Prediction of Drivers’ Speed Behavior on Rural Motorways Based on an Instrumented Vehicle Study

Alfonso Montella, Luigi Pariota, Francesco Galante, Lella Liana Imbriani, and Filomena Mauriello

Several studies have developed operating speed prediction models. Most of the models are based on spot speed data, collected by radar guns, pavement sensors, and similar mechanisms. Unfortunately, these data collection methods force the users to assume some invalid assumptions in driver behavior modeling: constant operating speed throughout horizontal curves and occurrence of acceleration and deceleration only on tangents. In this study, an instrumented vehicle with GPS continuous speed tracking was used to analyze driver behavior in terms of speed choice and deceleration or acceleration performance and to develop operating speed prediction models. The data used in the study were from a field experiment conducted in Italy on the rural motorway A16 (Naples–Avellino). Models were developed to predict operating speed in curves and tangents, deceleration and acceleration rates to be used in the operating speed profiles, starting and ending points of constant operating speed in a curve, 85th percentile of the deceleration and acceleration rates of individual drivers, and 85th percentile of the individual drivers’ maximum speed reduction in the tangent-to-curve transition. The study results showed that (a) the drivers’ speed was not constant along curves, (b) the individual drivers’ maximum speed reduction was greater than the operating speed difference in the tangent-to-curve transition, and (c) the deceleration and acceleration rates experienced by individual drivers were greater than the deceleration and acceleration rates used to draw operating speed profiles.

This kind of speed measurement can induce bias because the data are not collected at the beginning and the ending deceleration or acceleration points. The measurement derives acceleration and deceleration profiles that do not represent the drivers’ behavior. In addition, deceleration and acceleration length cannot be determined, so the actual acceleration and deceleration rates cannot be accurately obtained (5, 6).

To avoid these deficiencies in data collection, there are other methods based on continuous speed tracking, such as instrumented test vehicles and driving simulators. In the past years, a great deal of research has demonstrated that driving simulator studies can be an effective tool for research on driving speeds (7–12), although the use of driving simulators has some potential shortcomings, including physical limitations and realism, simulator sickness, and, most important, validity (10–12). Investigation of drivers’ behavior in a real-world setting produces data with the greatest validity. The widespread availability of lower-cost and more advanced methods of vehicle instrumentation and recording technologies supports an increasing number of studies that use instrumented test vehicles. These are normal vehicles with extensive instrumentation and sensors hidden in the infrastructure. The studies also use defined driving routes to study drivers’ speed and acceleration and deceleration behavior on various road classes based on experimental data collected during real-road driving (5, 6, 13–16).

To provide useful findings to model drivers’ behavior and develop operating speed models without predefined underlying assumptions, this study used an instrumented vehicle with GPS continuous speed tracking. The data used in the study were from a field experiment conducted in Italy on the rural motorway A16 (Naples–Avellino). The aim of the study was to develop models to predict operating speed on curves and tangents, deceleration and acceleration rates to be used in the operating speed profiles, the 85th percentile of the deceleration and acceleration rates experienced by individual drivers, and the 85th percentile of individual drivers’ maximum speed reduction in the tangent-to-curve transition. Furthermore, the study was aimed at answering the following questions: (a) Is speed along curves constant? (b) Is the difference between operating speeds in the approach tangent and in the curve equal to the speed reduction experienced by individual drivers? (c) Are the deceleration and acceleration rates of the operating speed profiles different from the deceleration and acceleration rates of individual drivers?

The next section will describe the experiment; the following sections will describe the analysis methods and explain and discuss the results, with a specific focus on comparison with the results of the previous studies.
EXPERIMENT

Participants

Thirty-nine subjects with the following characteristics were involved: 14 females and 25 males, ranging in age from 23 to 70 years (mean = 35.77 years, SD = 11.99 years). More than 60% of the participants drove more than 10,000 km per year and more than 80% drove at least 5,000 km per year. Prescreening and psychological questionnaires were provided. The screening assembled information on gender, age, years of driving experience, occupation, frequency of driving and type of route, and vehicle type and number of crashes, which was useful for grouping the participants. Psychological data will be used in a further study that will group the drivers with respect to aggressiveness levels and explore the relationship between drivers’ behavior and the self-reported propensity to drive in a dangerous and aggressive manner.

