). At this aim the multiple linear regression technique was used and the following criteria were adopted:

- high value of the coefficient of determination $R^2$;
- significance of each independent variable;
- simplicity and logical explanation of the model;
- lack of problems of multicollinearity between the independent variables.

In order to define the predicting models, for each configuration the geometric features of the approach and departure tangent (length and grade) and the horizontal curve (length of the approach and departure clothoid, length of the circular curve, radius, CCRs, deflection angle and length of the curve), as well as the geometric characteristics of the previous configuration were considered as independent variables.

*Models proposed to predict V85 on tangent*

Concerning the maximum operating speed on the last 200 m of the tangents ($V_{85max\_200}$), the best model found gives the values of the parameter in function of the length of the approach tangent ($L_{at}$) and the longitudinal grade (i)

$V_{85max\_200}$ = 122.51 + 0.024$L_{at}$ – 5.6 i (2)

$V_{85max\_200}$ is in km/h; $L_{at}$ is in meters; i is in %.

The determination coefficient is equal to 0.713 and the independent variables are significant at the level of 1%. The model appears to be fully congruent; as a matter of fact it provides the maximum speed on the last 200 m of the approach tangent which increases as the length of the approach tangent increases and as the local longitudinal grade decreases. Then it emphasizes that the $V_{85}$ on tangent depends on local horizontal and vertical features.

Also the predicting model of the operating speed at the midpoint of the tangents ($V_{85mid,t}$) was developed. The most significant model obtained returns the values of $V_{85mid,t}$ as a function of CCRs of the preceding curve, the length of the tangent ($L_{dt}$) and the longitudinal grade (i):

$$V_{85mid,t} = 138.98 - 0.133\ CCRs + 0.016\ L_{dt} - 4.03\ i \qquad (3)$$

$V_{85mid,t}$ is in km/h; CCRs is in gon, $L_{at}$ is in meters; i is in %.

The determination coefficient is equal to 0.882 and the independent variables are significant at the level of 1%. Therefore it seems that the $V_{85}$ at the midpoint of the tangent depends on local horizontal and vertical features ($L_{dt}$ and i), as well as by the horizontal features of the previous geometrical element (CCRs), but it doesn't depend on those of the successive geometrical element.

*Models proposed to predict V85 on curve*

Concerning the minimum operating speed on the curve ($V_{85min,c}$) a predicting model was developed (4). It gives the value of the dependent variables $V_{85min,c}$ as a function of CCRs and longitudinal grade (i)

$$V_{85min,c} = 120.14 - 0.08\ CCRs - 2.55\ i \qquad (4)$$

$V_{85mid,c}$ is in km/h; CCRs is in gon, i is in %.

The coefficients of determination is 0.762 and the independent variables are significant at the level of 5%. The relationships emphasize that the $V_{85}$ on curve depends only on local horizontal and vertical features; it doesn't depend on those of the adjacent geometrical elements.

Also the model that predicts the operating speed at the midpoint of the curve ($V_{85mid,c}$) was determined. The best model found was similar to the model (4). It gives $V_{85mid,c}$ in function of CCRs and longitudinal grade (i)

$$V_{85mid,c} = 126.03 - 0.087\ CCRs - 2.872\ i \qquad (5)$$

The model is significant at the level of 1% and characterized by a determination coefficient of 0.709.

**Speed differential**

A comparative analysis was performed in order to: verify if the difference between the $85^{th}$ percentile of the distribution of the maximum speed reduction experienced by each driver (85MSR) and the speed reduction given by the difference between the maximum operating speed on the last 200 m of the approach tangent ($V_{85max\_200}$) and the minimum operating speed on curve ($V_{85min,c}$) is statistically significant. To this aim a two-sided t-test for paired samples was carried out and the following two hypotheses were formulated:

- null hypothesis $H_0$: the two parameters, 85MSR and $\Delta V_{85} = V_{85max\_200} - V_{85min,c}$, are equivalent, meaning that it doesn't matter if we use either one or the other parameters for the calculation of the speed differential;
- alternative hypothesis $H_1$: the two methodologies for the calculation of the speed differential lead to different results.

Therefore:

$H_0$: $\overline{85MSR} = \overline{\Delta V}_{85}$

$H_1$: $\overline{85MSR} \neq \overline{\Delta V}_{85}$

The outcome of the test (mean of the paired differences 85MSR – $\Delta V_{85}$ = 11.06; t = 15.01; confidence interval: 9.56 – 12.56) showed, at 0.001 level of significance, that the null hypothesis is rejected. This result highlights that the calculation of the speed differential according to a traditional approach, using the maximum operating speed on the last 200 m of the approach tangent ($V_{85max\_200}$) and the minimum operating speed on curve ($V_{85min,c}$), underestimates the amount of speed reduction experienced by the drivers in the tangent-curve transition. It confirms the need of calculating the maximum speed reduction in the tangent-curve transition on the basis of the speed profile of each driver, in accordance with Hirsh's hypothesis (13) and the outcomes of previous researches (7)(9)(14).

