OPERATING SPEED MODEL ON TANGENTS OF TWO-LANE RURAL HIGHWAYS

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ABSTRACT

The prediction of the operating speeds is a very remarkable aspect for the adjustment planning of the existing road network. The problem can be solved more easily on curve than on tangent, because the drivers' behaviour depends on few factors as curvature, slope and adherence. Instead, on tangent, the elements that influence the adopted speeds are more numerous. They are related to different features, like length, radius of preceding and following curves, transversal section, vertical alignment, etc.

Numerous studies have been conducted, in different Countries and on various typologies of roads, to determine, on the basis of the statistic analysis of instrumental direct measurements, the links among operating speeds and some characteristic parameters of the roads.

The objective of this experimental study is to get relationships of general validity for the prediction, in phase of project, of the speeds that will be indeed practiced on the infrastructure.

The experimental investigation, object of the present paper, has been conducted employing traffic counters, able to record, for every vehicular passage in both senses: length, instant speed and direction of the vehicle.

The plan of survey has been elaborated to satisfy different objectives of search (speed in free flow conditions, in entry and in gone out of the intersections, in rural to urban transition, etc.) and it has been applied to some roads belonging to the network of the Province of Salerno. The measures have been performed holding every section under observation for 2 or 3 hours. Then the data have been used for starting the formalization of some analytical relationships to predict the operating speeds.

This paper introduces a prediction model of operating speed and the other parameters of free flow conditions on more than 36 tangents. In meaningful way, the surveyed speeds are correlated to the entrance one that depends on geometric parameters of the preceding curve.
Keywords: operating speed, tangent length, design consistency, two-lane rural roads

1. PREVIOUS STUDIES

The models that correlate the geometric characteristics and the operating speed on tangent are divided into two categories. The former is represented by the models that derived from the prediction of speed on curve and the extension to the endless of the range of the independent variable R (radius of curvature). The advantage of this typology of models is to make continuous the function of operating speed (V_{85}). It depends on the same parameters used for the curves, but it is not very exact because the relationships are formulated for the curves and optimized for them. In the latter the models correlate operating speed to length of tangent, speed of the preceding curve, access density, road width, vertical slope, etc.

Although the issue of speeds on tangent sections has not been studied extensively, several U.S. and international researchers have studied operating speeds and average running speeds, design speeds, speed limits, and the impact of geometric and traffic measures on speeds.

Cardoso J. L. in Portugal developed two models for speeds on tangents using multiple non linear regression. The same explanatory variables were incorporated in the best fitted models for both speed percentiles. The most important explanatory variable is the radius of the preceding curve segment (R_p) followed by shoulder width. The removal of L from the equations has only a minor influence on the R-squared and in the variable's coefficients, pointing towards the measurement of desired free speed on straights in the tangent sites used (Cardoso, 1995).

Polus A. et al. in the United States presented a methodology for estimating the expected 85th percentile speed on tangent sections of two-lane rural highways. The extensive database provided ample geometry information and knowledge on the driver behaviour and speed selection. The models developed are valid for two-lane rural highways where the volume is rather low and does not affect speed. The analysis showed that when determining 85th percentile speeds in the middle of a tangent section, it is necessary to observe a longer section, one that includes the preceding and succeeding curves, because these constitute the primary variables affecting speed. The influence of other, secondary geometric variables was found not to affect speed as much as do the primary variables. Several geometric measures characterizing the geometry of the entire section were developed, and the best measure was adopted for the development of the prediction models. After considerable examination of the 162 sites, the data were assembled into four groups of similar characteristics: Group 1, small radii and short tangent length. Separate prediction models for the 85th percentile speed were developed for each of the four groups separately. The models for Group 1 and Group 2 sections provided a good fit to the data and could be adapted for prediction purposes. The models for Group 3 and Group 4 sections were preliminary. The authors suggested further research on the impact of some secondary variables, such as the lane width and roadside characteristics, the direction of the curves, and the longitudinal slope on the operating speed (Polus et al., 2000).

