Review Article

Operating Speed Prediction Models for Tangent Segments: A Brief Review

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Abstract

This paper provides a review of studies aimed at developing operating speed prediction models for road tangent sections. The review included many studies, conducted in different geographical areas of the world, in terms of road classification, types of vehicles, techniques and devices used in data collection, number of study sites, the principle adopted in extracting the free-flow speed, as well as the topography that the road path passes through and grads of the studied sections. Moreover, this review mentioned the analysis methods adopted in the modeling, and included the model formulas that the researchers have reached in their studies, as it showed all the geometric elements and traffic characteristics that appeared in the models as independent variables. The author has avoided critiquing or evaluating the methodologies of the reviewed research and accordingly this paper has been prepared for documentation only. The author aims primarily to save the effort and time of graduate students and researchers interested in modeling the operating speed on straight segments, as all data and information are arranged in tables and coordinated for this purpose.

Keywords: Speed Model; Operating Speed; Free-Flow Speed; Geometric Design; Tangent Section; Horizontal Curve.

1. Introduction

Vehicle speed is the most important factor in the design process for the various geometric elements of roads. Speed is the key value in assessing design consistency and the primary reference in driver behavior and traffic safety research [1, 2]. In the design stage, the design engineer selects a value of speed known as "design speed" and then the design values of all road features are calculated. Krammes [3], however, reported that the design of highway features based on design speed does not necessarily yield uniformity of operating speeds. Therefore, researchers have started to promote the operating speed concept in an attempt to reduce the disparities of operating speeds.

The operating speed is defined in the Green Book by the American Association of State Highway and Transportation Officials [4] 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".

In other words, eighty-five percent of drivers do not exceed the value of operating speed under free-flow conditions, and for calculation purposes, it is expressed to the 85th percentile free-flow speed [5]. Among other measures, operating speed can be used to evaluate the design consistency of roadways by evaluating the difference between speeds on successive elements [6]. With the widespread development of the concept of "Operating Speed", many models of operating speed prediction on curved sections have been developed for roads with two lanes (e.g. [7-10]), and for multilane roads (e.g. [11-17]). Through a review of literature, it can be concluded that the studies concerned with modeling the relationship between operating speed and elements of straight sections (tangents) and analyzing their properties are less than studies of speeds on curved sections.

This paper aims to provide a comprehensive review of studies that have developed operating speed prediction models on straight sections of various types of roads in different geographic regions of the world. The reviewed information was arranged in tables to facilitate reading by researchers, as it included the classification of the studied roads, the types of vehicles, the techniques and devices used in data collection, the number of study sites, the principle adopted in extracting the free flow speed, the terrain that the road path passes through, as well as the grades of the studied sections.

The remaining sections of this paper are structured as follows: the Second Section provides a review of what has been mentioned in the literature regarding tangents as geometric design elements. In the Third Section, the schemes and methodologies that have been followed in the literature are described. The Forth Section presents the models that were developed. The references are included in the end of this paper.

2. Tangent as a Geometric Design Element

Tangent grade and tangent length were important factors for the researcher in the operating speed approach. Boroujerdian [8] divided the study sections into two categories; upgrade and downgrade, and conducted analyzes for each category independently. On the other hand, Andueza [18] analyzed spot speeds of passenger vehicles measured at the middle points of 36 tangents. The longest straight section was 555 m in this study. The author recommended a further study of the impact of highway geometric characteristics on free-flow speeds of vehicles on long tangent sections. Polus et al. [19] assembled the study sites into four groups based on the tangent length (TL) and radii of preceding (R_1) and succeeding (R_2) horizontal curves: Group 1: TL≤150 m and R_1 and R_2≤250 m, Group 2: 150 m<TL≤1000 m and R_1 and R_2≤250 m, Group 3: 150 m<TL≤1000 m and 250 m<R_1 and R_2≤1000 m, and Group 4: TL>1000 m and R_1 and R_2>1000 m. Separate prediction models for the 85th percentile speed were developed for each of the four groups separately. Model of Group 1 showed that the operating speed is determined primarily by the radii, while the Group 2 model showed that the length of the tangent and the radii are the significant variables. The authors indicated that the models for Group 3 and Group 4 sections are preliminary and they need additional data. Ottesen and Krammes [20] measured speeds of free-flowing passenger cars on long tangent sections at which desired speeds were believed to be attained. A minimum tangent length of 244 m (800 ft) was specified in this study. Pérez-Zuriaga et al. [21] selected tangents with lengths greater than 90 m to develop the operating speed model. The authors reported that speed cannot be fully developed on short tangents because of the influence of the adjacent curves. Dell'Acqua and Russo [22] associated the predictive operating speed models with the segment length. Two models were developed; the first was for the tangents with a length of less than 500 m and the second for tangents with a length greater than 500 m.

