Operating Speed Prediction Model For Two-Lane Rural Roads

Bruno Crisman
Aurelio Marchionna
Paolo Perco
Roberto Roberti
Department of Civil Engineering - University of Trieste

SYNOPSIS

One of the most frequent roadway characteristics that affect accidents is the horizontal curve. Accident rates increase in proportion to decreases in the radius of curves, in particular for radii of less than 250 m on two-lane rural roads. Moreover, there are important differences in accident rates between similar curves, mainly due to the approaching speed. For this reason many countries have introduced in their standards certain rules, in different forms, to evaluate the design consistency that identifies unacceptable speed changes along the speed profile of the horizontal alignment.
The Italian Road Design Standard also requires an evaluation of design consistency. In order to identify the speed differences between successive geometric features, a design speed profile has been prepared. However, the design speed does not always represent the real speed used by the driver on taking the curves, especially on sharp curves that are precisely the curves with the highest accident rate. Previous research in the Department of Civil Engineering of the University of Trieste showed that the operating speed (85^{th} per centile speed) could also be 20 km/h higher than the design speed. The natural consequence is that the design speed profile does not correspond to the real speed profile and so cannot identify all the unacceptable speed differences. Moreover, the stopping sight distance depending on the design speed would not be enough to guarantee the safety of the braking action. To solve these problems, an operating speed prediction model for two-lane rural roads was developed. The model uses the horizontal radius and the environmental speed as the main variables to determine operating speed on curves and on tangents. The data used to conduct the regression analysis were collected at forty curves and at ten “independent” and “not independent” tangents.
The results show that the model effectively estimates the operating speed along the road alignment, depending on its geometric features. Consequently, this simulation model can be used in order to evaluate the consistency of new and existing roads, stopping sight distance, and, finally, to promote overall traffic safety.

Operating Speed Prediction Model For Two-Lane Rural Roads

INTRODUCTION

Various analyses of the relationship between road geometry and accident rate have made clear that the speed of a vehicle on any road section plays an important part in accident occurrence. The driver's choice of speed is heavily conditioned not only by the geometric features of the road section but also by the approaching speed to the road section and hence by the geometric features of the road that immediately preceeded. For this reason the design standards of different countries request not only the verification of compatibility between speed and the geometric characteristics of the single elements that follow each other along the horizontal alignment, but also controls based on a comparison between the travelling speeds of adjacent elements in order to limit the difference between their values. Normally these controls use an operating speed which is a good approximation of real travelling speed. In fact, in order to estimate operating speed, models are used that have been obtained by means of a statistical analysis of the data gathered during an experimental survey. Previous studies carried out by the Department of Civil Engineering of the University of Trieste have made it possible to predispose an operating speed prediction model which, besides taking into consideration the variables of the single geometric elements (tangent or curve), also introduces a variable that characterises the road overall: environmental speed (1). Environmental speed is defined as the maximum speed that can be reached on tangents or very large radius curves belonging to a homogeneous road section identified by an analysis of the curvature change rate, CCR.

In the present study we present an evolution of previous models for the construction of the operating speed profile (2). This was made possible by further surveys carried out with a view to amplifying the field of validity of the models on new two-lane rural roads characterised by different conditions to those already present in the data of the department. The surveys were designed above all to improve the environmental speed prediction model by introducing a further independent variable; namely, the road width. What's more, indications about driver behaviour along transition sections obtained from recent studies carried out by the Department of Civil Engineering, have made it possible to formulate criteria for a more accurate evaluation of the operating speed profile on spiral curves.

EXPERIMENTAL SURVEY

The experimental survey of this study started out as one of the principle objectives in amplifying the samples of available data relative to the speed of independent tangents and in integrating the speed levels on curves. The research was carried out, like previous studies, using laser equipment that was concealed in order to prevent their presence influencing driver behaviour. Non passenger cars and vehicles with less than a 5 second headway from the preceding vehicle were not considered for the purpose of the analysis. The new survey sections involve two important rural roads in the Friuli Venezia Giulia region.

