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EXPERIMENTAL ANALYSIS ON HAIRPIN CURVES

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Abstract. The consistency of a highway alignment refers to the conformity of its geometry to driver expectancy and to the improvement of the design consistency and consequently it is necessary to know real speed behavior in order to calculate highway safety. The disparity between design and operating speeds has been shown, in fact several different studies were undertaken to predict the operating speed in different conditions as a function of the alignment features: horizontal and vertical curves, combinations of tangent sections of horizontal and vertical curves; sections prior to or following horizontal curves. In literature however, no studies speak of the operating speed on hairpin curves of mountain roads where driver behavior is influenced by the combination of small radius curves, limited sight distance and the approach to the slope of a tangent. Therefore, a mathematical model was developed specifically for mountain roads using speed data collected on hairpin curve and tangent approaches. The experimental study was carried out using traffic counters capable of recording the following variables during the passage of each vehicle in both directions: vehicle length, instant speed and direction. Video cameras were also used. In this paper the author also investigated the real speed driver behavior by analyzing deceleration and acceleration rates. These rates were calculated for each vehicle and then the 85th percentile of the rate distribution was also calculated. With the availability of acceleration and deceleration rates that respect real driver behavior, it is possible to analyze the defects of existing mountain roads and to evaluate corrective measures that can be implemented.

Keywords: operating speed, driver behavior, mountain roads.

1. Introduction and objectives

Design speed is a critical input to the design process for many geometric elements. For some of these elements, however, the relationship between the design speed and the actual operating speed of the roadway is weak or it changes with the design speed magnitude. Recent studies have documented a noticeable disparity between design and operating speeds, therefore, the evaluation of changes in operating speeds along the alignment is fundamental so as to check road inconsistency and to identify elements that need to be altered in order to guarantee road safety. Nie *et al.* (2007) has studied the driver speed behavior compare to the different classification roads while, Oke *et al.* (2006) has developed a model to set the speed limit. Vorobjovas and Žilionienė (2008) have documented the importance of road elements on the safety so like Babkov and Zamkhayev (1967) have studied the relationship between some characteristics of these elements and traffic accidents in order to improve the road safety. The road traffic has thence become a priority field worldwide and one of the major factors describing the transport system's condition with its positive and negative changes (Ratkevičiūtė *et al.* 2007).

Several countries have included speed profile evaluations into rural alignment design procedures in order to address operating speed inconsistencies. All these models have the objective of representing real driver behavior: drivers have a desired speed that they seek to maintain, but if it is necessary, for safety reasons, they reduce their speed at horizontal curves. The models consider that all acceleration and deceleration rates that occur upon approach and departure and at the departure tangents of a curve are the same, or rather, that speeds are constant throughout a curve.

The Swiss standards *SN 640080 a/b: 1991 Speed as a Design Element of the Horizontal Alignment* use constant deceleration and acceleration rates of 0.80 m/s^2, while the deceleration and acceleration rates that came from Lamm *et al.* (1988) collected using a car-following technique are nearly equal at a rate of 0.85 m/s^2.

Krammes *et al.* (1995) and Misaghi *et al.* (2005) have studied operating speed by using roadside features as independent variables to estimate speed on curves, but none of their models consider the general character of road alignment in the speed estimation process either on curves or on tangents. Only the model developed by Fitzpatrick *et al.*

(2000) considers the combination of horizontal and vertical alignments using different equations to predict the operating speed on curves depending on vertical alignment conditions. All models use constant acceleration and deceleration rates, with the exception of the model developed by Fitzpatrick *et al.* (2000) which includes acceleration and deceleration rates depending on the curve radius.

On mountain roads, driver behavior and consequently speed is influenced by road features but also by unfavorable visibility conditions. In this context, it is necessary to produce designs in accordance with drivers' expectancies to improve road safety.

The objective of this research is to support planners whilst designing mountain roads by means of the analysis of operating speed and acceleration/deceleration rates at hairpin curves.

