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STATISTICAL ANALYSIS OF V_{85} MODELS ON HORIZONTAL CURVES OF ITALIAN TWO-LANE RURAL ROADS

Claudia Piras, Ph.D. Eng.
Department of Land Engineering
University of Cagliari - ITALY

Francesco Pinna, Research Assistant
Department of Land Engineering
University of Cagliari - ITALY

Abstract

Injuries are one of the main causes of death according to the new report published by WHO (World Health Organization). For this reason the attention of road safety research especially regards the study of the relationship between driver and road environment, in order to obtain a reduction of injuries number and severity.
Several studies were developed to find the relationships between road geometrical and design features and driver behaviour.
Generally driver behaviour is expressed by the operating speed. In scientific literature there exist several analytical models to calculate real speed as a function of geometrical road characteristics.
In this work some of them were collected and their hypotheses were studied. Generally the values of these parameters were similar in the majority of the models and they can be found in the Italian rural roads in order to make surveys.
The next step was the statistical analysis of the existing models with hypotheses that could be applied to Italian roads in order to define the best one.

Résumé

Blessent sont l'une des plus importantes causes de décès selon le nouveau rapport publié par l'OMS (Organisation mondiale de la santé). Pour cette raison, l'attention de la sécurité routière en particulier ce qui concerne l'étude de la relation entre le conducteur et l'environnement routier, en vue d'obtenir une réduction des blessures "nombre et la gravité.
Plusieurs études ont été développées pour rechercher les relations entre la route et les caractéristiques géométriques et le comportement des conducteurs.
En général, le comportement du conducteur est exprimée par la vitesse d'exploitation. Dans la littérature scientifique existe plusieurs modèles d'analyse pour calculer la vitesse réelle en fonction des caractéristiques géométriques des routes.
Dans ce travail, certains d'entre eux ont été collectées et de leurs hypothèses ont été étudiées. En général, les valeurs de ces paramètres ont été similaires dans la plupart des modèles et on peut les trouver dans l'Italie des routes rurales afin de faire des enquêtes.
La prochaine étape est l'analyse statistique du modèle existant avec l'hypothèse qui peut être appliquée à des Italiens en route afin de définir le meilleur.

INTRODUCTION

Road crashes are one of the main causes of death among young people according to the new report published by WHO (World Health Organization). For this reason the main interest of road safety research is the study of relationships between driver behaviour and road environment. Several research studies remark that crash probability increases in lack of design consistency. In fact, geometrical and design road features involve in driver behaviour; so geometric design consistency criteria can improve road safety conditions. For this reason some works have been developed in order to find a methodological approach to define design consistency and the effects of road features on driver behaviour.

Several studies have showed that the car speed plays an important role in accident occurrence, in particular when considerable speed reductions are required.
Operating speed (V_{85}) is one of the most wide-spread driver behaviour analytical approaches. Besides it is an analytical expression of real speed. AASHTO defines operating speed as "the speed at which drivers are observed operating their vehicles during free-flow conditions, the 85th percentile of the distribution of observed speeds is the most frequently used measure of the operating speed associated with a particular location or geometric feature" [1].

A lot of analytical models calculate V_{85} as a function of geometrical road characteristics. The most common operating speed models, presented by several researchers of different countries, provide V_{85} as a function of the Curvature Change Rate of the single curve (CCRs) or of the horizontal curve radius (R). The most of operating speed studies focus on horizontal curves of two-lane rural highways because along which accident rate is up to 4 times higher than along tangents [2].

This paper describes the test (through statistical analysis and with data collected on a local highway) of the existing curve speed prediction models. The most important national and international models, that permit to calculate operating speed, have been reviewed.
The hypotheses used as basis for these models, like type of road cross section, longitudinal grade, etc., have been studied. A lot of these hypotheses are similar.
Then, among the international models, those applicable on Italian rural roads have been chosen.

The horizontal curves, on the Italian roads (within Sardinian road network), have been chosen in order to test the international models.
Italian two-lane rural roads can be divided in two main categories:

- two lane rural highways designed before 2001;
- two lane rural highways designed after 2001.

The new Italian standard [3] came into force in November 2001. The main differences between these two road categories are:

- on two-lane rural roads designed before 2001 there are not transition curves;
- the new Italian standard forces designer to insert transition curves (preceding and succeeding horizontal curve).

Then speed surveys have been carried out. Some of the main international models have been tested (through statistical analysis) on Italian two-lane rural roads in order to find out which of them are applicable on Italian highways. This has underlined the existence of strong difference in the application of the international models, between rural roads designed before and after 2001.
The research work carried out by the Department of Land Engineering of the University of Cagliari aims to develop a speed model relating road features to operating speed.

1. Background

The design standard of several countries uses operating speed to calculate the main geometrical road characteristics. Numerous methodologies are available to find the main road features (of horizontal alignment) influencing operating speed value. The problem is to define an analytical model to calculate V_{85} as a function of horizontal alignment elements. A lot of international models allow to calculate operating speed as a function of roads features, among which: lane width, shoulder width, degree of curvature, radius of horizontal curve, length of tangent, longitudinal grade, etc.