Moreover, in terms of the sequence of design elements or alignment combinations on two- lane two-way roads, the horizontal curves were classified into two classes; simple curve and continuous curve, and the straight sections classified as independent or non-independent design elements. Al-Masaeid et al. [23] defined the simple horizontal curve as a circular curve preceded by a straight tangent section with a length of at least 800 m and suggested that a tangent less than 300 meters in length is considered to be a non-independent element. Lamm et al. [24] indicated that a tangent length of up to 260 m (850 ft) may be considered an independent tangent if the traffic speed is approximately 80 km/h. On the other hand, Alkherret et al. [11] divided tangents of multilane highways based on length into three groups; the first group included the shortest of 300 meters, the second included the longest of 500 meters, and the third group included what was in between. The authors performed several analyzes and concluded that the tangent with length less than 300 m may be considered a non-independent design element.

3. Schemes and Methodologies

Table 1 presents a summary of the schemes and methodologies reported in the previous studies that developed models to predict operating speed on tangent sections in different geographical areas of the world. These studies are arranged in descending order of date. The information listed in the table included: the country in which the study was carried out, road classification, number of study sites, the topography that the road path passes through and grads of the studied sections, types of vehicles, techniques, and devices used in data collection, as well as principle adopted in extracting the free-flow speed. Some information was not provided by the authors, so it is denoted as N/A.

As shown in Table 1, most studies have focused on two-lane rural roads while speed studies on other roads (multilane urban/ rural and mountain roads) were limited. The number of study sites ranged from 7 to 251. However, few researchers have expanded their studies to include several classes of roads. Leong et al. [25] used data collected at 16 sites of four-lane divided and undivided highways located in rural and suburban areas. Thiessen et al. [31] selected 126 tangents on urban arterial and 123 tangents on urban collectors. Nie and Hassan [43] analyzed driver speed behavior on horizontal curves and tangents of two-lane rural highways and urban and suburban roads. Fitzpatrick et al. [49] prepared a study to explore the relationship between operating speed and roadway features of tangent sections. The authors selected 79 tangents to collect speed data: 35 on urban/suburban arterial, 22 on urban/suburban collector, 13 on local streets, and 9 on rural arterial. On the other hand, the study sites were similar in their gradations. In general, most of the sites were located in flat terrain areas or with little slope. The large longitudinal grades of the studied tangents were mentioned in only two papers (± 11% in [8] and ± 12% in [26]).

The majority of the studies were analyzed the speeds of passenger cars (PC) and developed their prediction models. Two studies did not include the PC speeds in the analysis. Cardoso [52] studied light and heavy vehicles, while Hernández et al. [26] devoted his paper to heavy vehicles only. Also, some researchers have included other classes of vehicles (such as heavy and light trucks, and buses) in their studies. Among those, four researchers [9, 23, 25, and 51] classified vehicles into several classes and developed a set of models accordingly, as described later.