To achieve this objective, the following tasks were performed:

- the selection of the mountain roads with
- hairpin curves;
- the development of a survey plan (selection of the hairpin curves and measurement sections);
- numerical restitution of road features and sight distance at each section of the hairpin curves under research;
- the measurement and collection of speed data and acceleration/deceleration rates;
- the development of a mathematical model to predict operating speed on hairpin curves;
- the development of a model to predict the acceleration/deceleration rates depending on curve radius and sight distance.

The survey plan was elaborated in order to satisfy different research objectives (speed in free flow conditions, during the entrance to and exiting from intersections etc.) and it was applied to three mountain roads in the Province of Salerno. The measures were taken by observing each section for a 12 hour-period. The sample size of free-flow passenger cars ranged from 52 to 89 vehicles for each curve and direction.

Data was used in order to set-up analytical relationships to predict operating speeds while the acceleration and deceleration rates were calculated using the observed operating speeds at each section of the curve and depending on the relative distance.

2. Data collection

The experimental investigation was conducted on three mountain roads situated in the Province of Salerno in the South of Italy. Generally, the design of mountain roads is conditioned by both their orography and steep grades, therefore in order to overcome such difficulties, it is necessary to insert curves with small radii that do not guarantee vehicle stability even if there is a good side friction-factor calculated using the following equation:

$$R_{\min} = \frac{V^2}{127\left(0.01e + f\right)}, \qquad (1)$$

where $R_{\min}$ – min radius, m; V – design speed, km/h; e – superelevation, %; f – side friction factor (dimensionless).

The majority of international road design standards do not give information regarding the design of hairpin curves. Only Swiss standards *SN 640080b – 1991* support planners with tables that indicate the radius of hairpin curves depending on the lane width.

On these roads, the combination of inadequate sight distance and small curve radius is frequent. Their availability is necessary in order to understand the influence on drivers' behavior. In this context, the main objective of this paper is to develop two mathematical models that estimate the operating speed and deceleration/acceleration rates for mountain roads depending on road features.

Three mountain roads characterized by their steep grade and with two types of hairpin curve were studied (Fig. 1):

- consecutive hairpin curves with small radii and spaced between small tangent (type 1);
- hairpin curves preceded by and following long tangents (type 2).

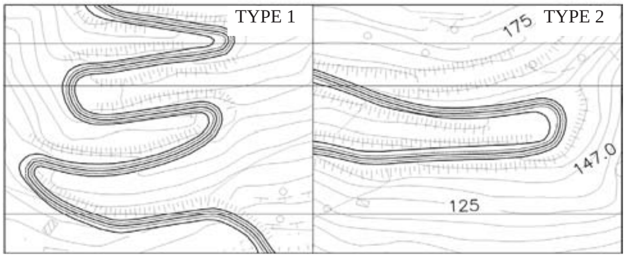

Fig. 1. Hairpin curves underresearch

The operating speed data for this study was collected in February 2008 and in March and May 2008.

Speed was measured on 46 hairpin curves and 92 tangents on three mountain roads in the South of Italy. The traffic counters were situated along the tangents at 40–20 m before and after the point of curvature of the hairpin curve, while two cameras were positioned so as to record the vehicle and its speed in 5 sections of the hairpin curve: at the beginning, at a 0.25 point of the road, in the center, at a 0.75 point and at the end.

Table 1 summarizes geometric characteristics of the sites. The curves do not have a spiral transition and the traffic never exceeded 40 vph during the data collection period.

In order to measure the real speed behavior at each hairpin curve traffic counters and cameras were used as shown in Fig. 2. All data was collected during the day, in off-peak periods on a dry road and the equipment was always hidden from oncoming traffic in order to minimize the effects of its presence on drivers and, consequently, on speed behavior. As for the three mountain roads, the author obtained the relative geometric road characteristics by using software design and field measurements.