Table 1: Geometric Characteristics of the roads surveyed

ROADS	Width (lanes + shoulders)	Max Radius	Min Radius	Max tangent length
	[m]	[m]	[m]	[m]
S.S. n.55 I part	6,50	150	50	225
S.S. n.55 II part	7,00	250	125	150
S.S n.14 Basovizza	7,50	340	100	800
Cimpello - Sequals	10,50	2200	400	2500
S.P. n.19	7,30	840	320	790
S.P. n.6	7,00	700	60	270

The first road is S.P. n° 19 which links Monfalcone to the tourist resort of Grado in the province of Gorizia. The road width is approximately 7.5m. The second one is S.P. n° 6 which links the village of Sales to that of Gabrovizza in the province of Trieste. The road width is approximately 7.0m. All two roads, like those which were the object of previous surveys, have a vertical alignment characterised by a very slight longitudinal gradient (0 ÷ 3%).
All new data, like the previous, were collected during daylight hours under dry pavement condition and in the presence of low traffic (less than 400 vehicle/hour). At least 70 observation were taken at each site used for the analysis and there were no posted speed limits in all survey sections.
Table 1 indicates the geometric characteristics of all the roads used for the purposes of the study of speed on tangents divided into sections characterised by the same vertical alignment and by the same cross section.

DATA ANALYSIS

The environmental speed is defined as the maximum 85th percentile value of the speeds surveyed on long tangents or very large radius curves belonging to a homogeneous road section. It represents "the speed which drivers tend to go at when they are not conditioned by traffic or by horizontal alignment".
The environmental speed was evaluated using the curvature change rate, the road width and the average radius of the homogenous section.

The Determination of Homogeneous Sections

In order to single out the road sections with homogenous horizontal alignment characteristics to associate with a single value of environmental speed, reference was made to the indications present in the German standard (4). This provides a method for singling out homogenous road sections by evaluating the curvature change rate (CCR = $(\Sigma_i |\gamma_i|) / L$ gon/km). The summation of the deflection angles of the successive elements of the horizontal alignment is represented in a diagram as a function of distance (L).

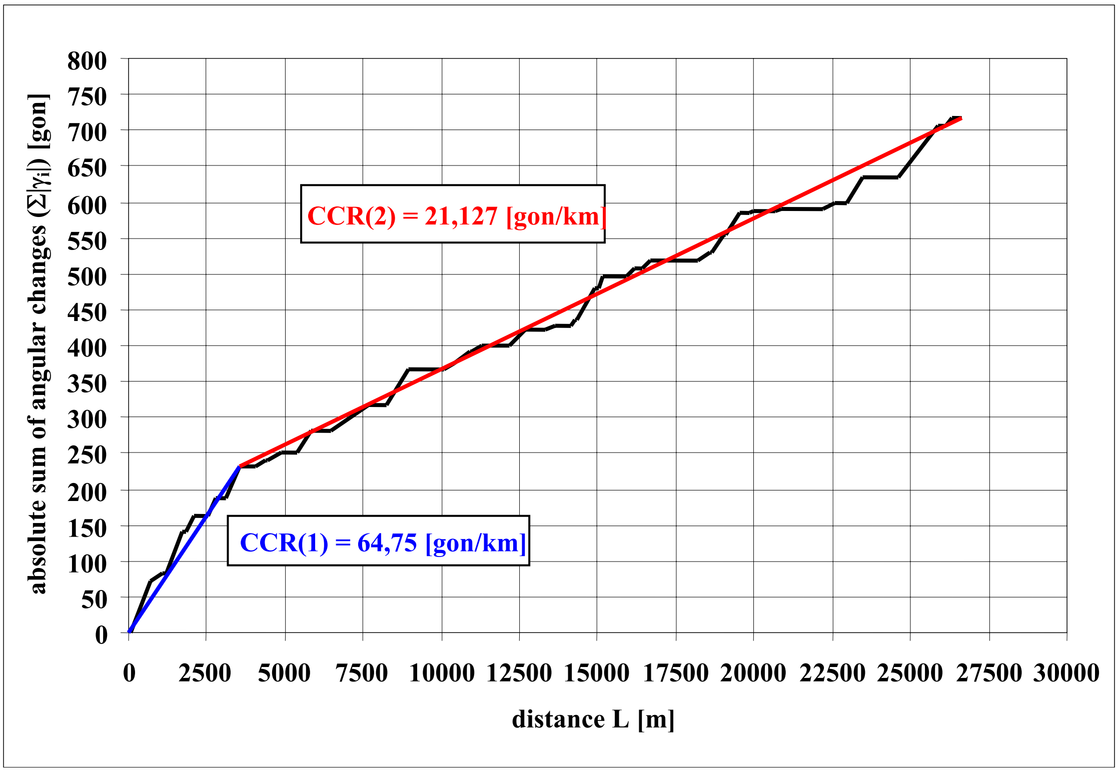

Figure 1: Diagram of the Curvature Change Rate CCR calculated for Cimpello – Sequals road