On the basis of the previous considerations, attempts for defining predicting models of 85MSR were performed. The multiple linear regression technique was used and the same criteria of the previous analysis to identify $V_{85}$ predicting models were adopted. Two 85MSR predicting models were developed. The first model only includes geometrical characteristics (approach tangent length, $L_{at,}$ and the longitudinal grade, i) as independent variables:

$$85MSR = 56.23 - 3445.51/L_{at} - 3.18\ i - 0.029R \qquad (6)$$

85MSR is in km/h; $L_{at}$ and R are in meters; i is in %.

The coefficient of determination is equal to 0.64 and the independent variables are significant at the level of 1%. The model appears to be congruent. As a matter of fact it gives us the speed reduction as a vehicle enters a horizontal curve which increases as the length of approach tangents increases and as the radius as well as the longitudinal grade decrease.

The second model, besides the geometrical features (radius and tangent length), also includes the maximum operating speed on the last 200 m of the tangent approaching the curve ($V_{85max\_200}$); this latter parameter can be derived from the model (2).

$$85MSR = -46.85 + 0.66\ V_{85max\_200} - 0.025\ R + 0.01\ L_{at} \qquad (7)$$

85MSR and $V_{85max\_200}$ are in km/h; $L_{at}$ is in meters.

The model has a determination coefficient equal to 0.840 and appears to be congruent. As a matter of fact it gives us the speed reduction as a vehicle enters a horizontal curve which increases as the length of approach tangents increases, as the speed on the approach tangent increases and as the curve radius decreases. It must be noted that a check of multicollinearity of the model showed a correlation coefficient of 0.31 for the variables $L_{at}$ and $V_{85max\_200}$ and variance inflation factors (VIF) of 1.1. Consequently, there does not appear to be any problems of multicollinearity. However given that the model was obtained from a sample of 32 configurations and since a previous research (24) demonstrated that the operating speed on tangents depends primarily on tangent length, the least important variable between $L_{at}$ and $V_{85max\_200}$ was removed from the model. Therefore, considering the standardized coefficients of $V_{85max\_200}$ (equal to 0.844) and of $L_{at}$ (equal to 0.208), the variable $L_{at}$ was removed. Hence the model became:

$$85MSR = -49.76 + 0.706\ V_{85max\_200} - 0.023\ R \qquad (8)$$

The coefficient of determination is equal to 0.801 and the independent variables are significant at the level of 1%. Moreover, it is not influenced by potential multicollinearity and it is fully congruent.

## CONCLUSION

The analysis on the local speeds of drivers recorded on 32 configurations of tangent-curve-tangent transition of four two-lane rural roads implemented in the CRISS driving simulator allowed the following main conclusions to be drawn.

The maximum operating speed on the last 200 m of the tangents ($V_{85max\_200}$) is higher than the operating speed at the midpoint of tangent ($V_{85mid,t}$) confirming that the maximum speed before decelerating is reached on the last 200 m of the approach tangent.$V_{85mid,c}$ overestimates the minimum speed of the drivers on the curve ($V_{85min,c}$). Then $V_{85max\_200}$ and $V_{85min,c}$ appear to be the most appropriate parameters to evaluate the speed differential through the traditional approach that is based on the simple subtraction of $V_{85}$ on two locations.

A relationship between the point along the horizontal curve where the minimum operating speed is achieved ($P_{minV85,c}$) and the geometric features of the tangent-curve transition was defined. It was found that a significant correlation exists between $P_{minV85,c}$ and the radius of the curve, the length of the approach tangent as well as the longitudinal grade of the transition.

Predicting models of operating speed of the maximum operating speed on the last 200 m of the tangents ($V_{85max\_200}$) and of the minimum operating speed on the curve ($V_{85min,c}$) were found.

A two-sided t-test for paired samples highlighted that the calculation of the speed differential according to a traditional approach, using $V_{85max\_200}$ and $V_{85min,c}$, underestimates the amount of speed reduction experienced by the drivers in the tangent-curve transition. It confirms the need of calculating the maximum speed reduction in the tangent-curve transition on the basis of the speed profile of each driver.

Two predicting models of the 85$^{th}$ percentile of the distribution of maximum speed reduction experienced by each driver (85MSR) were developed. The first model only includes geometrical characteristics (approach tangent length, longitudinal grade and radius) as independent variables. The second model, besides the radius, also includes the maximum operating speed on the last 200 m of the tangent approaching the curve ($V_{85max\_200}$).

It should be stressed that further research is necessary in order to analyze different vehicle performance (in the present study only one vehicle type was used) and enlarge the data base of road configurations, especially with respect to grade.