Laser beams were used because of their low power and therefore, they are harmless for the drivers and passengers of vehicles; vehicle speed was transmitted upon

Table 1. Mountain road features

Rural environment (road name)	C. TURINA	C. FOSSE	C. MADONNA
Lanes, n	2	2	2
Width, m	3.00	3.00	2.75–3.00
Tangent length, m	15–70	20–60	10–90
Hairpin curves, n	12	16	18
Internal radii, m	5.0–15.0	7.50–25.0	3.75–11.30
Grade, %	± 3.50–15.0	± 6.50–15.0	± 6.0–13.5
Hard shoulder areas, m	0.50	0.50	no present
Speed limits, km/h	25	25	25
Height flex beam guardrail	h = 1.00 m	h = 1.00 m	h = 0.65 m
Paving age, years	10	15	10
Paving conditions	not too good	not too good	not too good
Vehicle	40	34	18
$V_{85}{}^{th}$ [min÷max] surveyed, km/h	29.0 ÷ 36.0	27.0 ÷ 55.0	32.0 ÷ 53.0

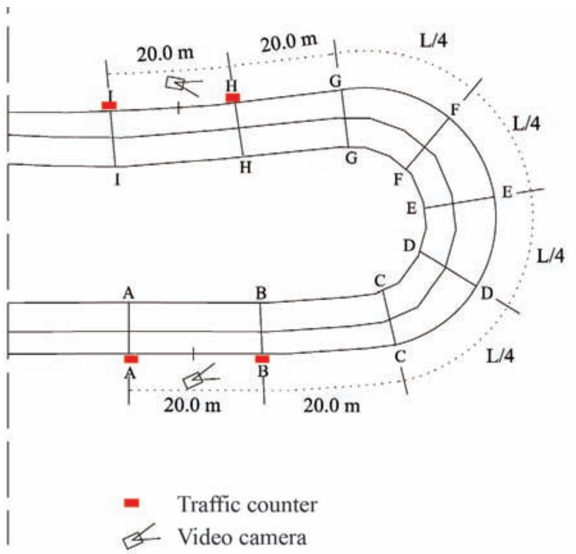

Fig. 2. Instrument position on hairpin curves

the passage of the vehicle from the first photocell to the second one.

For each vehicle that passed, the devices recorded:
– time (date, hour, minutes, seconds);
– vehicle speed (km/h);
– vehicle length (m);
– traveling direction (binary variable: "direction 0" and "direction 1").

Vehicle headways measuring less than 5 s were removed, leaving only free-flow speeds in the database collected using the laser speed-detection device. Moreover, to avoid the presence of motorcycles or heavy vehicles in this database, vehicles shorter than 3 m and longer than 6 m were also removed. According to Li *et al*. (2007) and Kanhere *et al.* (2007; 2008) the camera orientation was set-up to record the speed of vehicles traveling in both directions along the sections studied. The author has evaluated also the trajectories according to Dragčević *et al*. (2008). The chosen configuration, with an angle of inclination less than 45° with respects to a horizontal line allowed the monitoring, from a stationary point of view, of traffic from a wider part of the roadway.

To confirm the accuracy of speed measurements obtained by the camera, a validation experiment was set up only on the road under research. In particular, this validation compared video and laser speed measurements on the tangent approach to the hairpin curve (sections B-B and H-H of Fig. 2). In addition, a pilot car was used to compare the speed of the pilot car to the speed measured on video.

In order to obtain validation, the test statistics were estimated by using the Eq (2):

$$t_{paired} = \frac{d_{ave} - \Delta_0}{\frac{S_D}{\sqrt{n}}}, \tag{2}$$

where t_{paired} – test statistic; d_{ave} – sample mean of differences between video and laser measurements; Δ_0 – hypothesized difference between video and laser speed measurements (assumed to be 0), S_D – standard deviation of the differences between video and radar speed measurements; n – sample size.