It is quite easy to identify the sections in which to subdivide the road. They are characterised by various constant slopes interpolating the overall curvature. The length of these homogenous sections cannot be less than 2km. For example, the section of Cimpello - Sequals of about 27 km is characterised by two homogenous sections (Figure 1) both with long tangents adapted to estimate the environmental speed. Following this criterion seven homogenous sections, as indicated in Table 2, were singled out. Two sections belong to the Cimpello-Sequals road, two belong to S.S. n° 55, one belong to S.S. n° 14, one belongs to S.P. n° 19 and one to S.P. n° 6. The width of the roads varies from 6.50m to 10.50m and is such that it includes all possible types of single two-lane rural roads. The environmental speed obtained by the analysis of speeds measured on the survey part (on average six for every section) was associated with every homogenous section. The fact that the division into homogenous sections was carried out correctly is confirmed by observing the levels of speed on tangents. In fact all the speeds registered on long tangents belonging to the same section are very similar and tend to reach the environmental speed of the same section.

Table 2: *Geometric* Characteristics of the homogeneous sections

ROAD	Mean Radius	Width (lanes + shoulders)	CCR	Venv
	[m]	[m]	[gon/km]	[km/h]
Cimpello – Sequals	740,00	10,50	64,75	115,0
Cimpello – Sequalls	1872,91	10,50	21,13	129,5
S.S. n. 14 basovizza	249,50	7,00	72,88	100,0
S.S. n. 55	175,00	7,00	199,56	90,0
S.S. n. 55	113,30	6,50	346,46	80,0
S.P. n.19	620,39	7,30	32,52	112,6
S.P. n.6	311,16	7,00	60,97	97,0

Models for the Prediction of Environmental Speed
Using the data in Table 2, it is possible to single out an exponential curve which is a good representation of the environmental speed as a function of a single geometric characteristic of the road: for example, the curvature change rate CCR in Figure 2 or the average radius of the homogenous section R_m in Figure 3. With the data at our disposal it was also possible to evaluate the regression equations with a second independent variable: the road width L_p. All these equations and the relative coefficients of determination are pointed out in Table 3. All the regression parameters (β_i) of the analysis are statistically significant (P-value < 0,05).