Along horizontal curves, accident rate is up to 4 times higher than along tangents [2]. For this reason, operating speed models for curves have been widely developed [2]. In fact, the most of operating speed studies focus on horizontal curves of two-lane rural highways. The form of the operating speed prediction models and the number of variables used in each of them vary considerably. The most common operating speed models, proposed by many researchers of different countries, provide V_{85} as a function of the Curvature Change Rate of the single curve (CCRs) or as a function of the horizontal curve radius (R).
The CCRs is calculated by the following equation:

$$CCRs = 63700 \frac{\left(\frac{L_1}{2R} + \frac{L_2}{R} + \frac{L_3}{2R} \right)}{L} \qquad (1)$$

(where: CCRs [gon/km], R = radius of circular curve [m], L_1 and L_3 = lengths of clothoids, preceding and succeeding the circular curve, [m], L_2 = length of circular curve [m], L = overall length of curve section [km], 63700 = 200/π × 103).

Some of the international analytical models allow to calculate V_{85} as a function of CCRs or R and other parameters like longitudinal grade, length of adjacent tangents, lane width, and so on; but different research works confirm that the radius of circular curve and CCRs are the most important factors affecting the driver cruise speed on horizontal curves.
The other models are more complex to use even if they are more complete. Besides statistical literature shows that, fixed the number of samples, the increasing of the interpolating curve degree produces an increase in the coefficient of determination value (R^2), but this does not correspond to an equal increase in model accuracy.
Consequently the models with only one variable are more widespread.

2. Data collection

In this part of the paper a lot of existing international models (available for horizontal curve) are examined. The hypotheses (type of road cross section, longitudinal grade, and so on) of each of them have been studied in order to verify those applicable on Italian rural highways and choose the Italian road sections where surveying the operating speed.
The local two-lane rural road curve sections chosen for the speed surveys have the following characteristics:

- 3.00 m ≤ width of lane ≤ 3.75 m;
- 0 m ≤ width of shoulder ≤ 1.50 m;
- longitudinal grade ≤ 5% (even if its effect is generally ignored).

In this paragraph several international models, that permit to calculate operating speed as a function of curve radius or Curvature Change Rate of the single curve, are reviewed (table 1). All operating speed models considered in this paper have been developed through regression analysis of the adopted speed on two-lane rural roads.

MODELS	**R^2**
McLean (Australia): $V_{85} = 101.2 - 0.043CCRs$ [4] [5]	0.87
Lamm et al. (Germany): $V_{85} = \frac{10^6}{(8270 + 8.01CCRs)}$ [6] [5]	0.73
Lamm et al. (Germany): $V_{85} = 95.6 - 0.0438CCRs$ [6] [5]	0.82
Lamm e Choueri (U.S.A.): $V_{85} = 93.85 - 0.05CCR_s$ [7] [8]	0.79
Krammes e Ottesen (U.S.A.): $V_{85} = 103.04 - 0.053CCR_s$ [9]	0.80
Psarianos et al. (Greece): $V_{85} = \frac{10^6}{(10150.1 + 8.529 \times CCRs)}$ [5]	0.81
Choueri et al. (Lebanon): $V_{85} = 91.03 - 0.056CCRs$ [25]	0.81
Lamm et al. (Germany): $V_{85} = 94.398 - \frac{3188.656}{R}$ [6] [5]	0.79
Krammes e Ottesen (U.S.A.): $V_{85} = 103.66 - 1.95\frac{1746.38}{R}$ [9]	0.80
Kannellaidis et al. (Greece): $V_{85} = 129.88 - \frac{623.1}{\sqrt{R}}$ [10]	0.78
Bird et al. (U.K.): $V_{85} = 104.379 - \frac{4698.216}{R}$ [11]	0.95
Hassan et al. (Canada): $V_{85} = 94.30 + 8.67\frac{R^2}{10^6}$ [12]	n.a.*
Islam et al. (U.K.): $V_{85} = 103.03 - 2.41\frac{1746.38}{R} - 0.029\left(\frac{1746.38}{R}\right)^2$ [13]	0.98
Crisman et al. (Italy) : $V_{env} = 200.97CCR^{-0.16}$ [2]	0.87
Crisman et al. (Italy): $V_{85} = \frac{V_{env}}{1 + \frac{4.75}{R^{0.58}}}$ [2]	0.88
Where: *n.a. = not available; V_{85} [km/h], CCRs [gon/km]; R [m]	