In addition, coefficients for a linear relationship between video and laser speed measurements were estimated by using a least-squares approach. Both methods were used by Taylor *et al.* (1989) in a comparison of video and radar speed readings from a parking lot study (Taylor *et al.* 1989), and therefore they were thought to be appropriate for this validation.

The results of the regression experiments were both significant with a high R^2 value.

Table 2 summarizes the experiment results and it shows the excellent correlation between video and laser data, in fact the test statistic value is lower than in the critical t-test.

The comparison between video measurement and pilot car speeds as shown in Fig. 3 were used to see how closely video measurements corresponded with actual vehicle speeds. It was assumed that when a vehicle is stationary, its speed is equal to zero, such parameter was set for both laser and video and in this way it was to obtain an equivalent value for both laser and video. Substantially, with the pilot car, the reliability of the data obtained was verified by means of the laser and the video.

Table 2. Paired – data comparison of video – laser and pilot car

	Video	Laser	Difference	Video	Pilot car	Difference
Sample size	54	54	54	25	25	25
Mean	29.50	29.70	0.20	34.97	34.33	– 0.64
Standard deviation	3.79	4.18	1.324	11.22	11.06	1.849
P - value			0.108			0.102
t - statistic			0.856			– 1.804
t - critical			1.241			2.139
R^2			0.891			0.955

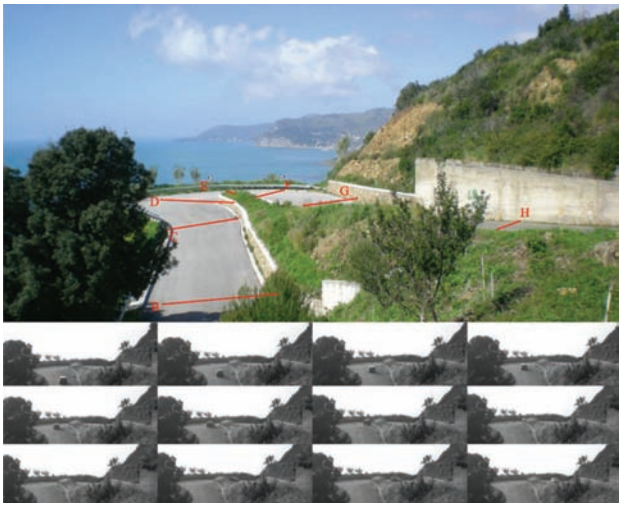

Fig. 3. Sections of the hairpin curve under research

3. Operating speed model

It was documented that driver behavior was conditioned by the road features such as vertical and horizontal alignment, radius curve, sight distance with a noticeable disparity between design and operating speeds and consequently with an increase of the hazard. For this reason, it is important to investigate and understand factors which influence driver expectancies along the road and correct the driver errors in order to improve both safety and comfort. Mathematical models were developed to estimate vehicular speed on hairpin curves and deceleration/acceleration rates. In particular, the 85th percentile speed for curves was estimated by using the internal radius of the hairpin curve under consideration, the sight distance, the grade and the length of the tangent approach. To determine relationships between operating speeds, available sight distance and tangent characteristics, this study involved collecting speed relating to both directions of the mountain roads and limited sight distance sections.

To analyze driver speed on mountain roads, these independent variables were studied:

– R_i – internal radius of the hairpin curve, m;
– D – min sight distance for the curve, m;
– L_a – length of the tangent approach, m;
– P – ± grade of tangent approach (%) (+ % for traveling downhill and – % for traveling uphill).

The internal radius used is represented in Fig. 4. It was taken from existing maps and checked on-site. The sight distance was obtained by using existing maps in some cases and by means of field measurements in others using an optic laser positioned in each section of the hairpin curve. This measurement was obtained by drawing the visibility obstruction line in the presence of vegetation, bridge rails directly from the map or via field measurements.