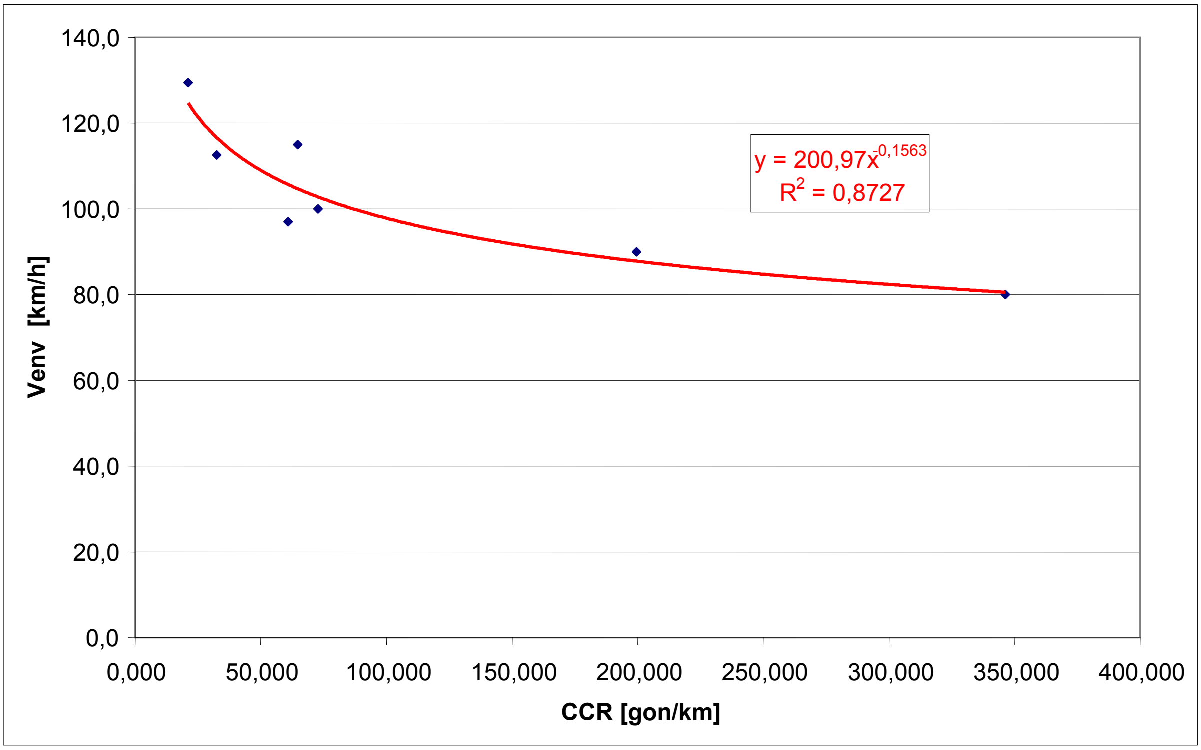

Figure 2: Environmental Speed as a function of the Curvature Change Rate CCR

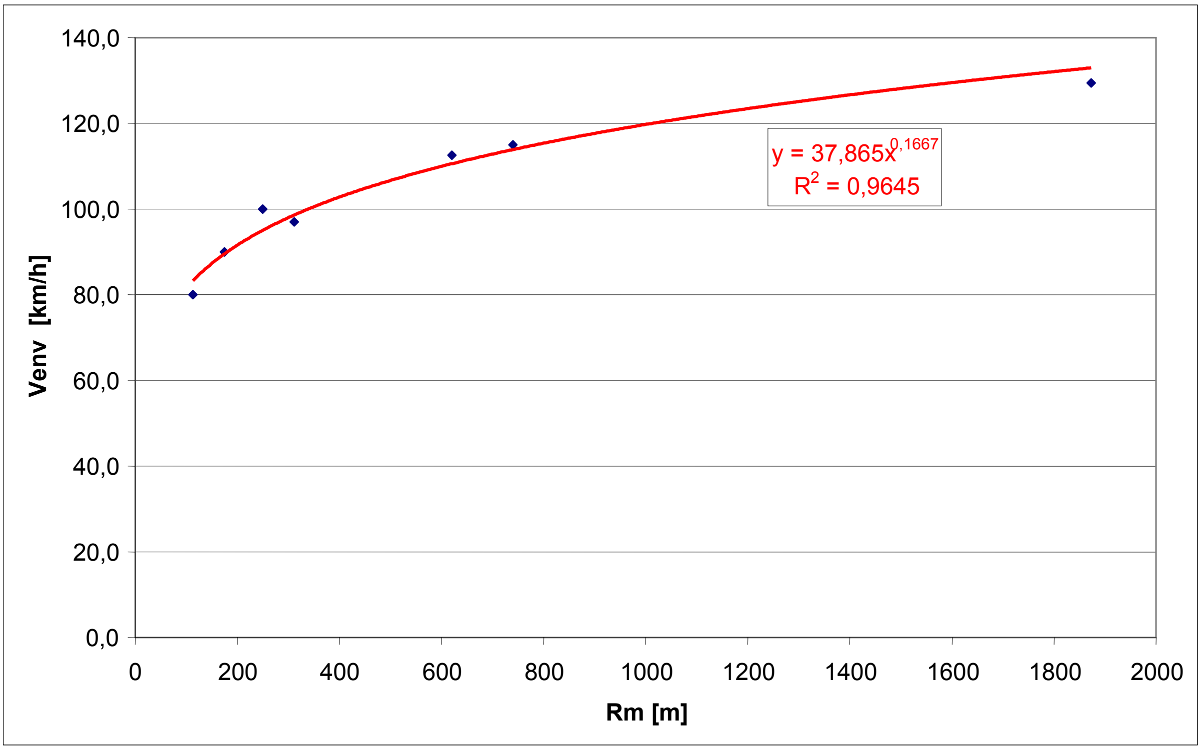

Figure 3: Environmental Speed as a function of the Mean Radius R_m of the homogeneous section

Table 3: Environmental Speed V_{env} prediction models

INDIPENDENT VARIABLES	EQUATION	R^2
CCR	$V_{env} = 200{,}97 \times CCR^{-0{,}1563}$	0,87
R_m	$V_{env} = 37{,}865 \times R_m^{0{,}1667}$	0,96
CCR ; L_p	$V_{env} = 14{,}99 + 138{,}24 \times CCR^{-0{,}216} + 4{,}15 \times L_p$	0,98
R_m ; L_p	$V_{env} = 70{,}18 - 0{,}0176 \times R_m + 2{,}88 \times L_p$	0,83

The environmental speed prediction model for the two variables proposed in Table 3 uses as independent variables the curvature change rate CCR (gon/km) and the road width L_p (m) or, alternately, the average radius R_m (m) and the road width L_p (m). Both the models show quite a high R^2. The equation proposed for the construction of the operating speed profiles is that which uses CCR and the width Lp not only because it predicts more accurately the environmental speed but also because the CCR is better able to represent all the geometric characteristics of a homogenous road section. This equation is presented in Figure 4 from which it clearly emerges that the CCR has a greater influence on environmental speed than the road width L_p.