Andueza P.J. in Venezuela presented mathematical models of vehicular speed on mountain roads on tangent sections of two-lane rural roads. The correlation coefficient is high for all models. Selected variable coefficients are statistically significant with significance levels at 5 percent. In short tangent sections, typical of mountain roads, the relationship between speed and tangent length is linear. The author suggests better model specifications for long straight sections in terms of L_a should be explored because, there should be a length from which drivers level out their speed to a certain value. This was not carried out in the study because the longest straight section was 0.555 km. To estimate tangent speed, the most significant variable is the radius of the previous curve (R_a). According to field data, the independent variables and variation ranges were as follows: R_a (130 m; 3.970 m) and L_a (55 m; 555 m). There are no limitations for L_a in terms of its lower value. For the upper limit, it is estimated that values up to about L_a 0.600 km can be used. It was observed that the influence of L_a is greater in the 85^{th} percentile of speeds in tangents than in average speeds (Andueza, 2000).

Ottesen J.L. et al. presented Speed-Profile Model for a Design-Consistency Evaluation Procedure in the United States. Among the independent variables tested on tangent sections, the only statistically significant results related to geographic region and terrain. The only statistically significant difference among the means of the 85^{th} percentile speeds on long tangents was between those in level terrain in the South (Texas) 102.4 km/h and those in rolling terrain in the East and West 95.5 km/h. The East and West regions were combined because otherwise sample sizes for level terrain were too small to make statistical comparisons. The mean of the 85^{th} percentile speeds of all tangent sections was 97.9 km/h. Travel-way width, total pavement width, characteristics of the preceding and of the succeeding curve, tangent length, and AADT were not significant in modeling 85^{th} percentile speeds on long tangents. The finding that neither the characteristics of the preceding and succeeding curves nor the length of tangent was significant suggests that the tangents studied were sufficiently long that the speeds measured were desired speeds and were not constrained by other alignment features. The finding that AADT was not significant is consistent with the intent to measure free-flow speeds (Ottesen et al., 2000).

Lamm R. et al. provided an important review about the safety evaluation process for two-lane rural roads. They put special attention to tangents required. The authors distinguished independent (long) tangent, in whose case it will be regarded in the design process, from not independent (short), in whose case it is simply ignored. To draw a distinction between long and short tangents, they considered the operating speed, V_{85}, that can be achieved on the tangent in relation to the operating speeds appropriate to the curves on either side of it. They distinguished three possibilities. In Case 1 the tangent length (TL) is such that it either is not, or is just, possible, in going from a shorter to a longer radius, to accelerate to the operating speed of the following curve within the length of the tangent; $TL \leq TL_{min}$ (non-independent tangent, not considered in the safety evaluation process; the curve-to-curve sequence is relevant). In Case 2 the tangent length allows acceleration up to the maximum operating speed, V_{85Tmax}, on tangents; $TL \geq TL_{max}$ (independent tangent, considered in the safety evaluation process; the tangent-to-curve sequence is relevant). In Case 3 the tangent length is such that it is possible to achieve an operating speed higher than the one of the following curve but not as high as the one achieved without the constraint of nearby curves; $TL_{min} < TL < TL_{max}$ (independent tangent, considered in the safety evaluation process; the tangent-to-curve sequence is relevant). The calculation of the tangent lengths, TL_{min} and TL_{max}, requires calculation of the operating speed under the various circumstances. This calculation is based on an average acceleration or deceleration rate of a = 0.85 m/s^2, which was established by application of car-following techniques (Lamm et al., 2002).

Crisman, Marchionna et al. in Italy proposed that a statistical analysis has been carried out on 24 couples composed of a tangent and its preceding curve in order to predict the maximum speed reached on dependent tangents. The equation proposed was an upgrade of a previous equation based on fewer data and it calculates the operating speed on tangents (V_{85t}) as a function of the operating speed on the previous curve (V_{85cp}) and of the length of the tangent (L_t) (Crisman, Marchionna et al., 2005).

