



DEVELOPMENT OF A LOCAL OPERATING SPEED MODEL FOR CONSISTENCY ANALYSIS INTEGRATING LASER, GPS AND GIS FOR MEASURING VEHICLES SPEED

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Abstract. Design consistency refers to the condition whereby roadway geometry does not violate driver expectations. As such, most evaluations of highway geometric design consistency are based on operating speed profile analysis, which relates safety with speed variability. This paper presents a new operating speed model in which the operating speed depends on curve radius. The model uses car speeds collected for 42 curves on two-lane rural highways in South-west Spain. A comparison between this model and several models developed previously in other European countries has been made. This comparison emphasizes the influence of the model chosen on the results obtained. In addition, the incorporation of laser, GPS and GIS for vehicle speed measurement in the inexpensive yet reliable manner is discussed.

Keywords: laser, speed predictions, highway design, consistency, Global Positioning System (GPS), Geographic Information System (GIS).

1. Introduction

Design consistency refers to the condition in which roadway geometry does not violate driver expectations. As such, the methods most widely used to date to evaluate this consistency have been based on operating speed profile analysis, estimating the operating speed at which vehicles circulate throughout the segment under study and establishing comparisons with defined criteria.

Several models have been developed to predict operating speed. As a result, different variable types have been used to analyse actual driver speed behaviour, including functional factors (pavement distress, distance to intersections, number of residential driveways per kilometre, sight distance, traffic), geometric factors (radius of circular curve, etc.), and speed factors (some operating speed models of an element depend on the speed of other alignment elements) (Dell'Acqua 2011; Dell'Acqua, Russo 2011; Discetti *et al.* 2011). However, most researchers have proposed determining the operating speed using geometric characteristics of the horizontal alignment, such as the radius of the circular curve (r), the degree of curvature (DC), the deflection angle (Ω) and the length of the circular curve (L_c). The degree of curvature (DC) is the ratio between the curve length and its radius.

Most models use a single variable, usually the radius of circular curves or the degree of curvature (DC) (Castro

et al. 2008; Kanellaidis *et al.* 1990; SETRA 1986: *Vitesse Pratiques et Géométrie de la Route*; Lamm, Choueri 1987; McFadden, Elefteriadou 1997; Morrall, Talarico 1994; Pérez *et al.* 2010). From these models it is deduced that if radius increases (or degree of curvature decreases), vehicle speeds increase. The model proposed by Kanellaidis *et al.* (1990) uses only one variable, namely the radius, although this model is not linear as the operating speed on the curve depends on the square root of the radius. This study was performed in Greece using a sample of 58 curves; the value of the coefficient of determination (R^2) was 0.78.

Although most univariate models use radius or degree of curvature as the independent variable, some researchers have proposed models that make use of other independent variables, such as deflection angle (Ω) (Gibrel *et al.* 2001) or curvature change rate (CCR) (Pérez *et al.* 2010), the latter of which is the absolute angular change (measured in degrees or decimal degrees, depending on the authors) in the horizontal direction per unit distance (measured in kilometres).

Other authors have proposed models with several variables based on the geometric characteristics of the horizontal alignment, such as length of horizontal curve, deflection angle, and degree of curvature or curve radius (Krammes *et al.* 1995).

Furthermore, there are also models in which, in addition to the geometric characteristics of the horizontal alignment, the cross-sectional characteristics (lane width (LW), shoulder width (SW) or superelevation (e)) are taken into account (Lamm, Choueiri 1987; SETRA 1986). The effect of lane width on speed prediction has been studied using a French model developed by SETRA (1986), which used different equations depending on the lane width.

Along similar lines, Fitzpatrick *et al.* (2000) have proposed models that use the horizontal radius as the independent variable but select the equation to be applied on the basis of the characteristics of the horizontal and vertical alignment. Likewise, several Italian researchers have proposed curve speed models that depend on the CCR value of the curve (or the radius) and on the vertical grade (i) (Bevilacqua *et al.* 2004).