Before the experiment, the participants signed an informed consent form and did not have any information on the real purpose of the experiment except the description of the driving route. The experiment was carried out between June 2011 and September 2011, between 9:30 a.m. and 4:30 p.m., on weekdays, and under dry weather conditions. Although the instrumented vehicle looked like a normal car, each participant was provided with a long familiarization session (driving at least 5 km in a rural area) to reduce initial embarrassment and awareness at being part of an experiment. The sessions took place before the principal test drive, on a road chosen close to the test route.

One researcher in the passenger seat was present to give navigation directions. During the whole experiment, the drivers were encouraged to drive as naturally as possible and to imagine being the owner of the vehicle. No speed restrictions were imposed. Each participant was asked to adjust the vehicle seat and steering wheel position controls for his or her driving comfort.

Instrumented Vehicle Characteristics

The instrumented vehicle used for experimentation was a normal vehicle, a 2004 Fiat Multipla 1.9 TDI, with extensive instrumentation and sensors hidden in its infrastructure, which allowed qualitative and quantitative assessments of on-road driver performance. The core of the system was KIT, a software developed in LabWindows CVI for data acquisition via CAN interfaces and PCMCIA DAQ devices. The software runs in a Windows XP portable workstation. Data synchronization and collection were performed in a KIT environment.

A Topcon GPS was used to track the position of the test vehicle. It employed a differential GPS antenna that was mounted on the roof of the vehicle directly over the central rear seat. The GPS samples data at 10 Hz. Two TRW Autocruise AC10 radars mounted on the front and back of the vehicle enabled the collection of headway data (the relative distance and speed of a maximum of four surrounding vehicles for each radar).

Three potentiometers were used to collect data on the position of the brake pedal, the gas pedal, and the clutch pedal. The steering wheel angle was measured by a draw-wire displacement sensor, and the angular velocity was measured by a gyroscope.

Two black-and-white analog cameras collected video data of the experiment. The cameras had a resolution of 512 x 384 pixels and a frame rate of 25 fps. To synchronize video and data acquisition, time and other GPS and radar main information were stamped on the video streams. The two cameras were strategically placed, facing front and back windscreens, to record the behavior of the surrounding traffic and the characteristics of the road environment. The equipment was completed by a 5.6-in. LCD monitor with a switch for front or back camera. All instrumentation was mounted to be as unobtrusive as possible, and all wiring and cables were hidden in the ceiling and floor panels of the vehicle.

Test Route

Drivers ran the Naples–Avellino East section of Motorway A16 Naples–Canosa, which is part of the Trans European Road Network (Road E841). It is located in the south of Italy and links the west coast (Motorway A1) and east coast (Motorway A14). It is a divided highway with two lanes in each direction (lane width = 3.75 m, right shoulder width = 0.50 m to 3.50 m, median width = 2.00 m), access control, and interchanges. Many characteristics of the motorway are substandard, which allowed the study to investigate a wide spectrum of geometric configurations (Table 1). The length of the Naples–Avellino East section is 49.5 km.

The general speed limit was 130 km/h, which is the maximum legal speed in Italy. Local speed limits of 80 km/h were present in both travel directions. On the test route, there were 45 horizontal curves and 46 tangents. The radius of the horizontal curves varied between 250 m and 2,775 m. There were no spiral transitions. Deflection angles varied between 5 gon and 109 gon (100 gon = 90 degrees, in circle of 400 angle units). The mean superelevation was 3.25%. The maximum longitudinal grade was 6.35%. Sight distance was often less than stopping sight distance and ranged between 86 m and 840 m.