Bella in Italy proposed a relationship using driving simulator; it highlights that the V_{85} decreases as the value of $CCR_{s(i-1)}$ of the previous curve increases and as the value of the local longitudinal grade increases, while V_{85} increases as the length of the tangent increases (Bella, 2005).

Figueroa et al. used free-flow speed measurements and two-lane rural highway characteristics were used to develop the speed models. The models demonstrated their efficiency in identifying relationships between drivers road characteristics and speeds. One important contribution is the fact that the impact of the cross-section dimensions is present in the tangent speed model. In addition, it is equally easy to quantify the impacts of the variables on mean speed and on speed standard deviation. The tangent speed model includes 10 different variables, six of them working as both mean speed and speed dispersion factors. The advantages of the models developed in this study over those of the traditional OLS (ordinary-least-squares regression) models include predicting any user-specified percentile, involving more design variables than traditional OLS models, and separating the impacts on mean speed from the impacts on speed dispersion (Figueroa et al., 2006).

Nie B. et al. presented a unique study of driver speed behaviour in accordance with the specific road class: two-lane rural highways and urban/suburban roads. On two-lane rural highways, tangent speeds are positively proportional to the tangent length (Nie et al., 2007).

2. DATA COLLECTION

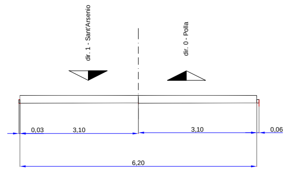
The KV Laser made by SODI Scientific are used for data collection. The operation feature of these devices is endowed with two photocells. It is based on the issue and the receipt of a laser couple beams perpendicularly direct to the road axis.

The measurers have been performed during the year 2006, every station for 2 or 3 hours, using two measurers on next stations contemporarily and 6-8 stations everyday (Tables 1, 2, 3). The stations were located on tangents of the road network of Piana del Sele and Vallo di Diano (Dell'Acqua et al., 2007a).

We filtered preventively the data for getting a sample of transits really representative of the passages of cars in free-flow conditions, because the environmental speed is more possible on "faster" layouts and operating speeds is necessarily referred to low traffic conditions.

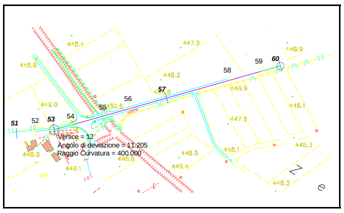
So we enucleated the only transits of vehicles with: length between 2.5 and 9.0 meters, like to cars for private use; gap superior to 5 seconds from the preceding vehicle (Table 4).

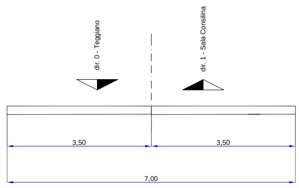
Table 1 Major highway SS426



DATE: 4th April 2006				TIME			
				11.02		13.17	
Direction POLLA				Direction S. ARSENIO			
TIPOLOGY	N.	%	MEAN SPEED [Km/h]	TIPOLOGY	N.	%	MEAN SPEED [Km/h]
Motorbike	4	1,48	48,25	Motorbike	4	1,48	61,75
Car	230	85,19	65,82	Car	233	85,35	69,71
Van	14	5,19	45,57	Van	5	1,84	38,20
Truck	9	3,33	44,00	Truck	14	5,14	60,43
NC	13	4,81	5,00	NC	16	5,87	5,00
TOTAL	270	100,00	63,68	TOTAL	272	100,00	68,46

Table 2 Minor highway SP52





DATE: 30th March 2006				TIME			
				8.24		10.54	
Direction SALA CONSILINA				Direction TEGGIANO			
TIPOLOGY	N.	%	MEAN SPEED [Km/h]	TIPOLOGY	N.	%	MEAN SPEED [Km/h]
Motorbike	2	0,87	32,00	Motorbike	3	2,17	20,33
Car	215	93,48	59,02	Car	124	89,86	50,42
Van	8	3,48	41,50	Van	9	6,52	43,56
Truck	3	1,30	22,00	Truck	2	1,45	19,50
NC	2	0,87	5,00	NC	0	0,00	0,00
TOTAL	230	100,00	57,68	TOTAL	138	100,00	48,87