In addition to geometric factors, some curve-speed prediction models also take into consideration other factors, such as functional or speed factors. Thus, Dell'Acqua and Russo (2011) have proposed two models for operating speeds on horizontal curves: one for horizontal curves with a mean CCR of less than 240 gon/km (51 curves, $R^2 = 0.81$) that uses the variables CCR, width of travel lanes plus shoulders, length of single circular curve, number of residential driveways per kilometre, length of preceding tangent, intersection distance indicator and pavement distress indicator, and another for horizontal curves with a mean CCR of more than 240 gon/km (43 curves, $R^2 = 0.72$) that uses the variables CCR, width of travel lanes plus shoulders, length of single circular curve, number of residential driveways per kilometre, radius of preceding curve, and pavement distress indicator. In their extended model, Lamm and Choueiri (1987) use traffic (Annual Average Daily Traffic – AADT, vpd (vehicles per day)) as one of the variables, whereas various other authors take into account the speed in the approach tangent (McFadden, Elefteriadou 1997). Likewise, some authors have suggested that the speed on curves depends on the “environmental” speed (V_{env}) (Crisman *et al.* 2005), a concept similar to the “desired” speed of the *Australian Design Standard (AUSTRROADS 2003: Rural Road Design – a Guide to the Geometric Design of Rural Roads)* that is defined as the max V_{85} in km/h value in long tangents or large radius curves placed in homogeneous sections of highways.

Other authors propose speed models that include sight distance as one of the independent variables. Thus, in Venezuela, Andueza (2000) developed speed models for rural highways that include the radius of consecutive curves, length of approach tangent and sight distance as independent variables. In Italy, Discetti *et al.* (2011) have proposed four operating-speed models for curves that use radius, radius of the previous curve, CCR in gon/km, curve length and the minimum sight distance for the curve as variables. The best of these models, as indicated by the coefficient of determination ($R^2 = 0.73$), makes use of the radius, radius of the previous curve and the minimum sight distance for the curve.

Several devices have been used to measure vehicle speeds, with the most popular being traffic counters/classifiers and radar meters (Andueza 2000; Fitzpatrick *et al.* 2000; Gibreel *et al.* 2001; Krammes *et al.* 1995; McFadden, Elefteriadou 1997; Morrall, Talarico 1994;). Recently, however, the use of laser devices (Castro *et al.* 2008; Crisman 2005; Dell'Acqua 2011; Dell'Acqua, Russo 2011; Dell'Acqua *et al.* 2010; Discetti 2010, Discetti *et al.* 2011) and video cameras (Discetti 2010) has increased, especially as lasers allow the speed of a vehicle to be measured in a reliable and inexpensive manner by unequivocally identifying the vehicle that is being measured, the distance to the laser and whether the vehicle is approaching, or moving away from, the laser measurement device. Such devices are not detectable by drivers using radar detectors, and, in addition, as the laser is not located in the road, it is not necessary to interrupt traffic to set it up.

The Global Positioning System (GPS) has been used for several transportation applications, including vehicle navigation, fleet management, route tracking, vehicle arrival/schedule information systems (bus/train) and on-demand travel information; in specific vehicles for highway inventorying or for taking highway geometry data (Castro *et al.* 2006, Lipar *et al.* 2011); travel surveys; and for collecting continuous speed data (Pérez *et al.* 2010). Geographic Information Systems (GISs) have also been applied in different areas of transportation since the 1980s. In some cases, information obtained using GPS has been incorporated into a GIS (*TRB 2002: Collecting, Processing, and Integrating GPS Data into GIS*).

In Spain, both Castro *et al.* (2008) and Pérez *et al.* (2010) have determined speed models from vehicle speed measurements. However, as these studies have shown differences between measured speeds and those predicted using non-local models (Castro *et al.* 2012; Pérez *et al.* 2010), it is of interest to continue studying vehicle speeds in Spain. In addition, this paper presents a combination of laser, GPS and GIS for vehicle speed measurements.

2. Data collection

Vehicle speeds were measured using a laser device that measures the speed of a vehicle and the distance between the vehicle and the device. The measured speed has a positive sign if the vehicle is approaching the laser and a negative sign if it is moving away from it. Although the speed and distance of a vehicle appear in the display of the laser device when its speed is measured, this device has no memory or internal data logger to store these data. Thus, the only way of automatically storing the measured data is to connect an external data logger to the laser device by means of its embedded serial interface.