**TABLE 1 Geometric Data Summary Statistics**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of horizontal curves (m)</td>
<td>360.86</td>
<td>195.39</td>
<td>85.54</td>
<td>1,091.01</td>
</tr>
<tr>
<td>Radius of horizontal curves (m)</td>
<td>979.30</td>
<td>635.00</td>
<td>250.00</td>
<td>2,775.00</td>
</tr>
<tr>
<td>Deflection angle (gon)</td>
<td>31.07</td>
<td>21.87</td>
<td>4.88</td>
<td>109.07</td>
</tr>
<tr>
<td>Superelevation (%)</td>
<td>3.25</td>
<td>1.09</td>
<td>1.30</td>
<td>6.42</td>
</tr>
<tr>
<td>Length of tangents (m)</td>
<td>726.60</td>
<td>658.60</td>
<td>143.20</td>
<td>3,509.10</td>
</tr>
<tr>
<td>Longitudinal grade (%)</td>
<td>2.41</td>
<td>1.70</td>
<td>0.00</td>
<td>6.35</td>
</tr>
<tr>
<td>Sight distance (m)</td>
<td>345.21</td>
<td>172.65</td>
<td>85.52</td>
<td>840.00</td>
</tr>
<tr>
<td>Right shoulder width (m)</td>
<td>2.26</td>
<td>0.75</td>
<td>0.50</td>
<td>3.50</td>
</tr>
</tbody>
</table>

Note: gon = 400 angle units in circle instead of 360 degrees (100 gon = 90 degrees).
Data Processing and Reduction

All data were recorded with a frequency of 10 Hz. To improve the GPS point positioning accuracy, the Precise Point Positioning (PPP) analysis technique was applied to correct GPS observations in post-processing mode. PPP is a cost-efficient positioning technique in which only a single receiver is required, without need for reference from base stations. The technique applied to code or phase measurements requires precise satellite orbit and clock products that use a network of global navigation satellite system (GNSS) reference stations distributed worldwide.

An open source program package for GNSS positioning (RTKLIB, ver. 2.4.1) was used for post-processing raw observations in PPP mode with a kinematic method. For PPP processing, high-accuracy ephemerides (final) and clock (5 s) data were downloaded from the website of the Center for Orbit Determination in Europe. The PPP technique was applied to increase the accuracy of the GPS position at the centimeter level. Instead, GPS speed was calculated in stand-alone mode via Doppler Shift with an accuracy of 1 cm/s. The resulting data were converted into local plane coordinates. Finally, the absolute GPS position data were projected onto the road axis to obtain the relative position.

Since the objective of the study was to investigate drivers’ behavior in relation to the geometric characteristics, only data in free-flow conditions were used for further analysis. Thus, data were removed if the distance from the preceding vehicle was less than 6 s, which was determined from the front radar and video data. Furthermore, data collected at the tollgate were removed.

METHODOLOGY

Operating Speed Profile

The operating speed \( (V_{85}) \) profile is a diagram that shows the 85th percentile of the speed distribution under free-flow, dry road conditions. To investigate the continuous speed profile, the noise in the data set was removed and the smoothing algorithm locally weighted regression scatterplot smoothing (LOWESS) was used to preserve underlying patterns. LOWESS is a generalized extension of the locally fitted polynomial smoothing techniques used by many statisticians in time-series analysis (17).

For speed \( y \) (m/s) in the basic underlying model, \[ y_t = g(x_t) + \epsilon_t, \]
where \( g(x_t) \) is a smooth function and \( \epsilon_t \) is a random sample from a normal distribution with \( E(\epsilon_t) = 0 \) and \( \text{var}(\epsilon_t) = \sigma^2 \). The smoothness of \( g \) can be approximated locally over the interval \( t-m, \ldots, t, t+1, \ldots, t+m \), by the linear function \[ y_t = \alpha + \beta_t x_t + \epsilon_t, \]
where \( x_t \) is the section and \( m \) is the half size of the band width (the point \( x_t \) is the midpoint of the band).

This technique makes it easier to distinguish \( g(x_t) \) through the noise \( \epsilon_t \). The parameters \( \alpha \) and \( \beta_t \) in the locally linear model are estimated with a locally weighted regression technique. Through LOWESS, the values of the operating speed and the parameters \( \alpha \) and \( \beta_t \) were obtained for each point \( x_t \). Values of \( \beta_t \) were used to identify the segments where the speed was constant or changed with a constant rate of deceleration or acceleration, that is, the beginning and the ending of deceleration and acceleration points.