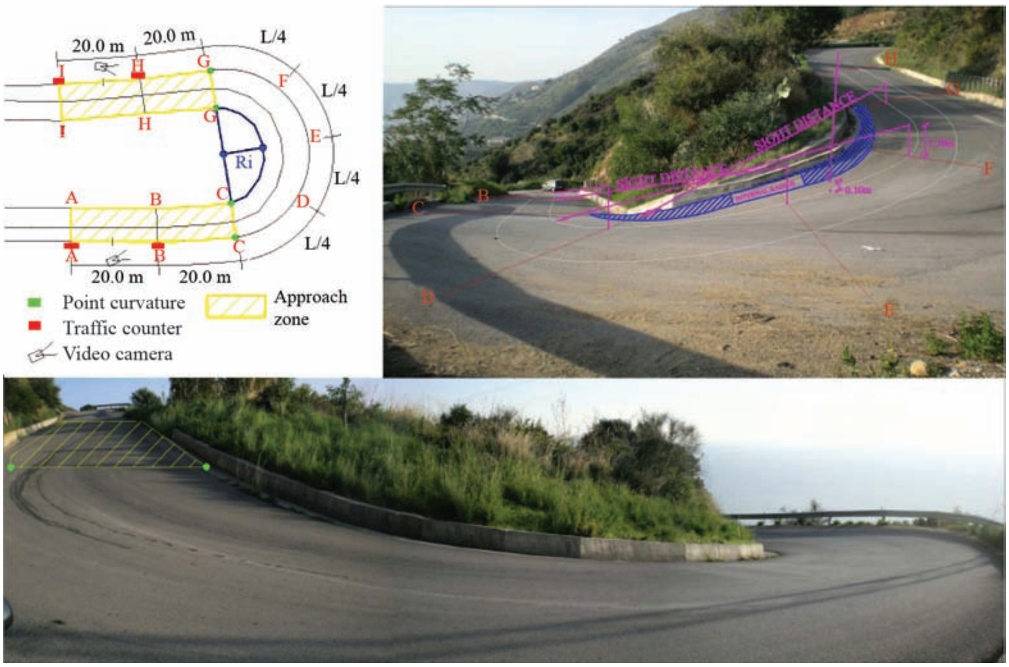

Fig. 4. Measuring sight distance

They were measured at heights of 1.10 m and 0.10 m from the pavement and that respectively represent the driver's eye level and a possible obstacle on the road.

These distances were traced on the maps and the visibility obstruction was drawn, subsequently for the different sections approaching a curve and inside which the available sight distances were evaluated and the sight distance was measured for each point. The smallest of these distance, in both directions (uphill – downhill), was used as the variable and examined in the linear regression analysis. Generally the min sight distance was measured in the center of the hairpin curves under research. While the min of sight distance used in acceleration/deceleration models measured in the approach zone of the curve, was obtained in sections C and G of Fig. 4 in both directions (uphill – downhill).

The tangent length and its grade were measured on map by using software design and that measured on-site.

According to field data the independent variables and variation range were as follows:

Variable	Min value	Max value	Mean
R_i, m	3.75	20	11.875
L_a, m	20	100	60
D, m	12.35	24.95	18.65
P, %	3.5	15	9.5

The analysis process was carried out on three sites characterized by grade ranging between 3.5% and 15%. Initially, also other variables were calculated such as the radii of previous curves and the correlation between the length of the hairpin curves and the sight distance, but the results were not satisfactory or in statistical terms (p-value) relating to the reliability of the model (ρ^2).

According to independent variables a model was developed as shown:

$$V_{85} = a_0 + a_1 \times \frac{1}{R_i} + a_2 \times D + a_3 \times (L_a \times P),$$

$$\rho^2 = 0.81. \tag{3}$$

The model proposed presents a good correlation level and the table 3 shows the variable values and their statistical significance. The correlation coefficient is very high and the chosen variable coefficients are statistically significant relating to significance levels equal to 5%, many of these are around 1%.