In this paper the design of a data-storage system which, in addition to vehicle speeds, records their distance and speed sign and allows the location where the measurements were made to be recorded is discussed. This system consists of a laser, a low-cost Global Positioning System (GPS; SIRF III type) receiver and a hand-held computer

(Personal Digital Assistant – PDA). The GPS device used records the location where the measurements are taken and has 20 L1 channels, a maximum update rate of 1 Hz and supports single sat updates in reduced visibility conditions, has good urban canyon performance and foliage lock for weak signal tracking. The horizontal position accuracy of this GPS device is 15 m root mean square (selective availability off). The GPS is inserted in the Compact Flash slot of the PDA and the laser is connected to the PDA by means of its serial interface, thus meaning that both the laser and the GPS device measurements are stored in the PDA.

New software that allows information from the laser and the GPS device to be stored in the PDA has also been developed. Tables 1 and 2 show an example of a data log. The first seven columns contain data gathered using the GPS, namely date, time, validity or availability (A = valid and available, V = not valid or not available; in this latter case, the fields latitude, longitude, elevation and HDOP are empty), latitude (format DDMM.MMMM), longitude (format DDDMM.MMMM), elevation, and the Horizontal Dilution of Precision (HDOP), which allows a more precise estimation of the horizontal (latitude/longitude) accuracy of the GPS location by adjusting the error estimates according to the geometry of the satellites used. Columns 8 to 11 contain data gathered using the laser, namely units of measurement (M = metric units, E = English units), speed (in km/h if metric units are used; negative speed means that the car is moving away), distance (m), and number of valid measurements made in this location. The last two columns show the PDA date and time corresponding to when the laser was “shot”. It is important to know the moment when a speed has been measured in order to determine the time interval between two measurements. This allows vehicle headway between successive measurements to be controlled and those measurements

that did not comply with the minimum headway threshold established to ensure free flow conditions to be filtered out.

The observers that operated the laser measurement device chose their location in order to remain as unnoticed as possible by drivers. Speeds were measured when the vehicle was located at the central part of the curve length, thus avoiding measurements at the beginning of the curve (where the vehicles brake) or at the end of the curve (where the vehicles start accelerating).

The following criteria were used to select the speed measurement points:

- possibility to place the speed measurement device at the roadside, thus ensuring accessibility and worker safety;
- no changes in lane or shoulder widths;
- grades lower than 5%;
- location away from the zone of influence of intersections or towns;
- no physical features either adjacent or in the course of the roadway that may create abnormal hazards, such as narrow bridges.

Data were collected in the Southwest region of Extremadura (Spain), in summer, under good meteorological conditions. The two-lane rural highways used had the following average values: 7.1 m roadway width, 2.8% gradient, 1.2 access points/km, 4003 vpd AADT, 0.6 personal injury crashes (5 years), and 0.18 personal injury crashes/10⁸ veh-km (Table 3). Commercial vehicle traffic accounted for around 20%.

The particular crash type that predominated was collision (56.70%), followed by run off-road crashes (33.20%), pedestrian collisions (5.50%), rollover (2.80%) and other (1.70%).

Speed measurements were performed under free-flow conditions, and only passenger vehicle speeds were

Table 1. First 7 fields of a speed data collection log

GPS date	GPS time	GPS	Latitude, °	Longitude, °	Elevation, m	HDOP
28/08/2007	6:18:03	A	3855.5220N	00557.7222W	264.60	1.4

Table 2. Remaining 6 fields of a speed data collection log

Units	Speed, km/h	Distance, m	Number	PDA Date	PDA Time
M	-90	0071.30	1	28/08/2007	8:22:26

Table 3. Characteristics of the two-lane rural highway sections study sample

Parameter	Mean	Std. Dev.	Min	Max
Width of roadway, m	7.10	9.00	6.00	14.40
Number of access points along the route, access/km	1.20	2.40	0.00	20.00
Gradient, %	2.80	1.80	0.00	9.30
AADT, vpd	4003	2724	379	19 530
Personal injury crashes, 5 years	0.60	1.10	0.00	10.00
Personal injury crash rate, picrashes/10 ⁸ veh-km	0.18	0.32	0.00	2.580