The starting point of deceleration was defined as the first section where the value of \( \beta_t \) was less than or equal to \(-0.05 \) (P1 in Figure 1) and the end point was defined as the section where the \( \beta_t \) became
greater than −0.05 (P2 in Figure 1). Similarly, the starting point of acceleration was defined as the first section after the end of the deceleration where the value of β was greater than or equal to 0.05 (P3 in Figure 1) and the end point was defined as the section where the β became less than 0.05 (P4 in Figure 1). Operating speed reduction is the difference between the speed at the starting and ending points of deceleration ($v_{85,1} - v_{85,2}$ in Figure 1).

The deceleration and acceleration rates were obtained by Equation 1:

$$d, a = \frac{\left| v_{85,(j+1)} - v_{85,j} \right|^2}{2S} \quad (1)$$

where

- $d$ = absolute value of deceleration rates (m/s²),
- $a$ = absolute value of acceleration rate (m/s²),
- $v_{85,j}$ = operating speed at section $j$ where deceleration or acceleration begins (P1/P3 in Figure 1) (m/s),
- $v_{85,(j+1)}$ = operating speed at section $j + 1$ where deceleration or acceleration ends (P2/P4 in Figure 1) (m/s), and
- $S$ = distance between sections $j$ and $j + 1$ (m), that is, the deceleration and acceleration lengths.

### Individual Speed Profiles

To investigate the drivers’ behavior in the tangent-to-curve transitions and along the curve, the last 300 m of the approach tangent and the first 300 m of the departure tangent were considered. Previous studies have shown that the length of the tangent affected by the presence of the curve is less than 300 m (5). The study hypothesis was that speed changes at a greater distance from the curve are not caused by the curve itself.

After removing the data in non-free-flow conditions, 2,720 speed profiles along the tangent-to-curve transition and along the curve were obtained. The beginning point of deceleration was defined as the first section where the value of deceleration was greater than or equal to 0.2 m/s² (P1 in Figure 2), and the ending point was defined as the section where the deceleration became less than 0.2 m/s² (P2 in Figure 2). The beginning point of acceleration was defined as the first section after the end of the deceleration where the value of acceleration was greater than or equal to 0.2 m/s² (P3 in Figure 2), and the ending point was defined as the section at which the acceleration became less than 0.2 m/s² (P4 in Figure 2). The speed reduction of driver $i$ is the difference between the speed at the starting and ending points of deceleration ($v_{85,1} - v_{85,2}$ in Figure 2).

The deceleration and acceleration rates of individual drivers were obtained by Equation 2:

$$d_{i}, a_{i} = \frac{\left| v_{85,i,(j+1)} - v_{85,i,j} \right|^2}{2S} \quad (2)$$

where

- $d_{i}, a_{i}$ = absolute values of deceleration and acceleration rates of driver $i$ (m/s²), respectively;

### FIGURE 2

Individual speed profile.
\[ v_{i,j} \] = speed of driver \( i \) at section \( j \) where deceleration or acceleration starts (P1/P3 in Figure 2) (m/s); and

\[ v_{i,j+1} \] = speed of driver \( i \) at section \( j+1 \) where deceleration or acceleration ends (P2/P4 in Figure 2) (m/s).

### Regression Models

Multilinear regression models were developed for the following parameters: operating speed in curves \( V_{\text{85\_curve}} \) and tangents \( V_{\text{85\_tangent}} \), deceleration \( d \) and acceleration \( a \) rates to be used in the operating speed profiles, starting (SP/Lc) and ending (EP/Lc) points of constant operating speed in curves, 85th percentile of the deceleration \( (d_{85}) \) and acceleration \( (a_{85}) \) rates of the individual drivers, and 85th percentile of the individual drivers’ maximum speed reduction in the tangent-to-curve transition \( (\Delta_{85} V) \). Explanatory variables related to horizontal alignment of the single element and the route preceding the element, vertical alignment, and roadside context were considered (see Table 2).