Table 1 - Existing operating speed prediction models using CCRs or R value

Graphical representations of these spot speed models, developed in those countries, are given next. These show the relationships between the operating speed on curve and the Curvature Change Rate of the single curve (figure 1a) or the radius of the circular curve (figure 3a).
The first graph (figure 1a) underlines that operating speed is always in inverse proportion to CCRs. Besides, the models trends of McLean (Australia), Lamm et al. (U.S.A.) and Krammes and Ottesen (U.S.A.) are very similar.
American researchers, such as Krammes and Ottesen, worked on the Lamm model (developed in Germany).
Lamm, after several studies, compiled two different equations for both German and American highways. This also confirms the strong relationship between the analytical model and the country where speeds are surveyed. In fact, Lamm drew up two different analytical models making speed surveys in two different countries (figure 1a). The differences between operating speed values calculated through the two Lamm models are high almost 30÷40 km/h, and also the speed differences between the Choueri et al. model (Lebanon) and the Lamm et al. model (Germany) are high almost 30 km/h.
Generally driver behaviour is influenced, for example, by society, driving style, and so on. American researchers, such as Krammes and Ottesen, developed an analytical model to calculate the speed on curves, as a function of both the Curvature Change Rate of the single curve (figure 1a) and the horizontal curve radius (figure 3a). The second graph underlines a similar trend among the Bird et al. model (U.K.) and the Islam et al. one (U.K.) (the two distribution curves almost overlapped): both have been drawn up in United Kingdom. This underlines a strong link between country (where the speed is surveyed and data are collected) and analytical model characteristics.

This paper describes the test of the existing curve speed models for two-lane rural roads through data collected on horizontal curves of local highways, according to the following steps:

- the most important national and international models, able to calculate operating speed, have been reviewed;
- the curve sections, where surveying real speeds in order to calculate operating speed and verify statistical significance of the existing models, have been chosen.

The horizontal curve sections have been chosen on the basis of the following characteristics:

- two-lane rural roads;
- lack of crossroads;
- lack of intersections and private accesses;
- lack of elements which could influence driving behaviour, such as work zone signs;
- longitudinal grade less than 5%;
- low traffic flow;
- 3.00 m ≤ lane width ≤ 3.75 m;
- shoulder width less than 1.50 m.

These assumptions are equal to the literature model ones, in order to permit a next comparison. The operating speed models have been deduced through regression analysis of collected speeds of free passenger cars (headway of at least 5 seconds).
The Italian two-lane rural roads designed before and after 2001 have the same preceding characteristics. The new Italian standard orders, in the horizontal alignment, an engagement of transition curves. Besides, on equal design speed, Italian rural roads designed after 2001 have longer curve radii than which designed before 2001. For this reason during this work two statistical analyses have been carried out: on roads designed before and after 2001.
The surveys have been carried out during the daytime, with dry pavement and good weather conditions. These have been carried out in the middle of the examined horizontal curves. For each site, speeds of over 300 vehicles per travelling direction have been recorded in order to have a number of

isolated passenger cars not lower than 100. Therefore totally more than 14000 speed data have been collected. Afterward the collected data have been processed in order to obtain 85th percentile.
The analysis is based on the study of 24 curve sections: 15 of roads built before 2001 and 7 inserted into an alignment designed in accordance with the in force rules. A radar instrumentation has been used for speed measurements. The distance between the radar and the first lane markings has been shorter than 2,00 meters and the height of installation has been lower than 1,00 meters. By respecting these distances, it has been possible to exploit the software installed on radar. It allows to have an automatic setting of the equipment. The instrumentation has been hidden in order to not influence driver behaviour. The surveys have been made on both travelling directions. The table 2 shows a summary of data collected.

	CURVE	**R** [m]	**L** [m]	**CCRs** [gon/km]	V_{85} [km/h]
designed before 2001	1	220	68	290	76
	2	65	33	990	61
	3	250	37	255	81
	4	75	39	849	69
	5	80	74	796	60
	6	60	59	1062	61
	7	60	33	1062	61
	8	580	222	110	98
	9	475	104	134	98
	10	407	134	157	102
	11	565	95	113	95
	12	338	132	189	93
	13	194	97	328	81
	14	55	80	1158	49
	15	50	40	1274	48
designed after 2001	1	1200	1190	45.57	119
	2	1500	128	37.35	128
	3	1500	135	32.06	135
	4	1500	133	30.31	133
	5	1500	133	35.47	133
	6	1500	135	32.33	135
	7	1515	137	33.65	137
Where: R, horizontal curve radius, [m]; L, length of horizontal curve, [m]; CCRs, curvature change rate of the single curve, [gon/km]; V_{85}, operating speed, [km/h].					

Table 2 - Horizontal curve geometrical features and operating speed

3. Data analysis

Every existing models has been compared with operating speed calculated on local horizontal curve sections, in order to verify their statistical validity on Italian roads.
Moreover, for each examined model, the following statistical parameters have been calculated:

- standard error of estimate of V_{85} on CCRs, given by the following expression:

$$s_{V85CCRs} = \sqrt{\frac{\sum (V_{85} - V_{85stim})^2}{n}} \tag{2}$$

- standard error of estimate of V_{85} on CCRs, given by the following expression:

$$s_{V85CCRs} = \sqrt{\frac{\sum (V_{85} - V_{85stim})^2}{\sum V_{85stim}{}^2}} \tag{3}$$

- the coefficient of determination (applied to the observed data, which is, in this paper, marked with R^{2*} so as to distinguish it from its typical coefficient, reported in bibliography) given by the following expression:

$$R^{2*} = 1 - \frac{\sum (V_{85} - V_{85stim})^2}{\sum (V_{85} - \bar{V}_{85})^2} \tag{4}$$

The existing models, in order to be analysed statistically, can be divided into two groups:

- expressing operating speed as a function of CCRs;
- expressing operating speed as a function of R.