Fig. 1. GIS: sites where speeds were measured

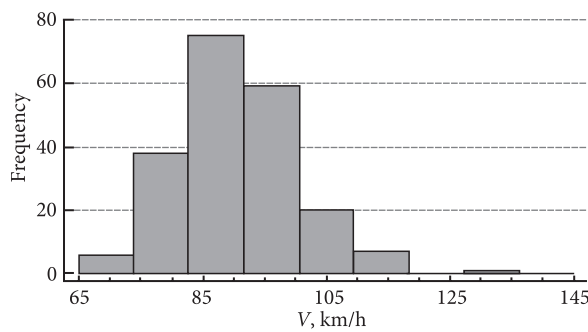


Fig. 2. Measured speeds: histogram

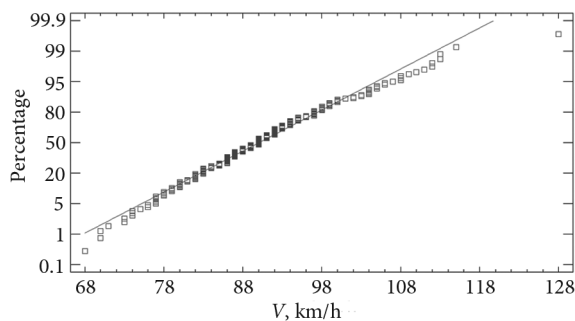


Fig. 3. Measured speeds: normal probability plot

registered. Speeds in 44 curves with radii ranging from 120 m to 1700 m and varying geometric characteristics (such as radius, length, vertical slope, etc.) were measured. A sample of speeds composed of more than 100 valid measurements was taken for each curve.

3. Data analysis

All the information collected during data collection (sites, speeds, geometric characteristics) was included in

Table 4. Summary of curve radius (m), and 85th percentile speed (V_{85} , km/h) calibration sample distribution parameters

Parameter	Radius	V_{85}
Count	42	42
Average	480.95	109.39
Standard deviation	254.38	11.79
Coeff. of variation, %	52.89	10.77
Minimum	120.00	80.39
Maximum	1010.00	122.52
Range	890.00	42.13
Std. skewness	1.5077	2.4968
Std. kurtosis	0.9908	0.1124

a GIS to simplify subsequent data management and information use. The information stored in the GIS is suitable to be used in the identification of potential problem spots for future maintenance works or road safety improvements, or at least to identify with precision the location of the sites where speeds were measured for future studies. Fig. 1 shows the sites where speeds were measured.

Descriptive statistics, including mean speed, 85th percentile speed, 99th percentile speed, standard deviation, skewness and kurtosis coefficients, and coefficient of variation were calculated for each site. Speed studies undertaken in numerous other countries have found that the speed distribution of free-flowing vehicles follows a normal distribution. The speed data for the study described herein were therefore tested using the Kolmogorov-Smirnov test to determine whether the sample came from a normally distributed population. Normal probability plots were also generated to check the normality of the observed speed data distributions. Figs 2 and 3 show the frequency histogram and the normal probability plot corresponding to one of the sites where speeds were measured.

The normality test results and normal probability plots indicated that the speeds followed a normal distribution.

4. Speed model

Several mathematical models were considered when studying vehicle speeds (linear, exponential, etc.). Furthermore, models using one (curvature = 1/radius, 1/radius ^{1/2}) and several variables (radius, 1/radius ^{1/2}, length of curve) were considered, and an analysis was performed to determine whether some of the values lying away from the trend were outliers. Studentized residuals resulting from the division of each residual by the estimate of its standard deviation were computed to conduct this outlier study. Those values with studentized residuals greater than 2 were considered to be outliers and therefore eliminated from the sample for model calibration. As a consequence, the speeds corresponding to 2 sites were considered outliers, thus reducing the sample to 42 sites. The radii ranged between 120 m and

Table 5. 85th percentile speed, R^2 (%) coefficient for studied models. Independent variable 1/radius