Besides, the review showed that several data collection techniques were used to record vehicle speed. Speed guns (Radar/Laser guns) and Global Positioning System (GPS) technology were the most commonly used by researchers. Video image analysis has been used to calculate speed in some research [8, 25, 29, and 37]. Also, driving simulators were adopted by three researchers [35, 38, and 46]. However, the technique used to collect the speed data had a major role in determining speed measurements: continuous or spot. Continuous speed data were collected in all the research that used GPS technology and the driving simulator technique. Wang et al. [45] reported that the speed profile data from GPS equipment can provide detailed and accurate information about acceleration and deceleration behavior. Pérez Zuriaga et al. [21] mentioned that it is possible, with this technology, to collect a large amount of continuous speed data without significant influence on drivers. Using vehicles equipped with GPS, Jacob and Anjaneyulu [9] conducted a pilot study to identify the speed observation locations and then used stopwatches to measure the time taken by vehicles to travel over a marked trap length of 15 to 20 m. On the other hand, Bella [46] stated that simulation is an innovative, useful, and increasingly used technique due to its high efficiency and the ease of data collection with it.

As mentioned previously, only free-flow speeds are included in the analysis for modeling purposes. In this matter, some researchers have adopted low traffic flow as evidence for the free flow condition [26, 27, 32, 39 and 45]. Montella et al. [35] and Bella et al. [38] controlled this condition using a driving simulation technique. The rest of the researchers characterized the speed of free flow depending on the headway time. As shown in Table 1, the minimum headway time value was 5 seconds in most cases. Thiessen et al. [31] analyzed their data based on headways ranged between 2 and 10 sec and indicated that using a 2-sec headway's threshold is sufficient and higher values are not necessary for the analysis of operating speeds on urban roads.

Table 1. Summary of Previous Developed Speed Prediction Models

Author	Country	Road classification	Sites	Terrain/Grade (%)	Vehicle Type	Data Collection Technique	FFS definition/Time headway (sec)
Leong et al. (2020) [25]	Malaysia	Four-lane rural/suburban divided/undivided Highways	16	Flat terrain	Different types	Video camera	8
Hernández et al. (2020) [26]	Spain	Two-lane rural roads	59	± 12%	HV	GPS	speed distribution without sudden changes
Mehrabani & Mirbaha (2019) [27]	Iran	Four-lane rural highways	108	From -7.80 to 14.36%	PC	Speed gun	traffic flow was less than 1000 vehicle/hr
Maji et al. (2018) [28]	USA	Two-lane rural highways	251	N/A	PC	N/A	N/A
Zedda and Pinna (2017) [29]	Italy	Multilane urban divided/undivided roads	7	N/A	Different Classes	Radar and digital video camera	N/A
Abbondati et al. (2017) [30]	Italy	Two-lane rural roads	36	≤ 6%	Different Classes	Laser detector	5
Thiessen et al. (2017) [31]	Canada	Urban roads	249	Flat terrain	Different Classes	Portable Traffic Analyzer	2
Hashim et al. (2016) [32]	Egypt	Two-lane rural roads	32	± 1%	N/A	GPS	Low traffic flow
Cvitanić & Maljković (2016) [33]	Croatia	Two-lane rural roads	64	N/A	PC	GPS	5
Boroujerdiana et al. (2016) [8]	Iran	Two-lane rural roads	21	± 11%	PC, HT	Video camera	5