The model presented is used to study how road features influence driver speed behavior.

As it is intuitive, the grade tangent before the hairpin curve influences speed depending on the direction: uphill or downhill, however on mountain roads the length of the tangent prior to the hairpin curve also has a great influence as shown in the next figures (Figs 5, 6).

In fact, in presence of a mountain road with a small tangent (ranging between 10–50 m) prior to the hairpin curve as shown in Fig. 1 (type 1) the driver behavior is conditioned by the radius of the previous curve or limited sight distance (Discetti, Dell'Acqua 2008). Instead, in the presence of a long tangent (ranging between 60–100 m)

Table 3. Parameter estimates model 1

	Estimate	Standard error	T-value df = 72	Lo. conf limit	Up. conf limit	p-level
a_0	28.4345	2.111648	13.46557	24.2044	32.66469	0.000000
a_1	–13.7044	3.470742	–3.94856	–20.6572	–6.75169	0.000060
a_2	0.4491	0.090315	4.97244	0.2682	0.63001	0.006435
a_3	0.3160	0.054065	–5.84410	–0.4243	–0.20766	0.000006

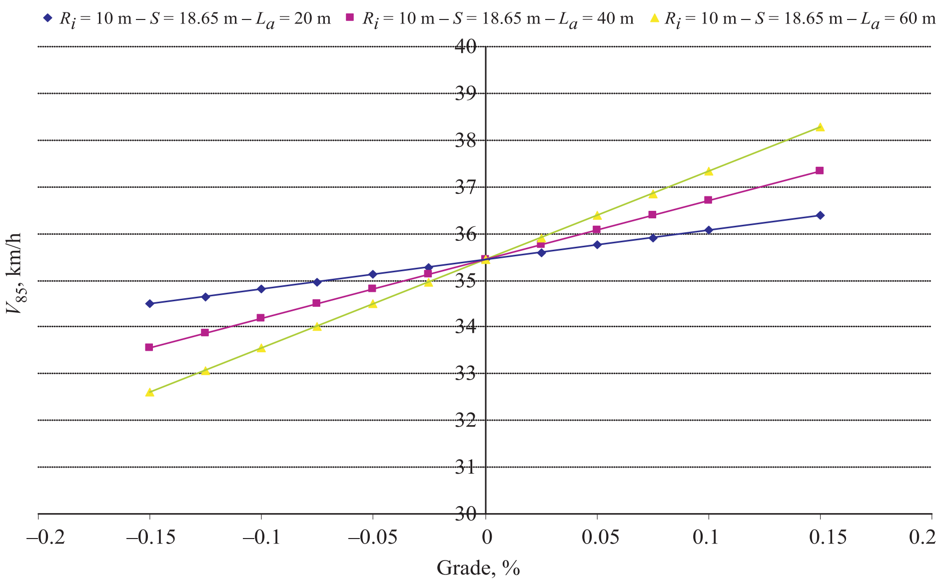

Fig. 5. V_{85} – grade

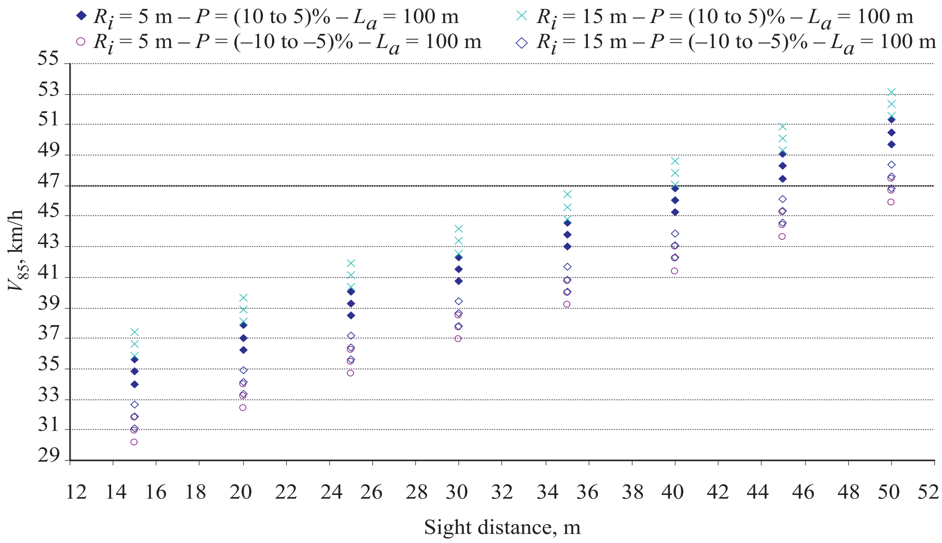

Fig. 6. V_{85} – sight distance

prior to the hairpin curve, the drivers increased their speed depending on road features and they suddenly reduced it when approaching the curve area recording a significant deceleration rate. The analysis confirms that the tangent grade is not a significant influence on driver speed behavior, as shown in Fig. 5. Heavy vehicles were penalized more. The influence of sight distance on driver speed behavior is shown in Fig. 6. It is predominant with respects to tangent grade in approach to the hairpin curve, with an average difference between uphill and downhill slopes measuring 6 km/h. The influence on the sight distance is greater at least as long as the length of the tangent when we have an extremely long tangent approaching a hairpin curve. In other words, the drivers adjusted their speed according to the physical characteristics they perceived on the road and in combination with sight distance.