Prediction Model for Speed on Curves

A statistical analysis was carried out taking into consideration the data on speed in both directions along thirty curves belonging to five different roads. The dependence of speed was evaluated according to two variables: the environmental speed along the homogenous section to which the curve belongs and the curve radius R. The radii of the curves are included within a wide interval (60m ÷ 2200m).
The following equation for the prediction of operating speed on curves, V_{85c}, was obtained. Also in these equation all regression parameters (β_i) are statistically significant (P-value < 0,05).

$$V_{85c} = 48{,}447 - 4995{,}01 / R + 163893{,}24 / R^2 + 0{,}5598 \times V_{env} \qquad R^2 = 0{,}88$$

It can be noted that by inserting into the analysis the data of all five roads, there are no significant improvements in the correlation compared to the previous analysis estimated according to the data obtained from a survey on three roads (2). Only a slight diminution of the standard error can be noted. What's more,

it should be emphasised that the proposed equation can't not be used for ample curves radii, because as regards this type of curve, no significant differences of speed in respect of adjacent tangents have been observed. In practice this equation can be used for R ≤ 2187m (corresponding to $R_{2.5}$ according to the Italian standard, or in other words, to the radius for which the super-elevation is equal to 2.5%). As regards radii higher than 2187m in particular, the proposed operating speed profile model calculates the speed with the equation formulated for tangents and not for curves. This hypothesis is confirmed by the speeds measured on curves of a radius higher than the one indicated and which show negligible differences in respect of those measured on a tangent.
Moreover, the equation gives anomalous result in same particular condition. Therefore, the equation can be used for radii between a minimum value of 80m and a maximum value depending on the environmental speed (V_{env} = 80km/h R_{max} = 340m; V_{env} = 90km/h R_{max} = 530m; V_{env} = 100km/h R_{max} = 1100m). Above the maximum radius, V_{85c} is equal to the environmental speed.
To improve the prediction it will be necessary to enlarge the data sample to develop new equations in relation to different values of environmental speed.