Table 3 Minor highway SP312

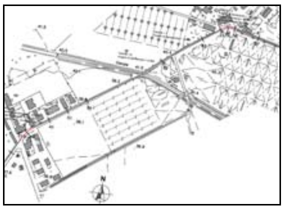
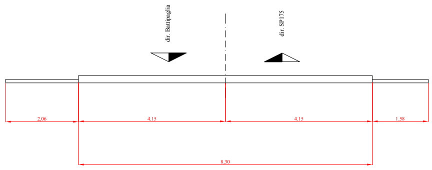
<table>
<tr><td colspan="4"></td><td colspan="4"></td></tr>
<tr><td colspan="4" rowspan="2">DATE: 11st May 2006</td><td colspan="4">TIME</td></tr>
<tr><td colspan="2">9.13</td><td colspan="2">11.40</td></tr>
<tr><td colspan="4">Direction BATTIPAGLIA</td><td colspan="4">Direction SP175</td></tr>
<tr><td>TIPOLOGY</td><td>N.</td><td>%</td><td>MEAN SPEED [Km/h]</td><td>TIPOLOGY</td><td>N.</td><td>%</td><td>MEAN SPEED [Km/h]</td></tr>
<tr><td>Motorbike</td><td>7</td><td>1,90</td><td>32,29</td><td>Motorbike</td><td>20</td><td>4,35</td><td>35,50</td></tr>
<tr><td>Car</td><td>303</td><td>82,34</td><td>45,50</td><td>Car</td><td>376</td><td>81,74</td><td>41,51</td></tr>
<tr><td>Van</td><td>33</td><td>8,97</td><td>39,70</td><td>Van</td><td>22</td><td>4,78</td><td>35,77</td></tr>
<tr><td>Truck</td><td>10</td><td>2,72</td><td>35,90</td><td>Truck</td><td>8</td><td>1,74</td><td>35,50</td></tr>
<tr><td>NC</td><td>15</td><td>4,08</td><td>5,00</td><td>NC</td><td>34</td><td>7,39</td><td>5,00</td></tr>
<tr><td>TOTAL</td><td>368</td><td>100,00</td><td>44,42</td><td>TOTAL</td><td>460</td><td>100,00</td><td>40,82</td></tr>
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Table 4 Measurement results for tangents

Sites	V_{85T} [km/h]	L_T [m]	V_{85Cp} [km/h]	Sites	V_{85T} [km/h]	L_T [m]	V_{85Cp} [km/h]
1	69,00	183	50,00	**29**	65,00	617	33,00
2	64,00	183	45,00	**30**	69,00	166	56,00
3	80,00	502	80,00	**31**	64,00	166	47,60
4	86,00	502	82,80	**32**	68,05	71	65,00
5	80,30	166	68,00	**33**	66,00	71	61,75
6	94,00	166	91,60	**34**	76,00	395	77,00
7	94,00	724	74,00	**35**	83,65	395	70,30
8	93,10	724	81,00	**36**	65,00	309	59,05
9	88,00	428	67,80	**37**	76,95	309	64,00
10	84,60	428	74,00	**38**	88,80	215	90,30
11	76,95	283	80,75	**39**	81,00	342	97,00
12	87,50	283	83,00	**40**	90,05	342	94,00
13	87,70	121	81,00	**41**	92,70	288	86,20
14	83,00	121	84,70	**42**	88,75	308	88,85
15	70,00	72	70,00	**43**	94,00	308	83,25
16	64,00	72	70,00	**44**	85,00	94	84,55
17	63,00	101	62,00	**45**	83,20	94	78,00
18	68,80	74	63,35	**46**	59,00	73	42,00
19	59,45	74	64,00	**47**	58,00	622	44,60
20	54,00	55	55,00	**48**	61,00	622	41,00
21	52,00	55	56,00	**49**	71,65	492	75,00
22	62,00	172	55,00	**50**	68,20	492	71,00
23	58,95	69	54,00	**51**	73,00	138	69,70
24	56,65	69	52,00	**52**	69,00	138	66,95
25	67,65	266	47,00	**53**	72,00	327	69,00
26	57,00	266	44,20	**54**	71,00	327	64,00
27	69,20	630	34,00	**55**	75,00	241	72,00
28	73,00	617	32,55				

3. MODEL FORMULATION

The model formulation (Eq. 1) to predict the operating speeds is finalized to determination of indications of general validity from a significant sample (n = number of tangents = 36) of experimental observations (s = number of sites = 55), realized on roads that are assailable for typological and functional features.