Models were developed in SPSS by the backward procedure with a significance level of 0.05. The backward elimination procedure begins with all variables in the model. At each step, the variable with a significance level of 0.05. The backward elimination procedure begins with all variables in the model. At each step, the variable yielding the largest \( p \)-value is removed. To calculate the \( p \)-value, the \( F \)-test criterion is used in this procedure. Variables are removed as long as all the variables are statistically significant or until there are no variables remaining.

### RESULTS AND DISCUSSION

#### Deceleration and Acceleration Behavior

The main result was that the hypothesis of constant operating speed along the curve was not verified. The analysis of the individual drivers’ behavior showed that 52% of the drivers experienced deceleration in the curve (see Figure 3). In 30% of the transitions, deceleration began in the approach tangent and ended in the curve (in the first half of the curve in 26% of the transitions). A frequent behavior (22%) was deceleration occurring entirely in the curve. It was noteworthy that deceleration behavior was affected by the curve radius. It was observed that 52% of the drivers began deceleration in the approach tangent and ended deceleration in the curve when the curve radius was less than or equal to 400 m, while the same behavior was observed in 24% of the transitions when the curve radii were greater than 400 m.

Similarly, acceleration began in the curve in 90% of the transitions (see Figure 4). In 27% of the transitions, acceleration began in the first half of the curve [46% for curves with \( R \leq 400 \text{ m} \), 23% for curves with \( R > 400 \text{ m} \), where \( R \) = radius (km)], whereas in 63% of the transitions, acceleration began in the second half of the curve (35% for curves with \( R \leq 400 \text{ m} \), 69% for curves with \( R > 400 \text{ m} \)).

### Models

The following models were fitted (see Table 3):

\[
V_{\text{85\_curve}} = 135.490 - \frac{7.483}{R} - 1.290 \times G_e - 0.080 \times CCR_2 - 14.427 \times \text{tunnel} - 4.083 \times \text{bridge} \tag{3}
\]

\[
V_{\text{85\_tangent}} = 139.543 + 1.751 \times L - \frac{4.983}{R} - 2.507 \times G_e - 0.068 \times CCR_2 \tag{4}
\]

\[
d = 0.277 + \frac{0.098}{R} - 0.0017 \times CCR_2 - 0.037 \times G_e \tag{5}
\]

\[
a = 0.159 + \frac{0.035}{R} + 0.025 \times G_e - 0.027 \times G_e \tag{6}
\]

\[
\frac{SP}{L_e} = \left( 0.093 + \frac{0.149}{R} - 0.003 \times CCR_1 \right) \tag{7}
\]

\[
\frac{EP}{L_e} = \left( 0.496 + \frac{0.175}{R} + 0.038 \times G_e - 0.004 \right) \times CCR_1 - 0.131 \times L_m \tag{8}
\]

\[
d_{\Delta 5} = 0.546 + \frac{0.134}{R} - 0.0015 \times \text{def} - 0.015 \times CCR_2 + 0.009 \times G_e + 0.156 \times \text{tunnel} \tag{9}
\]

\[
a_{\Delta 5} = 0.350 + 0.048 \times G_e - 0.022 \times G_e \tag{10}
\]