3.1. Statistical analysis of models with operating speed as a function of CCRs

Graphical representations of these spot speed models, developed in different countries, are given in the following. These show relationships between the operating speed on curve and the CCRs.
The first graphic representation includes the operating speeds which are calculated on Italian two-lane rural roads designed before 2001.

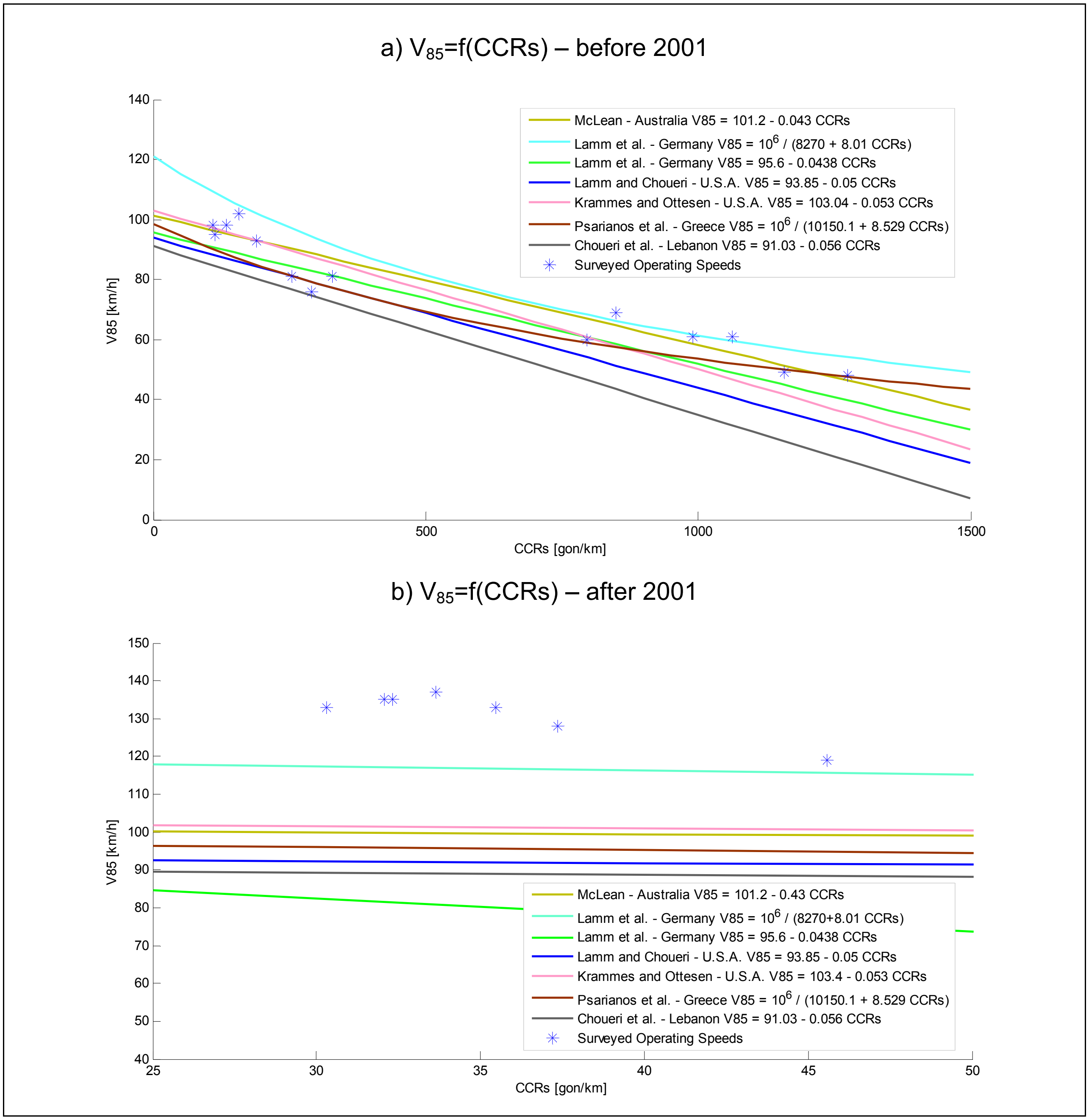

Figure 1 - Graphical representation of existing models with V_{85}=f(CCRs) and surveyed speed, elaboration made with MatLab 7.0

The graph underlines that making a statistical analysis of Choueri et al. model (Lebanon) comes to naught: the cloud dispersion of the calculated operating speed is totally over the model trend. The second graph includes V_{85} calculated on highways built after 2001: the calculated operating speeds are totally external from the cloud dispersion of model points.
For this reason, the following statistical analysis have been gathered only on Italian rural roads designed before 2001, in order to identify the most representative existing models for this case.