Model	Equation	R^2 , %
Exponential	$V_{85} = e^{(4.85107 - \frac{56.9212}{r})}$	79.71
Square root-Y	$V_{85} = \left(11.2617 - \frac{287.05}{r}\right)^2$	79.02
Double square root	$V_{85} = \left(12.1572 - 33.4798\sqrt{\frac{1}{r}}\right)^2$	78.69
Square root-X	$V_{85} = 144.207 - 680.13\sqrt{\frac{1}{r}}$	78.61
Reciprocal-Y square root-X	$V_{85} = \frac{1}{\left(0.00593453 + 0.0649486\sqrt{\frac{1}{r}}\right)}$	78.36
Linear	$V_{85} = 125.944 - \frac{5806.33}{r}$	78.27
Squared-Y square root-X	$V_{85} = \sqrt{19342.2 - 141435\sqrt{\frac{1}{r}}}$	78.20
Squared-Y	$V_{85} = \sqrt{15515.8 - \frac{1.19744 \cdot 10^6}{r}}$	76.57
Squared-Y logarithmic-X	$V_{85} = \sqrt{-10343.3 - 3724.3\ln\left(\frac{1}{r}\right)}$	75.67
Reciprocal-Y squared-X	$V_{85} = \frac{1}{\left(0.00855095 + \frac{62.8212}{r^2}\right)}$	75.06
Logarithmic-X	$V_{85} = 2.32085 - 17.7659\ln\left(\frac{1}{r}\right)$	74.86
Square root-Y logarithmic-X	$V_{85} = \left(5.1946 - 0.870909\ln\left(\frac{1}{r}\right)\right)^2$	74.31
Multiplicative	$V_{85} = e^{\left(3.65692 - 0.171216\ln\left(\frac{1}{r}\right)\right)}$	73.67
Reciprocal-Y logarithmic-X	$V_{85} = \frac{1}{\left(0.0193101 + 0.00166772\ln\left(\frac{1}{r}\right)\right)}$	72.10
Logarithmic-Y squared-X	$V_{85} = e^{\left(4.75904 - \frac{6230.55}{r^2}\right)}$	71.57
Square root-Y squared-X	$V_{85} = \left(10.7947 - \frac{31160.4}{r^2}\right)^2$	69.79
Squared-X	$V_{85} = 116.44 - \frac{625153}{r^2}$	68.00
Double squared	$V_{85} = \sqrt{13532.6 - \frac{1.26881 \cdot 10^8}{r^2}}$	64.44

Continued Table 5

Model	Equation	R ² , %
Squared-Y reciprocal-X	$V_{85} = \sqrt{8422.73 + 7.64906r}$	62.69
Reciprocal-X	$V_{85} = 92.0842 + 0.0359802r$	60.29
Square root-Y reciprocal-X	$V_{85} = (9.60105 + 0.00175101r)^2$	58.99
S-curve model	$V_{85} = e^{(4.52443+0.00034169r)}$	57.62
Double reciprocal	$V_{85} = \frac{1}{(0.0108358 - 0.00000327759r)}$	54.69

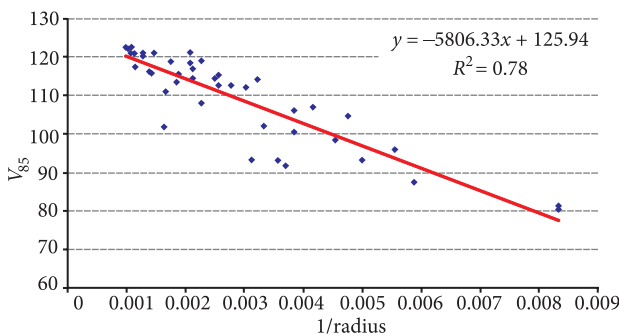


Fig. 4. Speed model

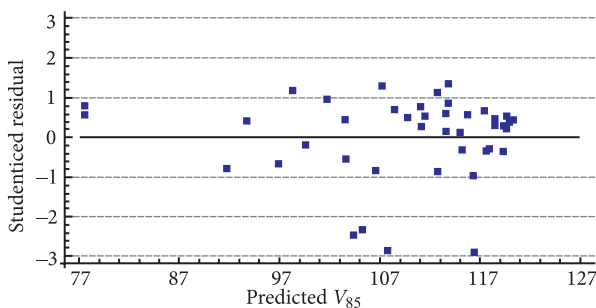


Fig. 5. Proposed model. Studentized residual versus predicted values

1010 m, the average radius was 481 m and the standard deviation 254 m. The operating speed (V_{85} , km/h) ranged between 80.4 km/h and 122.5 km/h, the average value was 109.4 km/h and the standard deviation 11.8 km/h. Table 4 shows a summary of the calibration sample curve radius and V_{85} descriptive statistics, along with measures of central tendency, variability and shape of its distributions.

Table 5 shows the R^2 coefficients obtained using different single-variable ($1/\text{radius}$) models for the reduced sample (42 curves; X is $1/\text{radius}$ and Y is V_{85}). Although the best fit corresponds to the exponential model ($R^2 = 0.79$), it was concluded that the linear model was the most appropriate when also considering goodness-of fit, simplicity and practicality.