The stations on tangents were located in the center, in starting and in finishing, and in the quarters of tangents along the roads S.S. 426, S.P. 262, S.P. 52, S.P. 30b and S.P. 312.

The best performances are insured from a model in which the operating speed on tangent depends from the length of the section and from the speed along the preceding curve (Figure 1).

$$V_{85T} = 15.45 \cdot Log_{10}\left(L_T\right) + 0.57 \cdot V_{85Cp} \qquad (\rho^2 = 0.73) \qquad \text{(Eq. 1)}$$

The speed on preceding curve (V_{85Cp}) can be esteemed with a model formalized in a preceding study in which the speed on curve depends from the CCR and from the "environmental" or "desired" speed (V_{env}) of the homogeneous section which the same curve belongs; the Venv is function of the mean CCR and of the lane width (L) of the road section.

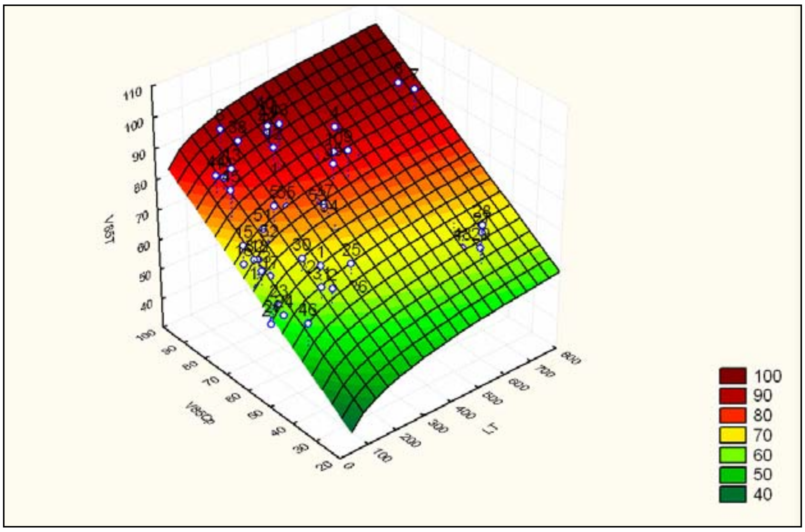

Figure 1 Plot of the model

The proposed model can predict the operating speeds on tangent on two-lane rural roads located in territories with level terrain (i << 6%) with tangent length from 50 to 750 m, pavement conditions not too good, lane width from 2.5 to 5.0 m and access density 6/Km The regression parameter of the equation is statistically significant at a less p-level. In Figure is showed the performance of the model.

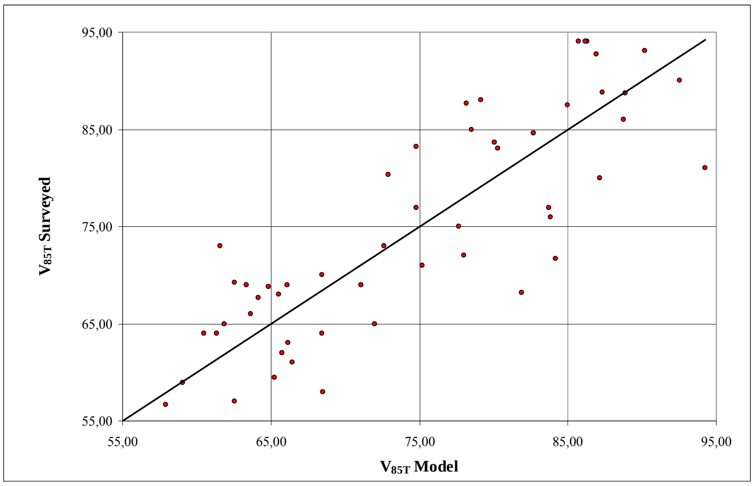

Figure 2 Performance of the model

Driver speed behaviour on tangent, grows to desired speed and depends on tangent length and operating speed of the preceding curve. To complete the analysis of the calculated equation it is important to observe that the environmental speed does not figure directly in the equation as an independent variable but indirectly through the speed of the preceding curve.