Eboli et al. (2015) [34]	Italy	Two-lane rural roads	15	Flat terrain (± 4%)	PC	GPS	N/A
Montella et al. (2015) [35]	Italy	Two-lane rural roads	N/A	Flat terrain	PC	Driving Simulator	Simulation
Bella et al. (2014) [36]	Italy	Two-lane rural roads	13	−0.8 to 4.7%	PC	GPS	N/A
Montella et al. (2014) [37]	Italy	Four-lane rural divided Highways	46	0.00 - 6.35%	PC	GPS and two cameras	6
Bella et al. (2014) [38]	Italy	Two-lane rural roads	39	−4.3 to +5.3%	PC	Driving simulator	Simulation
Dinh and Kubota (2013) [39]	Japan	Urban Residential Streets with a 30 km/h Speed Limit	85	± 2.5%	PC, LT	Radar gun	One vehicle appeared on a study section
Semeida (2013) [40]	Egypt	Multilane rural highways	41	Flat terrain	PC	Radar gun	5
Jacob & Anjaneyulu (2012) [9]	India	Two-lane rural highways	152	± 2%	Different Classes	GPS and a 15-20 m speed trap with stop watch	N/A
Singh et al. (2012) [10]	USA	Two-lane rural highways	193	N/A	PC, Trucks	N/A	N/A
Esposito et al. (2011) [41]	Italy	Two-lane rural highways	93	0.1 - 2.1%	PC	Radar	5
Dell'Acqua & Russo (2010) [22]	Italy	Rural low-volume roads	80	Level terrain and vertical grades of less than 6%	PC	Light detection & Lidar gun	5
Pérez-Zuriaga et al. (2010) [21]	Spain	Two-lane rural roads	53	± 4%	N/A	GPS	5
Dell'Acqua et al. (2007) [42]	Italy	Two-lane rural highways	36	Level terrain and vertical grades of less than 6%	PC	Laser detector	5
Nie and Hassan (2007) [43]	Canada	Two-lane rural highways and urban/suburban roads	10+	Level terrain	PC	Test vehicle with magnetic sensor and GPS	5
Ali et al. (2006) [44]	USA	Four- lane urban streets	N/A	N/A	PC	Radar gun	7
Wang et al. (2006) [45]	USA	Low-speed urban streets	35	± 4%	PC	GPS	Only daytime trips during off-peak time periods
Bella (2005) [46]	Italy	Two-lane rural roads	26	± 6%	PC	Driving simulator	6
Figueroa-Medina & Tarko (2005) [47]	USA	Two-lane rural highways	N/A	flat terrain −7.10 to 6.3%	N/A	Laser gun and rubber tubes	5
Crisman et al. (2005) [48]	Italy	Two-lane rural roads	10	± 3%	PC	Laser detector	5
Fitzpatrick et al. (2005) [49]	USA	Arterial, collector, and local Roads	79	± 4%	N/A	Laser gun	5
Fitzpatrick et al. (2001) [50]	USA	Suburban Street	36	± 4%	N/A	Laser gun	5
Polus et al. (2000) [19]	USA	Two-lane rural highways	162	N/A	PC	Radar and Counter/Classifier	5
Andueza (2000) [18]	Venezuela	Mountain Roads	36	± 3%	PC	Radar gun	6
AL-Masaeid et al. (1999) [51]	Jordan	Two-lane rural highways	22	Flat terrain	PC, LT, Trucks	Laser gun	6
Cardoso (1995) [52]	Portuguese	Two-lane rural highways	26	N/A	LV, HV	N/A	6
Krammes et al. (1995) [53]	USA	Two-lane rural highways	66	± 5%	PC	Radar gun	N/A
AL-Masaeid et al. (1995) [23]	Jordan	Two-lane rural highways	N/A	Flat terrain	PC, LT, Trucks	40-m speed trap	6

4. Operating Speed Models

Speed models developed in previous research along with analysis approaches are listed in Table 2. As shown, the multiple linear regression method (MLR) was the preferred approach by most researchers in developing the speed prediction models. The multiple non-linear regression analysis (MNLR) was used in two studies [9, 52], while the simple regression was used in one study [34]. Also, the Ordinary Least Squares (OLS) method was used in speed modeling. In Italy, Dell'Acqua and Russo [22] and Esposito et al. [41] adopted the OLS method to develop the 85th percentile speed models on rural roads. In the USA, Figueroa Medina and Tarko [47] used two approaches for modeling panel data: OLS-PD without random effects and generalized least squares (GLS) with random effects (RE).