Data obtained by statistics analysis are collected in table 3, in which R^2 is the determination coefficient that is stated by the authors of the model and R^{2*} indicates the determination coefficient that is calculated on the basis of the data collected locally.
None of the chosen models is applicable to the rural roads designed in accordance with the new guidelines in force in Italy. In fact, for all the tested models is detected a strong difference between the surveyed operating speed and the model trend. In all cases the surveyed operating speeds exceed the operating speed values that are calculate through the models.

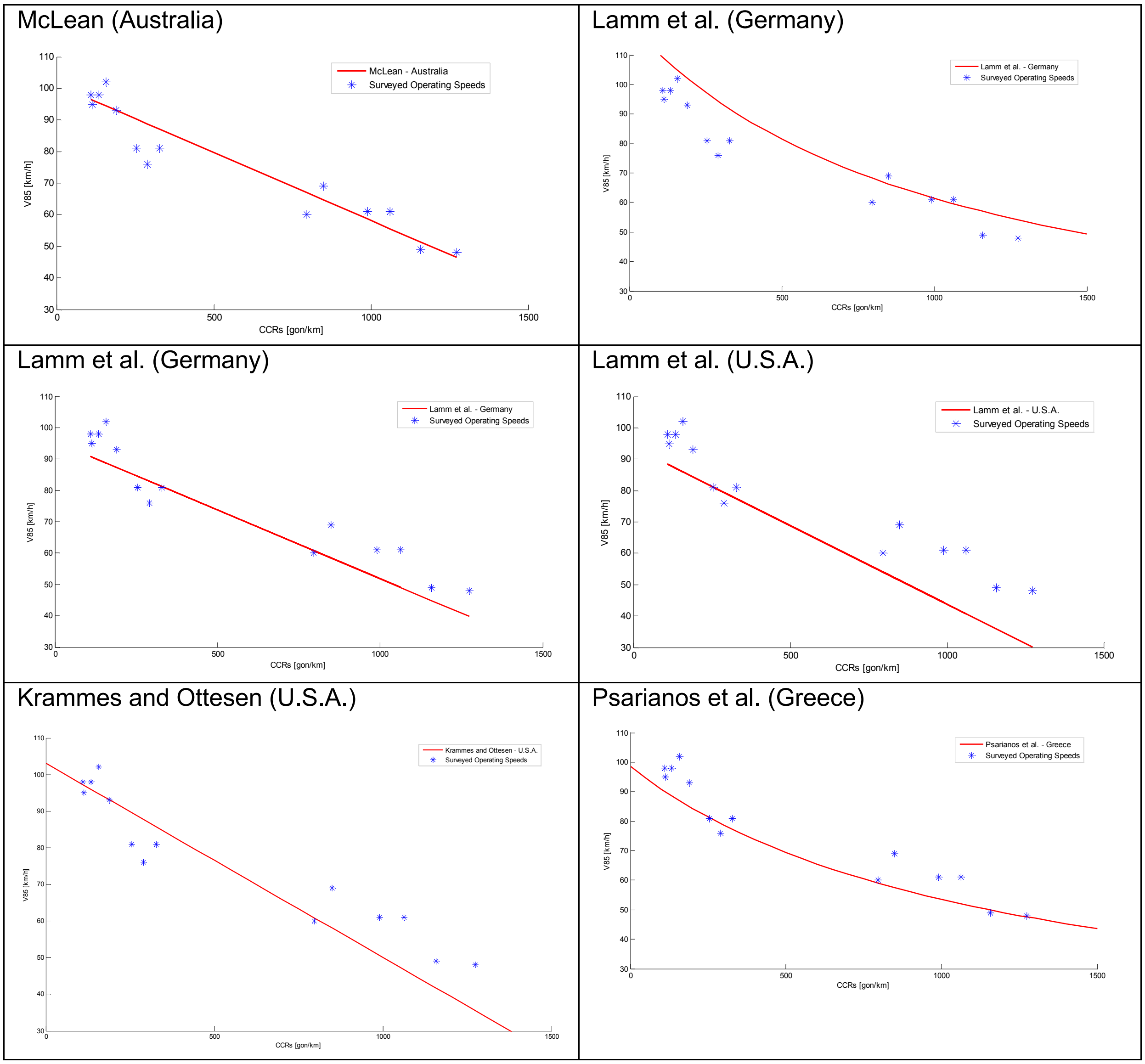

Figure 2 - Comparison between existing models with V_{85}=f(CCRs) and surveyed operating speeds (road designed before 2001), elaboration made with MatLab 7.0

As regards roads designed before 2001, five of the chosen models can be considered representative. The best model is the McLean et al.'s one. This model, which has been drawn up in Australia, assumes a determination coefficient, calculated on the basis of the data collected values, higher than which stated by the authors of the model. In fact, McLean declared a

determination coefficient equal to 0.87, while on the basis of collected operating speeds, it is calculated equal to 0.90. Another model with a good level of representation of the observed data is the one drawn up by Psarianos et al. (Greece). Also in this case statistical analysis has revealed a R^{2*} (=0,83)> R^2 (=0,81).
Finally, regarding the two Lamm et al. models: the one built in Germany has R^{2*} = 0.80; while the model drawn up in the United States, has a very low determination coefficient, R^{2*}= 0.47. Krammes and Ottesen operating speed model, drawn up in the United States, has a good determination coefficient, R^{2*} = 0.77.