## REFERENCES

1. Lamm, R., E.M. Choueiri, J.C.Hayward, and A. Paluri. Possible Design procedure to promote design consistency in highway geometric design on two-lane rural roads. In *Transportation Research Record,* 1195, TRB, Washington, D.C., 1988, 111-122.
2. Lamm, R., Psarianos, B., Mailaendere,T. Highway Design and Traffic Safety Engineering Handbook . McGraw-Hill, New York, 1999.
3. Fitzpatrick K., L. Elefteriadou, D. Harwood, J. Collins, J. McFadden, I. Anderson, R. Krammes, N. Irizarry, K. Parma, K. Bauer, and K. Passetti. *Speed Prediction for Two-Lane Rural Highways*. Report FHWA-RD-99-171, FHWA U.S., 2000
4. M. Awatta, Y. Hassan, T. Sayed. Quantitative evaluation of highway safety performance based on design consistency. In *Advanced in Transportation Studies*, vol IX July 2006, 29-44
5. Lamm, R., and Choueiri, E. M.. Recommendations for evaluating horizontal design consistency based on investigations in the State of New York. *Transportation Research Record*, *1122*, TRB, Washington, D.C., 1987, 68–78
6. Krammes, R. A., Rao, K. S., and Oh, H. 1995. "Highway geometric design consistency evaluation software." *Transportation Research Record*, *1500*, TRB, Washington, D.C., 19– 24
7. P. Misaghi, Y. Hassan. Modeling operating speed and speed differential on two-lane rural roads. In *Journal Transportation Engineering*, ASCE, june 2005, 408-417

8. Fitzpatrick K, Miaou, S., Brewer M., Carlson P., Wooldridge M. Exploration of the relationships between Operating Speed and Roadway Features on tangent Sections. In *Journal Transportation Engineering*, ASCE, aprile 2005, 261-269
9. J.McFadden, L. Elefteriadou. Evaluating horizontal alignment design consistency of two-lane rural highways: development of new procedure. In *Transportation Research Record:* 1737, TRB, Washington, D.C., 2000, 9-17
10. Ottesen, J., Krammes R. Speed-profile model for a design-consistency evaluation procedure in the United States. *Transportation Research Record,* 1701, TRB, Washington, D.C., 2000, 76-85
11. Fitzpatrick, K. Collins, J. Speed-profile model for two-lane rural highway. In *Transportation Research Record,* 1737, TRB, Washington, D.C., 2000, pp. 42-49.
12. Figueroa, A. M., Tarko, A. P. Speed changes in the vicinity of horizontal curves on two-lane rural roads. In *Journal Transportation Engineering*, ASCE, April 2007, 215-222
13. M. Hirsh. Probabilistic approach to consistency of highway alignment. *Journal Transportation Engineering* 113 (3), 1987, 268-276
14. Park, Y. Saccomanno, F. Evaluating speed consistency between successive elements of a two-lane rural highway. *Transportation Research part A ,* Vol. 40, 2006, 375-385
15. Bella, F. Parameters for evaluating speed differential: contribution using driving simulator. In *Transportation Research Record,* 2023. TRB, Washington, D.C., 2007, pp. 37-43
16. Bella, F. Can the driving simulators contribute to solving the critical issues in geometric design? accepted for publication in *Transportation Research Record,* TRB, Washington, D.C., 2009
17. Bella, F. Reliability analysis of speed measures on a two-lane rural road using driving simulator. Paper number 06-1444. Proceedings of the *85$^{th}$ Annual Meeting Transportation Research Board*. Washington, January 2006
18. Bella, F. Driving simulator for speed research on two-lane rural roads. *Accident Analysis and Prevention,* Vol. 40, 2008, 1078-1087
19. Hassan Y. Highway design consistency. Refine the state of knowledge and practice. In *Transportation Research Record,*1881, TRB, National Research Council, Washington, D.C., 2004, 63-71
20. Committee on Research Priorities and Coordination in Highway Infrastructure and Operations Safety. *Special Report 292: Safety Research on Highway Infrastructure and Operations: Improving Priorities, Coordination, and Quality*. TRB, 2008
21. Allen, R.W. Rosenthal, T.J., Aponso, B.L., Klyde, D.H., Anderson, F.G., Hougue, J.R. Chrstos, A low cost PC based driving simulator for prototyping and Hardware-in-the-Loop Applications. SAE Paper 98-0222. *Society of Automotive Engineers* Warrendale, Pa., 1998
22. Crisman, B., Marchionna, A., Perco, P., Robba, A., Roberti, R. Operating speed prediction model for two-lane rural roads. Proceedings *3$^{rd}$ International Symposium on Highway Geometric Design*. Chicago, 2005
23. Cafiso S. Experimental Survey of Safety Condition on Roadway Stretches with Alignment Inconsistencies. Proceedings *2$^{nd}$ International Symposium on Highway Design*. Mainz, Germany, 2000.
24. Polus, A., K. Fitzpatrick, and D. B. Fambro. Predicting Operating Speeds on Tangent Sections of Two-Lane Rural Highways. In *Transportation Research Record, No. 1737,* TRB, Washington, D.C., 2000, 50–57