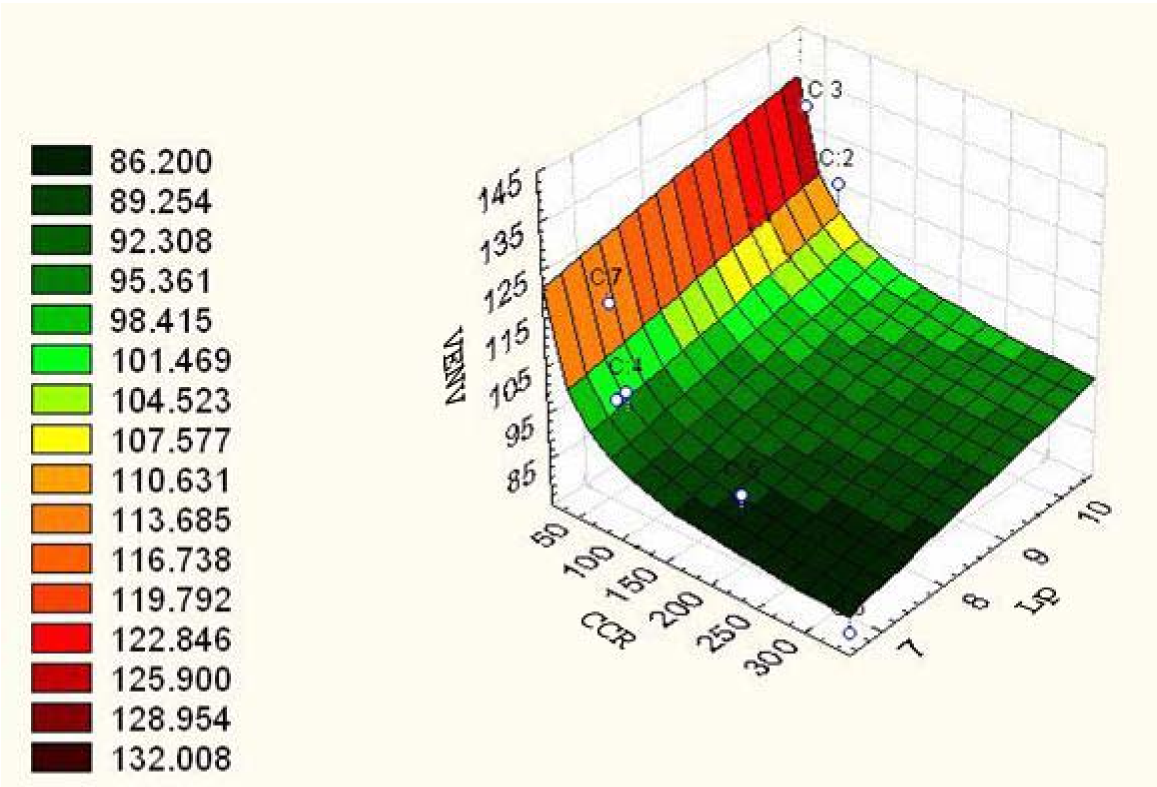

Figure 4: Environmental Speed as a function of the Curvature Change Rate CCR and Road Width L_p

In interpreting data, particular attention was paid to curves near the border between two homogenous sections characterised by different environmental speeds. The curves that are too close to these areas will be travelled with speeds that differ significantly according to the direction. Precisely because of the direction, they could be influenced by the environmental speed on the section that precedes them since the adaptation of the driver to new environmental conditions requires a certain amount of time.

Speed Prediction Model for Tangents
The results obtained from preceding phases of the research have shown that the maximum speed reached on a tangent depends on the length of the tangent itself and on the operating speed of the curve which precedes it. Two regression equations were developed, one of which is valid for tangents of a length below 200m and the other for tangents of a length above 200m (2). In this phase we decided to give preference to the simplicity of carrying out an operating speed model; hence we chose to use only the second of the two equations which provides a much better prediction of speed on long tangents and, at the same time, doesn't excessively overestimate speed on short ones. With a view to improving it, the sample on which the previous statistical analysis had been based was amplified. The data on another 7 couples tangent – preceding curve, characterised by different cross sections, were collected. These data were added to those already available, made up of 17 tangent - preceding curve couples on the basis of which a new equation of regression which presents an improvement both as regards the coefficient of regression and the standard error was obtained. The operating speed of the tangent function of its length, L, and of the operating speed of the preceding

curve, V_{85cp}, can be seen in Figure 5. All regression parameters (β_i) of the analysis are statistically significant (P-value < 0,05).

V_{85T} = -2,351 + 18,104 $\log_{10}$ (L) + 0,585 V_{85cp} $\qquad\qquad$ R^2 = 0,88