MODELS	**R^2**	**Standard error**	**Relative standard errror**	**R^2***
McLean (Australia)				
$V_{85} = 101.2 - 0.043CCRs$	0.87	5.733	0.073	0,90
Lamm et al. (Germany)				
$V_{85} = \frac{10^6}{(8270 + 8.01CCRs)}$	0.73	9.623	0.113	0,71
$V_{85} = 95.6 - 0.0438CCRs$	0.82	8.020	0.111	0,80
Lamm et al. (U.S.A.)				
$V_{85} = 93.85 - 0.05CCR_s$	0.79	13.012	0.191	0,47
Krammes e Ottesen (U.S.A.)				
$V_{85} = 103.04 - 0.053CCR_s$	0.80	8.709	0.115	0,77
Pasarianos et al. (Greece)				
$V_{85} = \frac{10^6}{(10150{,}1 + 8{,}529 \times CCRs)}$	0.81	7.456	0.104	0,83

Table 3 - Summary table of existing models statistical analysis, V_{85} = f (CCRs) (rural road designed before 2001)

3.2. Statistical analysis of models with operating speed as a function of R

Models with operating speed as a function of horizontal curve radius have been also developed. The next figure shows the change of the V_{85} values, for each model, according to the circular curve radius.
The first graph (figure 3a) compares the model trend with the operating speed values, which have been surveyed on the rural roads built before 2001. The second one (figure 3b) compares the model trend with the operating speed values, which have been surveyed on the rural roads built after 2001.