### Table 2

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_t ) (km)</td>
<td>Length of tangent</td>
</tr>
<tr>
<td>( L_c ) (km)</td>
<td>Length of curve</td>
</tr>
<tr>
<td>( L_{ta} ) (km)</td>
<td>Length of tangent following the curve</td>
</tr>
<tr>
<td>( 1/R ) (1/km)</td>
<td>Horizontal curvature</td>
</tr>
<tr>
<td>( 1/R_t ) (1/km)</td>
<td>Horizontal curvature of the curve preceding tangent</td>
</tr>
<tr>
<td>( 1/R_{ta} ) (1/km)</td>
<td>Horizontal curvature of the curve following tangent</td>
</tr>
<tr>
<td>def (gon)</td>
<td>Deflection angle</td>
</tr>
<tr>
<td>( G_d ) (%)</td>
<td>Equivalent downgrade</td>
</tr>
<tr>
<td>( G_u ) (%)</td>
<td>Equivalent upgrade</td>
</tr>
<tr>
<td>( CCR_1 )</td>
<td>Curvature change ratio of the 1 km preceding the curve</td>
</tr>
<tr>
<td>( CCR_2 )</td>
<td>Curvature change ratio of the 2 km preceding the curve</td>
</tr>
<tr>
<td>( S_i )</td>
<td>Binary variable, equal to 1 if the curve is preceded by another curve or by a tangent shorter than 250 m</td>
</tr>
<tr>
<td>tunnel</td>
<td>Binary variable, equal to 1 if the segment is on a tunnel</td>
</tr>
<tr>
<td>bridge</td>
<td>Binary variable, equal to 1 if the segment is on a bridge</td>
</tr>
</tbody>
</table>

\( a_{G_d} = \sum G_d \times L_{gs}/L_t; G_d = \) equivalent downgrade; \( G_d = \) grade of downgrade subsegment \( i \); \( L_{gs} = \) length of downgrade subsegment \( i \); \( L_t = \) length of subsegments (upgrade and downgrade) that make up the segment under consideration.

\( a_{G_u} = \sum G_u \times L_{gs}/L_t; G_u = \) equivalent upgrade; \( G_u = \) grade of upgrade subsegment \( i \); \( L_{gs} = \) length of upgrade subsegment \( i \).
FIGURE 3  Deceleration behavior of individual drivers.

FIGURE 4  Acceleration behavior of individual drivers.
\[ \Delta_{85}V = 3.089 + 0.037 \times \text{def} + 0.834 \times G_d + 3.923 \times \text{tunnel} - 0.042 \times \text{CCR}_1 - 1.710 \times S_1 \]  
(11)

where

\[ V_{85,\text{curve}} = 85\text{th percentile of operating speed on curves (km/h)}, \]
\[ V_{85,\text{tangent}} = 85\text{th percentile of operating speed on tangents (km/h)}, \]
\[ \text{SP} = \text{starting point of constant operating speed on curves (km)}, \]
\[ \text{EP} = \text{ending point of constant operating speed on curves (km)}, \]
\[ d_{85} = 85\text{th percentile of deceleration rates of individual drivers (m/s²)}, \]
\[ a_{85} = 85\text{th percentile of acceleration rates of individual drivers (m/s²)}, \]
\[ \Delta_{85}V = 85\text{th percentile of maximum speed reduction in tangent-to-curve transition (km/h)}, \]
\[ R = \text{radius of curve (km)}, \]
\[ R_{cb} = \text{radius of curve preceding tangent (km)}. \]

The study data show that individual drivers’ maximum speed reduction was greater than the operating speed difference in the tangent-to-curve transition. The relationship between the 85th percentile of the individual drivers’ maximum speed reduction between tangent and curve (\(\Delta_{85}V\)) and the difference in operating speed between tangent and curve (\(\Delta V_{85}\)) is expressed by Equation 12

\[ VV_V = 6.16 + 0.76 \times \Delta V_{85} \]  
(12)

**Discussion and Comparison with Previous Studies**

The study results showed that

1. Drivers’ speed is not constant along curves,
2. Individual drivers’ maximum speed reduction is greater than the operating speed difference in the tangent-to-curve transition, and
3. Deceleration and acceleration rates experienced by the individual drivers are greater than deceleration and acceleration rates used to draw the operating speed profiles.

Comparable results have been found in driving simulator and real-world studies. In a driving simulator study, Montella et al. found that in 28.3% of the cases, deceleration ended in a circular curve and in 41.5% of the cases, acceleration started in the circular curve (in this study there were spiral transitions between the circular curves and...
the tangents) (18). Similarly, Figueroa and Tarko found that 34% of the speed reduction and 28% of the speed increase occurred in curves (19); McFadden and Elefteriadou found significant differences in operating speeds along the curve (20); and Pérez Zuriaga et al. found that deceleration continues inside the curve in most cases (5).