4. Acceleration and deceleration models

The experimental analysis on hairpin curves regarded also the study of deceleration and acceleration rates so as to support planners during design and road safety analysis. In particular, by observing the results of the previous study, it is possible to notice that the deceleration in both directions (uphill "dir 0", downhill "dir 1") regarded the ¾ of the length of the hairpin curve with a max rate recorded in the center, while the acceleration begins at the end of the curve and continues for approx 20 m afterward.

In order to calculate the deceleration/acceleration rates of each individual vehicle in correspondence to the interval between two successive sections and then the 85th percentile of the rate distribution was calculated.

The acceleration and deceleration rates observed are very different from the constant values of 0.80 m/s^2 and 0.85 m/s^2 therefore confirming the results of Fitzpatrick *et al.* (2000). However, even if speed variation is not uniform, in order to support planners, it is useful to propose uniform accelerated and decelerated motions.

Mathematical models were developed in order to predict these rates:

$$d = 2.15 - 0.172 \times Ln(R_i) - 0.0823 \times Ln(S_a),$$
$$\rho^2 = 0.75; \qquad (4)$$

$$a = 1.32 - 0.073 \times Ln(R_i) - 0.038 \times Ln(S_e),$$
$$\rho^2 = 0.66; \qquad (5)$$

where d – deceleration rate, m/s^2; R_i – internal radius of the hairpin curve, m; S_a – min sight distance measured in the area approaching the hairpin curve, m; a – acceleration rate, m/s^2; S_e – min sight distance measure in the area approaching the end of the hairpin curve, m.

The following figure shows (Fig. 7) the speed profile in a generic hairpin curve obtained by using the average of the value collected.