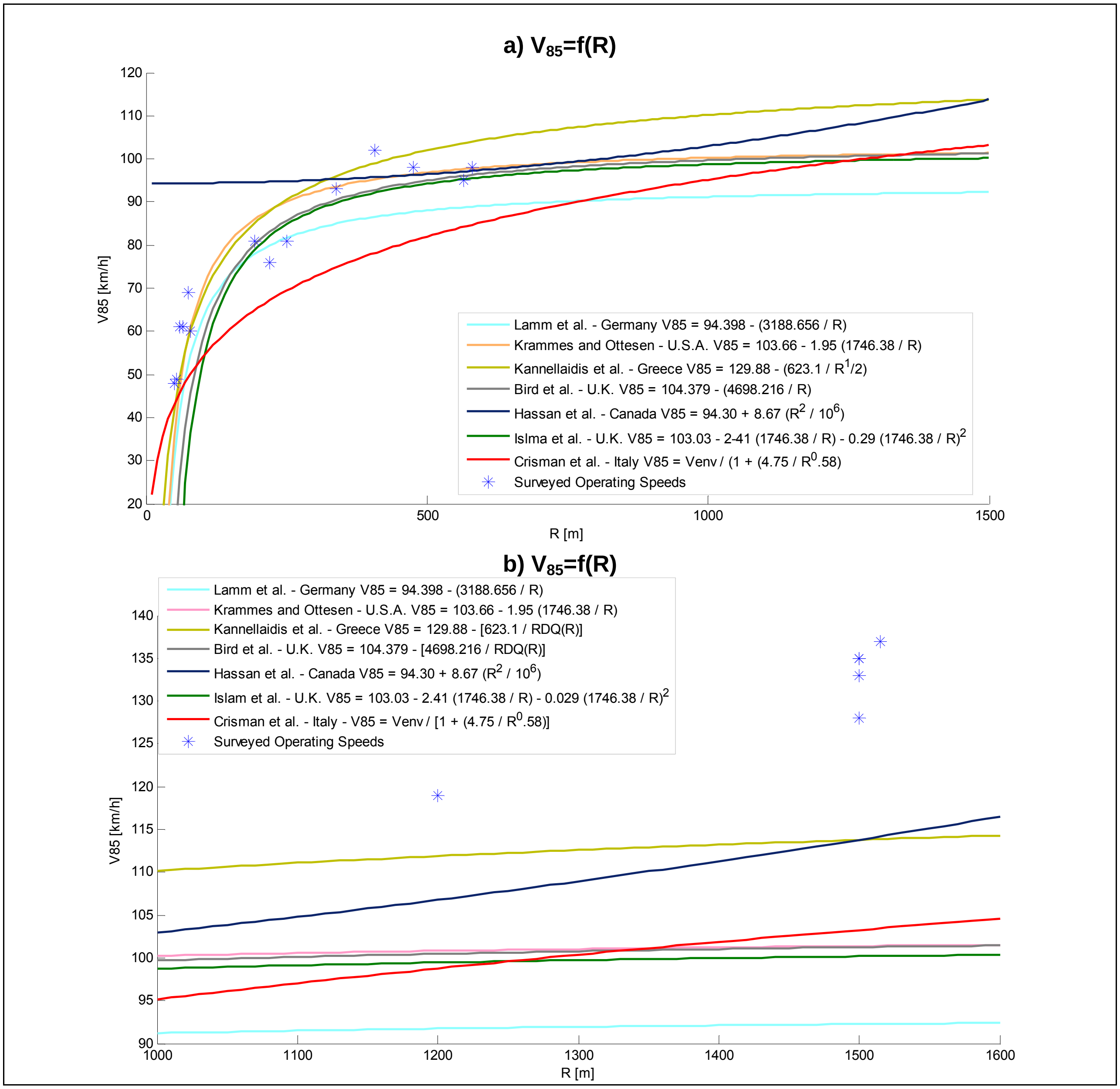

Figure 3 - Graphical representation of existing models with V_{85}=f(R) and surveyed speeds, elaboration made with MatLab 7.0

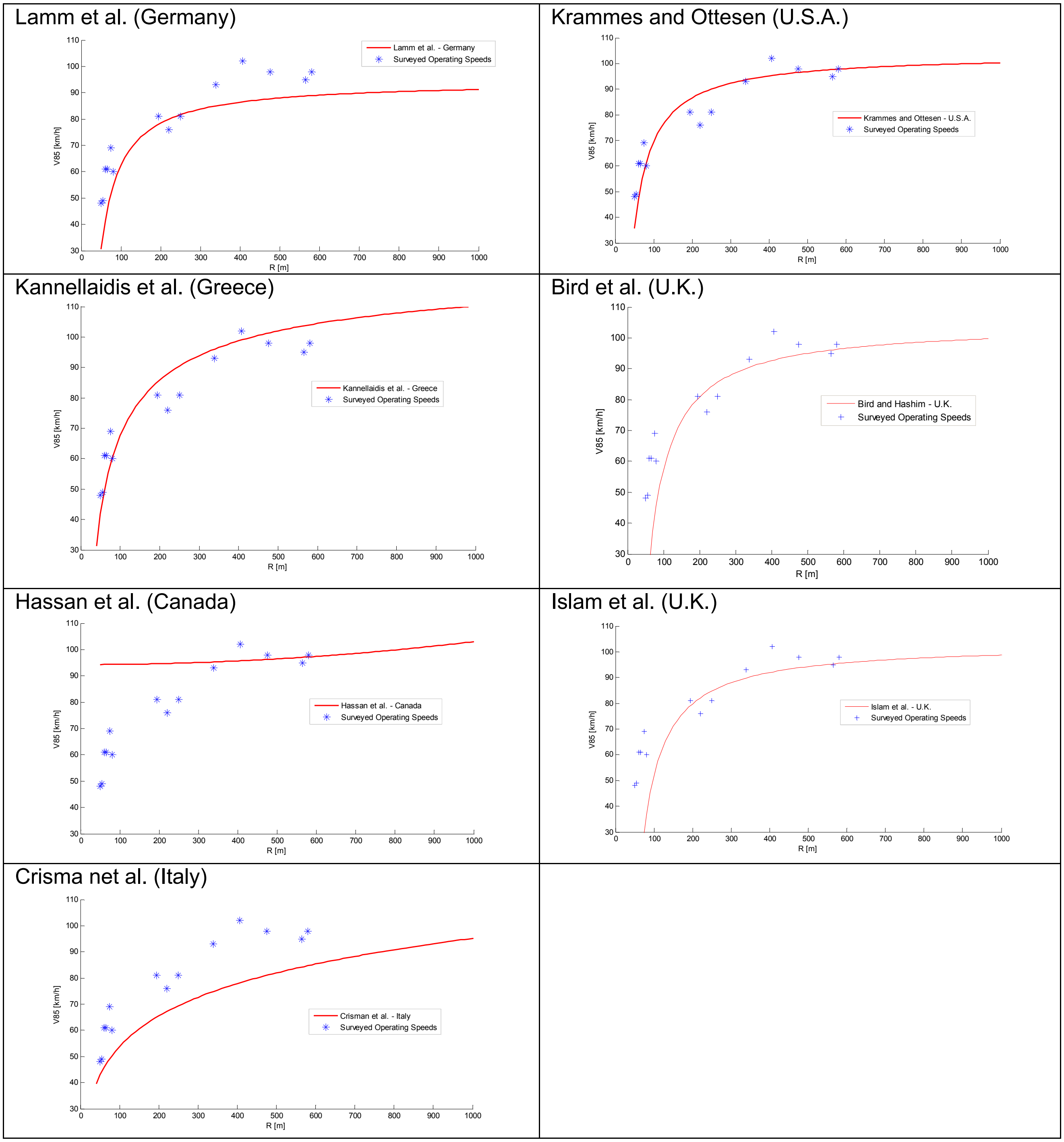

Figure 4 - Comparison between existing models with V_{85}=f(R) and surveyed operating speeds (road designed before 2001)

As in the preceding case, in the examination of existing models with V_{85} expressed as a function of radius R, it is possible to underline the following aspects:

- operating speeds, surveyed on the Italian rural roads (designed before 2001), do not fall within the dispersion cloud of any existing chosen models;
- all V_{85} values, surveyed on Italian curves (designed after 2001), are higher than values which are calculated through the existing models.