Other studies that have investigated the maximum speed reduction of individual drivers entering a curve have found that the 85th percentile of the maximum speed reduction distribution ($\Delta V_{85}$) is significantly higher than the reduction in operating speed ($\Delta V_{85}$) (see Table 4) (6, 14, 18, 20). Indeed, speeds vary from vehicle to vehicle and this leads to an underestimation of the measure of $\Delta V_{85}$ over successive elements. The research reported here confirmed this result.

Table 4 and Table 5 present a synthesis of the comparison between this study and previous studies (6, 7, 18–37). The studies included in the comparison are classified in relation to country, highway type, type of speed measure (spot speed or continuous speed), and data gathering tools (instrumented vehicle, driving simulator, Lidar guns, and so forth).

According to the model used in this study, operating speed on curves depends on horizontal alignment of both the curve (1/R) and the route preceding the curve (CCR$_3$), vertical alignment (G$_v$), and the roadside context (bridge and tunnel). Consistent with previous studies (see Table 5), operating speed decreases with increase in curvature. The effect of the alignment of the segment preceding the curve is reflected by the negative sign of the curvature change ratio in the 2 km preceding the curve. This means that, all else being equal, a curve is driven at a lower speed if the preceding 2 km has a greater curvature. Furthermore, longitudinal upgrade has a significant speed-reducing effect. This effect was not found in a few studies, probably because those studies analyzed geometric configurations with significant changes in longitudinal grade. Tunnels and bridges cause a decrease in speed, probably because drivers feel more uncomfortable negotiating curves in tunnels and bridges and both configurations produce a funneling effect, which gives the perception of greater speed.

In this study, operating speed on the tangent depended on a wide array of roadway characteristics, such as the length of the tangent, the radius of the curves before and after the section, the curvature change ratio of the 2 km preceding the tangent, and the longitudinal grade. As expected, the greater the tangent length was, the greater the operating speed was. The other parameters had a negative effect

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### TABLE 4 Comparison of Current Study with Previous Studies: $\Delta V_{85}$ Versus $\Delta a_{85}$, $d$, $a$, $\theta$

<table>
<thead>
<tr>
<th>Author</th>
<th>Country</th>
<th>Variable</th>
<th>Road Type</th>
<th>Measures</th>
<th>Tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>Montella et al. (18)</td>
<td>Italy</td>
<td>$\Delta V = 6.16 + 0.76 \times \Delta V_{85}$</td>
<td>Motorway</td>
<td>Continuous speed</td>
<td>Instrumented vehicle</td>
</tr>
<tr>
<td>Bella and Agostini (34)</td>
<td>Italy</td>
<td>$\Delta V = 2.04 \times \Delta V_{85}$</td>
<td>Two-lane rural roads</td>
<td>Continuous speed</td>
<td>Driving simulator</td>
</tr>
<tr>
<td>Montella et al. (18)</td>
<td>Italy</td>
<td>$\Delta V = 2.32 \times \Delta V_{85}$</td>
<td>Two-lane rural roads</td>
<td>Continuous speed</td>
<td>Driving simulator</td>
</tr>
<tr>
<td>Pérez Zuriaga et al. (6)</td>
<td>Spain</td>
<td>$\Delta V = 4.95 + 0.94 \times \Delta V_{85}$</td>
<td>Two-lane rural roads</td>
<td>Continuous speed</td>
<td>GPS</td>
</tr>
<tr>
<td>Castro et al. (30)</td>
<td>Colombia</td>
<td>$\Delta V = 4.48 + 0.71 \times \Delta V_{85}$</td>
<td>Two-lane rural roads</td>
<td>Spot speed</td>
<td>Radar</td>
</tr>
<tr>
<td>McFadden and Elefteriadou (20)</td>
<td>United States</td>
<td>$\Delta V = 1.97 \times \Delta V_{85}$</td>
<td>Two-lane rural roads</td>
<td>Spot speed</td>
<td>Light detecting and ranging guns</td>
</tr>
<tr>
<td>Park and Saccomanno (21)</td>
<td>Canada</td>
<td>$\Delta V = 1.56 \times \Delta V_{85}$</td>
<td>Two-lane rural roads</td>
<td>Spot speed</td>
<td>na</td>
</tr>
<tr>
<td>Misaghi and Hassan (25)</td>
<td>Canada</td>
<td>$\Delta V = 7.55 + 0.97 \times \Delta V_{85}$</td>
<td>Two-lane rural roads</td>
<td>Spot speed</td>
<td>Radar gun</td>
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**Note:** CCR = curvature change ratio of the curve; na = not applicable; NA = not available.
on speed. The curvatures of the curve before and after the tangent had significant effects on speed, but the impact of the curvature before the tangent was more than twice the impact of the curvature after the tangent. The length of the tangent was found to be significant in almost all the previous studies, whereas the other parameters were found significant in only a few studies.