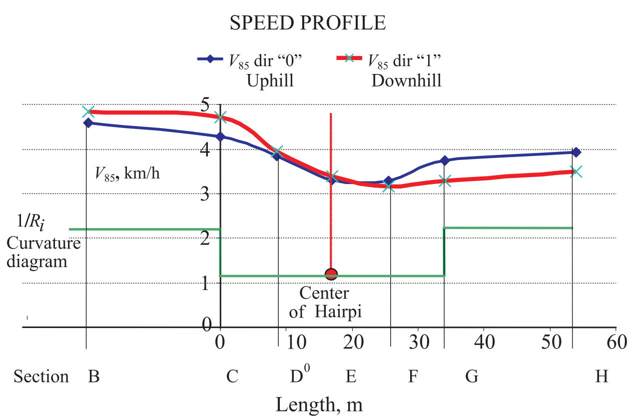

Fig. 7. Model 1 V_{85} – sight distance

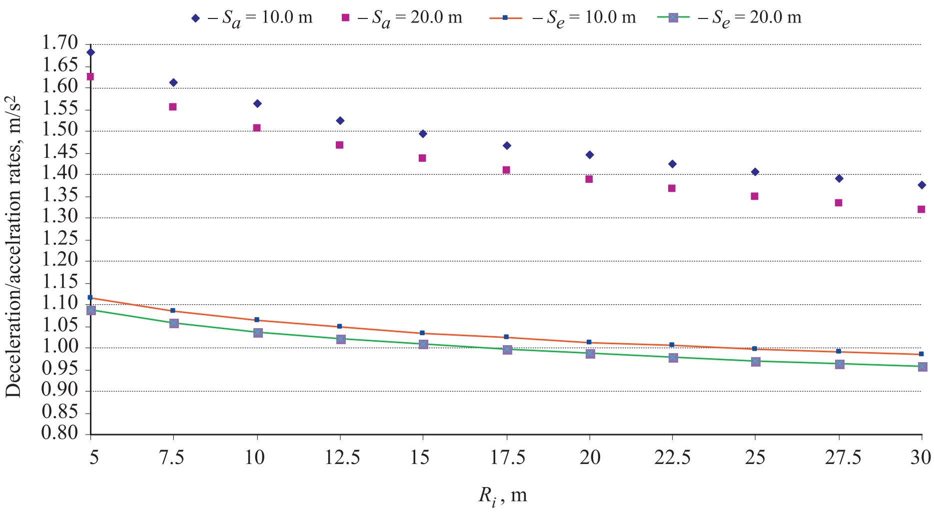

Fig. 8. Deceleration/acceleration rates – R_i

The results of the statistical analysis showed a good correlation for both models and the chosen variable coefficients are statistically significant with significance levels equal to 5%.

With the availability of acceleration and deceleration models that respect real driver behavior, it is possible to develop an operating speed-profile model representing a real speed-profile along a horizontal alignment (Fig. 8). Consequently, this operating speed-profile can be used to check the consistency of the mountain road alignment in a more efficient manner.

5. Conclusions

Driver speed is very different from design speed; it is in compliance with physical road characteristics. Therefore, the operating speed model is an effective tool for the safety analysis of existing roads because the availability of the speed on each element of the alignment makes it possible to identify possible road defects. Several different studies were carried out in order to predict operating speeds in different conditions such as horizontal curves, vertical curves and combinations of horizontal and vertical curves, tangent sections and prior to or after horizontal curves. In this study, drivers' behavior was investigated by means of a model of the operating speed that reflected the speed chosen by drivers depending on the internal radius of the hairpin curve, the available sight distance and the tangent features approaching to the curve. Speed data was collected at 46 hairpin curves and 92 tangents by using traffic counters and two video cameras. A regression equation was developed for the 85th percentile in free-flow conditions. Additionally, acceleration and deceleration rates were developed so as to consider the effects of horizontal curve radii and limited sight distance. The results of this study can help planners to better understand expected operating speeds when they design and evaluate hairpin curves. The models developed constitute useful tools that can be effectively used in the safety analysis of mountain roads.

The results of this study can help planners to better understand expected operating speeds when they design and evaluate hairpin curves. The models developed constitute useful tools that can be effectively used in the safety analysis of mountain roads. By applying such models, planners will be able to estimate both the differences of operating speeds between successive elements along the roadway and consequently the corrective measures to be taken such as: an increase in radii, a low – cost treatment for horizontal curves and the correct positioning of the speed limit.

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