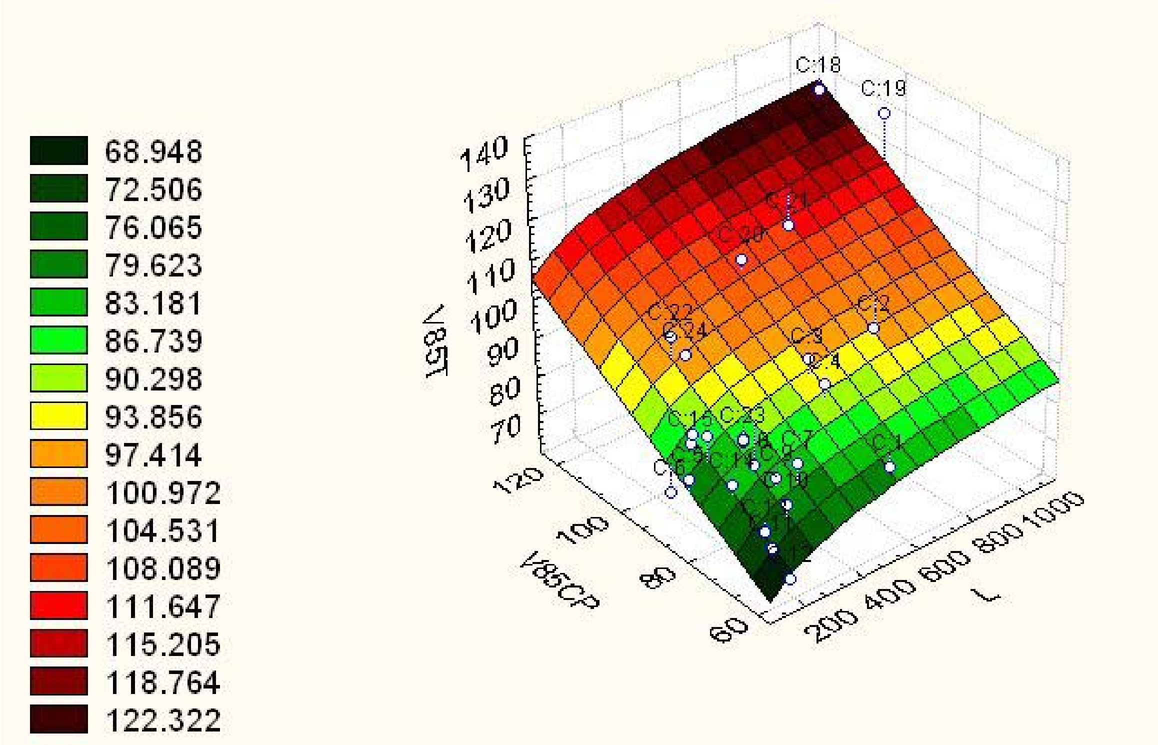

Figure 5: The operating Speed V_{85T} on tangents function of the tangent Length L and the operating speed V_{85CP} of the preceeding curve

It is important to observe that the environmental speed in respect of the overall geometric characteristics of the road does not figure directly in the equation as an independent variable but by means of the speed of the preceding curve which depends on it. Obviously the calculated speed in this equation cannot be higher than the environmental speed of the homogenous section of road to which the tangent belongs. In this case the speed must be limited to the environmental speed. This case could be found on very long tangents preceded by very ample curves. In reality this does not happen because the curves with a radius higher than 2187m in the proposed model are assimilated to a tangent for calculating the operating speed, including their length in that of eventual adjacent tangents.

Behavioural Model in the Transition Zone

Some recent studies have revealed that the deceleration and acceleration at the beginning and end of the curve are neither constant nor equal to each other (5). Consequently we decided not to fix a single constant value such as that in both the design speed profile of the Italian standard (6) and in that of the previous version of the model (2), but rather to adopt different values dependent on the radius of the curve, along the lines proposed in the recent report of the FHWA used for the carrying out of the IHSDM software (5). The recommended values were based on the experience of the FHWA (5) and on the research carried out by the Department of Civil Engineering of the University of Trieste as to the influence of the length of the spiral length on the behaviour of a driver entering a curve (3).The results of the latest study show that the value for deceleration is heavily dependent on the radius of the curve; they confirm in substance the various proposals of the IHSDM and show that the driver, in spiral transitions, decelerates along the spiral curve. It follows, therefore, that spiral transitions, in the construction of a speed profile, can be assimilated in the adjacent tangents as requested by the standard (6). Table 4 reports the values of acceleration and deceleration proposed for the construction of the the operating speed profiles. To simplify matters, the values of the radii indicated are those which correspond to the design speeds of 70 and 100km/h present in the Italian standard (6) for two-lane rural roads of the C and F type.

Table 4: The Acceleration and Deceleration Values

Radius [m]	Deceleration [m/s^2]	Acceleration [m/s^2]
R< 178	1.00	0.54
178 < R < 437	0.50	0.43
437 < R < 2187	0.20	0.20

THE OPERATING SPEED PROFILE MODEL FOR TWO-LANE ROADS

Using the equations for the prediction of the operating speed on curves and tangents and the values for acceleration and deceleration it is now possible to construct the operating speed profile with which to identify the inconsistencies of the horizontal alignment. Obviously this profile, unlike the one on design speed envisaged by the Italian standard, must be constructed for both directions since the speed reached on the same tangent could be different and acceleration has different values from deceleration. The construction of the profile is quite similar to the one required by the Italian standard. In practice it is based on the following steps:

- The road is divided into homogenous sections according to the procedure proposed by the German standard (4).
- The curvature change rate CCR is calculated for each homogenous section; hence with this and the road width L_p the environmental speed of the section is obtained.
- The speed is constant along the circle arc of the curves (R<2187m) and it is determined by the equation proposed with respect to the radius of curve R and to the environmental speed Venv of the homogenous section to which the curve forms part.
- Speed on tangents (including spiral curves and curves with a radius of 2187m) can be calculated by the equation proposed on the basis of the length of the tangent and of the operating speed of the preceding curve. Obviously, the calculated speed cannot exceed the environmental speed of the homogenous section of which the tangent is part. Hence the speed limit of the profile is exactly the environmental speed.
- From the end of the circle curve the speed increases to the calculated speed of the following tangent or, if the tangent is not sufficiently long, to the point where it begins to drop in order to reach the calculated speed of the next curve. The values of acceleration and deceleration that should be used depend on the radius of the curve.