An important result of this study was that operating speeds were affected by the single geometric element as well as the geometric characteristics of the route preceding the element (and departing the element for tangents). Furthermore, the vertical alignment had an important effect on operating speeds, although most standards do not take this effect into account.

Two types of models were calibrated for deceleration and acceleration. The first type of model aimed at drawing operating speed profiles, while the second type aimed at estimating the behavior of individual drivers. The two families of models have similar structures but the values of deceleration and acceleration relative to individual drivers' behavior are much higher. This finding is consistent with Bella et al. (14). Consequently, determination of the deceleration rate based on the operating speeds led to an underestimation of the deceleration and acceleration rates effectively experienced by the drivers. Both deceleration and acceleration increased with curvature and decreased with longitudinal upgrade. Longitudinal downgrade had a significant, positive effect on acceleration but did not have a significant effect on deceleration. The curvature change ratio of the 2 km preceding the curve had a negative effect on deceleration.

The study found different models for the acceleration and deceleration rates. A similar result was obtained by Marchionna and Perco.
(28) and Fitzpatrick and Collins (23). Deceleration and acceleration increased with curvature, while the curvature change ratio of the 2 km preceding the curve had a negative effect on deceleration. These findings were confirmed by the literature. In this study’s models, there was a significant effect of longitudinal grade. The longitudinal downgrade had a significant, positive effect on acceleration but did not have a significant effect on deceleration.

CONCLUSIONS

Several studies have developed operating speed prediction models. Most of the models are based on spot speed data, collected by radar guns, pavement sensors, and similar techniques. Unfortunately, these data collection methods force analysts to make some invalid assumptions about driver behavior modeling: constant operating speed throughout horizontal curves and occurrence of acceleration and deceleration only on tangents. In this study, an instrumented vehicle with GPS continuous speed tracking was used to analyze driver behavior in terms of speed choice and deceleration and acceleration performances and to develop operating speed prediction models. To investigate the continuous speed profile, the noise in the data set was removed; underlying patterns were preserved with a smoothing algorithm. Specifically, the LOWESS algorithm was used. The data used in the study were from a field experiment conducted in Italy on the rural motorway A16 (Naples–Avellino).

Models were developed to predict operating speed in curves and tangents, deceleration and acceleration rates to be used in the operating speed profiles, starting and ending points of constant operating speed in curves, 85th percentile of the deceleration and acceleration rates of individual drivers, and 85th percentile of individual drivers’ maximum speed reduction in the tangent-to-curve transition. An important result of the study is that speed parameters are affected by a single geometric element as well as the geometric characteristics of the route preceding the element (and departing the element for tangents). Furthermore, the vertical alignment has an important effect on operating speeds, although most standards do not take this effect into account.

As far as drivers’ behavior, the study results show that (a) drivers’ speed is not constant along curves, (b) individual drivers’ maximum speed reduction is greater than the operating speed difference in the tangent-to-curve transition, and (c) deceleration and acceleration rates experienced by individual drivers are greater than the deceleration and acceleration rates used to draw the operating speed profiles.

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REFERENCES


The Vehicle User Characteristics Committee peer-reviewed this paper.