The speed prediction model proposed is:

$$V_{85} = 125.94 - \frac{5806.33}{r}, \quad (1)$$

where V_{85} – the 85th percentile speed, km/h; r – the circular curve radius, m.

This corresponds to a sample of 42 curves and has a coefficient of determination (R^2) of 0.78 (Fig. 4). Since the P -value is less than 0.05, there is a statistically significant relationship between V_{85} and $1/r$ at the 95.0% confidence level. Fig. 5 shows a plot of the studentized residual versus predicted values.

The inclusion of other variables, such as length of curve, in the model together with the inverse of the radius did not improve the goodness of fit appreciably. Thus, the R^2 coefficient for a multiple-variable linear regression model fit using the length of curve and the inverse of the radius as covariates was 0.78. The t statistic of the variable length of curve in this model is 1.32, thus indicating that this variable is not significant at a confidence level of 95%.

The proposed model (Eq (1)) states that if the radius increases vehicle speeds also increase. This is a simple and easy to apply model that only requires knowledge of the curve radius, which are easily obtained from cartography, orthophotos or satellite imagery. This model is suitable for use in design consistency evaluation studies that compare speeds on consecutive alignment elements. For example, a commonly used criterion for this comparison states that the consistency is good if the difference in V_{85} between successive elements is less than 10 km/h, fair if the difference is 10 km/h or more but less than 20 km/h, and poor if the difference in V_{85} is higher than 20 km/h.

5. Comparison with European models

The curve speed model proposed here (Eq (1)) gives similar results to those of the model developed previously by Castro *et al.* (2008) using data from Spanish highways located in other geographic regions (Madrid), with a maximum speed difference of less than 5%. According to Castro *et al.* (2008, 2012), these speed models predict higher speeds than some international models, such as the American models of Lamm and Choueiri (1987) and Krammes *et al.* (1995), or the Canadian model of Morrall and Talarico (1994). As a result, the following comparison will focus on European models (Mediterranean countries), namely a French model (SETRA 1986), a Greek one (Kanellaidis *et al.* 1990), two Italian models (Dell’Acqua, Russo 2011; Discetti *et al.* 2011), and two Spanish ones (one of them is developed herein, developed herein, and the model by Perez *et al.* 2010).

As the French model (SETRA 1986) proposes several equations depending on lane width, the equation that

corresponds most closely to the lane width of the highway analysed (3.3 m; Eq (2)) was chosen. The coefficient of determination (R^2) for this equation was 0.75:

$$V_{85} = 93.83 - \left(\frac{2955.40}{r} \right), \quad (2)$$

where r – circular curve radius, m.

The Greek model (Kanellaidis *et al.* 1990; Eq (3)), which depends on the square root of the radius (r), was found to have a coefficient of determination (R^2) of 0.78:

$$V_{85} = 129.88 - \frac{623.1}{\sqrt{r}}. \quad (3)$$

Of the two Italian models chosen, which are based on a large sample of measured highway speeds, that of Dell’Acqua and Russo (2011) attempts to approximate reality by including several variables alongside the geometric ones and uses two equations depending on the curve CCR (gon/km) (Eqs (4) and (5)). The determination coefficients (R^2) for these equations were 0.81 and 0.72, respectively.

If $CCR_S < 240$ gon/km,

$$V_{85} = 55.74 + 5.57W - 0.038CCR_S + 10^{-5}CCR_S^2 - 0.03L - 0.48RES - 4.65INT + 7.3 \cdot 10^{-4}L_{PT} - 0.064CCR - 0.3PD. \quad (4)$$

If $CCR_S > 240$ gon/km,

$$V_{85} = 59.16 + 0.2W^2 - 0.023CCR_S + 10^{-5}CCR_S^2 - 0.69RES + 8.8 \cdot 10^{-2}R_{PC} - 3.5 \cdot 10^{-4}R_{PC}^2 - 2.63PD, \quad (5)$$

where CCR_S – CCR of single circular curve; W – lane width plus shoulders; L – length of single circular curve; RES – number of residential driveways/km; INT – intersection distance indicator, 1 if intersection is nearer than 150 m from the curve, 0 otherwise; L_{PT} – length of preceding tangent; CCR – CCR of section roadway; PD – pavement distress indicator: 0 = absent, 1 = low distress, 2 = high distress, 3 = very high distress; r_{PC} – radius of preceding curve.