Once the profile of operating speed has been completed, it is possible to carry out controls of the design consistency, paying particular attention to the transition zones between homogenous sections characterised by different environmental speeds. In particular it is possible to use the design consistency procedure proposed initially by Lamm (7) which classifies the succession of two geometric elements of the road in three cases on the basis of the difference between their operating speeds. Especially when the difference between the operating speed of the two elements that follow each other along the section is equal to or less than 10 km/h, the consistency is considered good; when such a difference falls between 10 and 20 km/h the consistency is considered fair. Finally, when the speed is higher than 20 km/h, the consistency is considered poor. In this way it is possible to identify the planning sequences that require an excessive lowering of speed and so eliminate them. It must be pointed out that the model for the construction of this profile of operating speed is based on data gathered only on roads characterised by a low longitudinal gradient (<3%) and should, therefore, be used prudently if the vertical alignment of the road has substantially different characteristics since, as demonstrated by many studies (5), it influences operating speed.

CONCLUSIONS

The model proposed for evaluating the operating speed profile of a single two-lane rural road is the evolution of a previous version (2) which did not include the use of environmental speed. What's more, the model is based on a sample of much more exhaustive data with the result that the equations are much more reliable. The use of environmental speed enables us to present driver behaviour more effectively. The driver, on the basis of the overall geometric characteristics of the horizontal alignment represented by the curvature change rate CCR, by means of a subjective evaluation of the risk, decides on a certain maximum speed, judging it "adequate" for the road and surrounding conditions. The statistical analysis so far carried out has highlighted the heavy dependence of this speed on the geometrical characteristics of the road section. However, external factors can also affect this speed. In effect, the British (8) and the Australian (9) standards use other more complex factors such as available sight distance, the frequency of junctions and accesses and the terrain type. Future developments of this research must concentrate on these aspects. As far as we are concerned, it is important to underline that the speeds registered for the determination of the environmental speed are very high, even exceeding the maximum design speed (100 km/h) of two-lane rural roads by as much as 10 – 30 km/h. This is enough to justify an effective operating speed in order to evaluate correctly the speed consistency of the horizontal alignment of these roads since the use of design speed might not pick up all the unacceptable speed differences.

REFERENCES

1 Crisman B.; Marchionna A.; Roberti R.; Fugaro L.; *Modello di previsione delle velocità praticate dagli utenti attraverso la definizione di una velocità ambientale*; Atti del XIII Convegno Nazionale S.I.I.V.; Padova, 30-31 ottobre 2003;

2 Crisman B., Marchionna A., Perco P., Roberti R., Glavina S.; *Operating speed prediction models*; Final Report, Research Project "Environment-Safety Interaction in Road Design"; Firenze, 23 Febbraio 2001;

3 Perco P.; Crisman B.; *Influence of Spiral Length on Path of Vehicle entering a Curve*; Proceedings 83rd Transportation Reasearch Board Annual Meeting, Washington D.C., 11-15 January 2004.

4 *Richtlinien für die Anlage von Strassen: Linienführung RAS-L*; Forschungsgesellschaft für Strassen-und Verkehrswesen; Bonn, 1995;

5 Fitzpatrick K., Elefteriadou L., Harwood D., Collins J., McFadden J., Anderson I., Krammes R., Irizarry N., Parma K., Bauer K., Passetti K.; *Speed Prediction for Two-Lane Rural Highways*; FHWA-RD-99-171;Federal Highway Administration, Turner-Fairbank Highway Research Center, 2000.

6 *Norme funzionali e geometriche per la costruzione delle strade*; D.M. 05/11/2001 Ministero delle Infrastrutture e dei Trasporti; Roma, 2001.

7 Lamm R., Choueiri E.M., Hayward J.C., Paluri A.; *Design on Two-lane Rural Roads*; Transportation research Record n°1195; Transportation Research Board; Washington D.C..

8 *Road Geometry: Highway Link Design*; Departmental Standard TD 9/93; Department of Transport; 1993.

9 *Rural Road Design: Guide to the Geometric Design of Rural Roads*; Austroads; Sydney, 1997.

ACKNOWLEDGEMENTS

The authors acknowledge Ing. Alberto Robba for his important contributions to the data collection and the following Administrations for the permission to collect the data along their roads:
ANAS – Compartimento di Trieste
Provincia di Trieste
Provincia di Gorizia