1. Introduction

Design consistency refers to the condition whereby 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, 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 southwest 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).
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) (Bevilaqua 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 (Venv) (Crisman et al. 2005), a concept similar to the “desired” speed of the Australian Design Standard (AUSTROADS 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/10^8 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

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

| GPS date | GPS time | GPS | Latitude, º | Longitude, º | 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     | 19530   |
| 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 |
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 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, 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 ½) and several variables (radius, 1/radius ½, 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

| 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    |
| Stnd. skewness            | 1.5077 | 2.4968   |
| Stnd. kurtosis            | 0.9908 | 0.1124   |
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   | $V_{85} = \frac{1}{0.00593453 + 0.0649486 \sqrt{\frac{1}{r}}}$          | 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                    | $V_{85} = \sqrt{15515.8 - 1.19744 \cdot 10^6 \sqrt{\frac{1}{r}}}$      | 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       | $V_{85} = \frac{1}{0.00855095 + 62.8212 \frac{1}{r^2}}$                | 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               | $V_{85} = e^{\left(1.65592 - 0.171216 \ln\left(\frac{1}{r}\right)\right)}$ | 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                    | $V_{85} = \frac{116.44 - 625153}{r^2}$                                  | 68.00    |
| Double squared               | $V_{85} = \sqrt{13532.6 - \frac{1.26881 \cdot 10^8}{r^2}}$              | 64.44    |
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/radius) models for the reduced sample (42 curves; $X$ is 1/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:

$$V_{85} = \sqrt{8422.73 + 7.64906r}$$

(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
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.

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