However a large data collection has already been processed and some single data are now available. A statistical analysis has been carried out on tangents and their preceding curve in order to predict the maximum speed reached on tangents. It is possible to determine if drivers reach and hold the environmental speed for a certain length, knowing the parameters of the model. But if the tangent is longer than the bonds related to the model, the operating speed on tangents of two-lane rural highways becomes the environmental speed of the homogeneous section to which the tangent section belongs to. Instead, if the operating speed on tangent section calculated with the model exceeds the value of the environmental speed of the homogenous section to which the tangent belongs, obviously the operating speed of the tangent must be considered equal to the environmental speed.

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.

In order to single out the road sections with homogenous horizontal alignment characteristics to associate with a single value of environmental speed, we referred to indications of the German standard. This provides a method for singling out homogenous road sections by evaluating the Curvature Change Rate ($CCR = \Sigma_i|\gamma_i|/d$ [gon/km]).

The authors evaluate the regression equations (Eq. 2) with two independent variables the curvature change rate CCR (gon/km) and the lane width L (m). The regression parameters of the analysis are statistically significant (P-value < 0,05) for the collected data.

$$V_{env} = 82.84 - 0.10 \cdot CCR + 3.44 \cdot L \qquad (\rho^2 = 0.84) \qquad \text{(Eq. 2)}$$

A statistical analysis was carried out taking into consideration the data on speed in both directions along 58 curves belonging to three different roads. The dependence of speed was evaluated according to two variables: the environmental speed V_{env} along the homogenous section which the curve belongs to and the curve radius R.

The following equation (Eq. 3) for the prediction of operating speed on curves V_{85c} was obtained. Also in these equation regression parameters are statistically significant (P-value < 0,05).

$$V_{85c} = -2073.70 \cdot \left(\frac{1}{R}\right) + 31029.00 \cdot \left(\frac{1}{R}\right)^2 + 0.87 \cdot V_{env} \qquad (\rho^2 = 0.81) \qquad \text{(Eq. 3)}$$

Where V_{85c} is the operating speed on curve, R is the radius (30 ÷ 5000 m), V_{env} is the environmental speed, CCR is the curvature change rate and L is the lane width (2,5 ÷ 5 m).

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.

The sensitivity analysis has been carried out giving particular attention to curves near the border between two homogenous sections.

These curves will be travelled with speeds that differ significantly according to the direction, so 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 (Dell'Acqua et al., 2007b).

4. CONLUSION AND OUTLOOK

The Province of Salerno road network is very big (about 3000 Km) and has very different environmental features, referring to different criteria and standard of road design (in some cases no more consistency with the actual conditions of traffic flow).

For facing the mutable conditions of traffic flow, the Administration conforms some road sections on addresses and criteria conditioned sometimes by the characteristics of the same infrastructures. They are very different in layout, environmental context and period of construction. So the Administration introduced nonhomogeneity elements in road design and environmental assessment along the different layouts.

The improvement of road safety needs generalized or located interventions of adjustment to effect according to coordinates actions. Working with the other administrations, the Province of Salerno individualizes and defines the interventions and the priorities of realization.

The designing of adjustments requires a series of analysis activity on the road network. So the University of Naples realizes, for the Province of Salerno, speed measurements, analysis of the geometric and functional features of the roads, surveys of traffic and crashes data. The setting and the validation of prediction models of operating speed in free flow conditions, and the study of driving behaviour, are some of the most important objectives of these activities to realize improvements of road network.

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