For these reasons, only the comparison between the existing models trend and the operating speed values (surveyed on rural roads designed before 2001) are showed below.
Data obtained from statistics analysis are collected in Table 4, in which R^2 is the determination coefficient declared by the authors of the model and R^{2*} indicates the determination coefficient calculated on the basis of the collected data values.
None of the chosen existing models is applicable on Italian rural roads designed after 2001. Only two, among the existing models tested, are applicable locally on the roads built before 2001: Kannellaidis et al. and Krammes and Ottesen ones.
The former, which has been developed in Greece, has a determination coefficient, R^{2*} = 0.81, higher than one declared by the researcher, R^2 = 0.78. The latter, which was developed by Krammes and Ottesen in the United States, has a good determination coefficient for locally data collected (R^{2*} = 0.77). This is comparable with the Krammes and Ottesen model that expresses V_{85} as a function of CCRs.

MODELS	**R^2**	**Standard error**	**Relative standard error**	**R^2***
Lamm et al. (Germany)				
$V_{85} = 94.398 - \frac{3188.656}{R}$	0.79	12.554	0.183	0.51
Krammes e Ottesen (U.S.A.)				
$V_{85} = 103.66 - 1.95\frac{1746.38}{R}$	0.80	8.669	0.114	0.77
Kannellaidis et al. (Greece)				
$V_{85} = 129.88 - \frac{623.1}{\sqrt{R}}$	0.78	7.734	0.099	0.81
Bird et al. (U.K.)				
$V_{85} = 104.379 - \frac{4698.216}{R}$	0.95	21.064	0.305	not valid
Hassan et al. (Canada)				
$V_{85} = 94.30 + 8.67\frac{R^2}{10^6}$		25.995	0.273	not valid
Islam et al. (U.K.)				
$V_{85} = 103.03 - 2.41\frac{1746.38}{R} - 0.029\left(\frac{1746.38}{R}\right)^2$		33.126	0.497	not valid
Crisman et al. (Italy)				
$V_{85} = \frac{V_{env}}{1 + \frac{4.75}{R^{0.58}}}$	0.88	14.490	0.227	0.35

Table 4 - Summary table of existing models statistical analysis, V_{85} = f (R) (rural road designed before 2001)

CONCLUSIONS

In general among the chosen existing models there are several differences. Some of them have a good representation level of surveyed V_{85} distribution on Italian roads built before 2001.
The statistical analysis had showed that the operating speed values surveyed on roads designed after 2001, do not belong to the dispersion cloud of any existing models chosen. For this reason the statistical analysis has been carried out only on Italian rural roads that have been designed before 2001.

Among the studied existing models with V_{85} = f (CCRs), the McLean et al.'s one (Australia) is very good in order to represent operating speed surveyed on Italian rural roads (roads designed before 2001 only). It assumes, as regards the distribution of speeds calculated locally, a determination coefficient higher than one which has been calculated by McLean in Australian rural roads. Another model with a good level of representation of the data observed is the Psarianos et al.'s one (Greece), which has a coefficient of determination, calculated on the data observed, higher than one produced by Greek surveys. Finally, one of the Lamm et al. models (Germany) has a high coefficient of determination with regard to local surveys.

Several studies show that operating speed models are country dependent or even region dependent. In fact, a strong relationship, between the model and the context in which the showed analysis is executed, exists. This underlines the importance to create ad hoc models for each country.
The fact that none of the chosen models is applicable on Italian rural roads designed after 2001 makes scientific curiosity arise and will also be topic of research. For this reason further speed data will be collected in other sites in order to find one relationship, among those analysed, representing operating speed trend on rural roads designed in accordance with the new Italian Road Guidelines.

Several studies show that the car speed plays an important role in accident occurrence, in particular when considerable speed reductions are required. On one hand, the standards of various countries are based on the operating speed concept; on the other hand most of the guidelines of the others refer to this concept only in the post-road design or they refer only to the design speed concept. The New Italian guidelines (in force since November 2001) are still based on design speed concept although several studies show that this speed is surpassed by driver. This creates big problems regarding road safety.

This paper represents a first step, of a research project, that, starting from the existing models, wants to create a nationally valid model. The following step will be the selection of other sites in order to find out which are the best models representing the driver behavior on rural roads designed in accordance with the new Italian Road Guidelines. These speeds will be collected on two-lane rural roads, having, obviously, similar geometric features to the roads considered by the research works of different countries that have been previously analysed.
Finally the target is to improve these prediction models. So it will be necessary to enlarge sample data and consider some other independent variables, as available sight distance, longitudinal grade, and so on.

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