Likewise, Discetti *et al.* (2011) proposed four models that include sight distance as one of the independent variables. The model with the highest coefficient of determination ($R^2 = 0.73$), which uses curve radius and radius of the preceding curve as variables in addition to sight distance, was chosen (Eq (6)).

$$V_{85} = 65.99 + \frac{1341.88}{r} + \frac{15543.49}{r^2} + \frac{130.91}{r_{PC}} + 0.07D, \quad (6)$$

where D – the minimum sight distance for the curve.

Perez *et al.* (2010) proposed three models, two of which are based on curve radius and the other on CCR . The coefficient of determination for the general curve radius based model (Eq (7)) was 0.76, whereas that for curves with a radius of less than 400 m was somewhat higher (0.84). As a result, Eq (8) was used for curves with

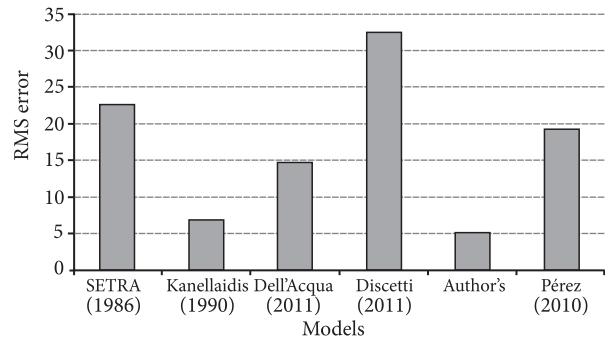


Fig. 6. Comparison of measured speeds and those predicted using selected European models

a radius lower than 400 m and Eq (7) for the remaining curves in this comparison.

$$V_{85} = 97.4254 - \frac{3310.94}{r}, \quad (7)$$

$$V_{85} = 102.048 - \frac{3990.26}{r}. \quad (8)$$

A total of 11 curves with radii ranging from 150 m to 2000 m were studied in the comparison. These curves were different to those used to calibrate the proposed model in order to allow model predictions to be compared with measured speeds. The root mean square (RMS) errors of the predictions made with the selected models for these curves are presented in Fig. 6, showing that the most accurate model (5 km/h RMS error) was the model proposed herein, followed by the model of Kanellaidis *et al.* (1990) (7 km/h RMS error). The models of Dell’Acqua and Russo (2011) and Pérez *et al.* (2010) show differences of less than 20 km/h (15 km/h and 19 km/h RMS error, respectively). The model of Pérez *et al.* (2010) is the only one based on continuous collection of speed data via a GPS device placed on-board the vehicles. However, the fact that drivers know that their driving speeds are being recorded in this procedure is highly likely to affect their driving behaviour and, as a consequence, their driving speed. In addition, this model is based on a sample of curves in which curves with radius larger than 300 m are underrepresented. These two particularities of this model are the main explanation of why it predicts lower speeds than the other Spanish models. The models of SETRA and Discetti *et al.* (2011) show larger differences (23 km/h and 32 km/h RMS error, respectively).

This comparative study emphasizes the effect of the model chosen on the results obtained. Future research will include speed models for tangents and also acceleration and deceleration models for use in design consistency evaluation studies.

6. Conclusions

1. The combination of laser and GPS devices provides an inexpensive and reliable alternative to perform vehicle speed measurements.

2. The use of GPS allows determining the coordinates of the points where speed measurements are taken. These measurements are stored in a GIS to simplify data collection management and to facilitate the use of the collected information in subsequent analyses.

3. A new operating speed model has been developed in Spain. According to this model, which is based on car speeds collected in 42 curves located on two-lane rural highways, the operating speed depends on curve radius (coefficient of determination = 0.78). This model is simple and easy to apply because the required data are easily available from cartography, orthophotos or satellite imagery.

4. This model is suitable for use in design consistency evaluation studies based on the comparison of speeds on consecutive alignment elements.

5. The comparative study using various European models emphasizes the influence of the model chosen on the results obtained.

6. Future research will include speed models for tangents and also acceleration and deceleration models for use in design consistency evaluation studies.

Acknowledgements

The research reported in this article was undertaken as part of the research project PT-2006-014-221CPP: DIS-CAM funded by the Centre for Public Works Studies and Experimentation (CEDEX) of the Spanish Ministry of Infrastructures (Ministerio de Fomento).

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