The model formulas allow predicting any user-specified percentile (from 5th to 95th percentile speed). Moreover, Dinh and Kubota [39] used a simultaneous equation regression with a three-stage least-square (3SLS) estimator for the modeling effort. Furthermore, Singh et al. [10] and Semeida [40] preferred to use the Artificial Neural Network (ANN) for analysis.

On the other hand, the development of the 85th percentile speed prediction models has been the main goal of most researchers. Prediction models for space mean speed were developed in four studies ([8, 29, 39, 44]). Boroujerdiana et al. [8] presented standard deviation speed models in addition to space mean speed models. Moreover, Wang et al. [45] developed two models: the first was with the 85th percentile speed and the second with the 95th percentile speed as dependent variables. Cardoso [52] developed models for the 15th and the 85th percentiles of observed free speeds. Figueroa Medina and Tarko [47] developed a model that allowed the user to calculate percentages from 5 to 95 for speed prediction. By reviewing the models developed in various previous studies, the following notes can be drawn:

- There are researches presented several models according to the type of vehicle [25, 26, 9, 23, 51], tangent length [19, 22, 45], tangent grade [8], and speed limit [10, 28, 49, 50].

- Tangent length is the most variable shown in speed models as a predictor.

- The independent variables in rural road models are less than in urban roads.

However, equations, dependent and independent variables, and the coefficient of determination (R^2) for each model are detailed in Table 2.

Table 2. Speed Models in Literature

Leong et al. [25]: Multiple Linear Regression

Authors classified vehicles into five classes:
 Class 1—Cars/small vans/ utilities;
 Class 2—Trucks (with 2 axles)/ large vans;
 Class 3—Large trucks/ trailers/ heavy vehicles with 3 axles or more;
 Class 4—Buses;
 Class 5—Motorcycles.
Three models were developed:

- Model 1— free flow speed of all vehicles (Class 1, 2, 3, 4, and 5):

$$FFS = BFFS - 43.502\,(3.65 - LW) - 4.462\,(1.8 - LC) - 3.437\,(APD) - 21.058(LD)$$ $R^2 = 0.954$

- Model 2— free flow speed of Class 1, 2, 3, and 4:

$$FFS = BFFS - 44.262\,(3.65 - LW) - 4.308\,(1.8 - LC) - 3.431\,(APD) - 21.058(LD)$$ $R^2 = 0.949$

- Model 3— free flow speed of only Class 1:

$$FFS = BFFS - 41.878\,(3.65 - LW) - 4.142\,(1.8 - LC) - 3.426\,(APD) - 20.329(LD)$$ $R^2 = 0.946$

Where:
 BFFS = Base free flow speed (100 km/h for multilane highways);
 LW = Lane width (ideal lane width = 3.65 m);
 LC = Lateral clearance, adjustment of shoulder width for the outer lane, and adjustment of median clearance for the inner lane (ideal lateral clearance = 1.8 m);
 APD = Access point density; and
 LD = Lane dummy (0 if inner lane, 1 if outer lane).

Hernández et al. [26]: Forward Multiple Linear Regression

$$V_{85L} = 85.98 - \frac{58.09}{e^{0.003\,L}} - 1.02\,g$$ $R^2_{adj} = 0.84$

$$V_{85U} = 45.58 + \frac{44.49}{e^{0.0024\,CCR_{C\_T\_C}}}$$ $R^2_{adj} = 0.77$

In case the 85th percentile speed of the preceding horizontal is available

$$V_{85L} = 5.70 + 1.05\,V_{85,pc} - 0.69\,g$$ $R^2_{adj} = 0.90$

$$V_{85U} = 72.95 - \frac{40.54}{e^{0.0017\,L}} + 0.39\,V_{85,pc}$$ $R^2_{adj} = 0.85$

Where:
 V_{85L} = 85th percentile of the speed distribution for loaded trucks (km/h);
 V_{85U} = 85th percentile of the speed distribution for unloaded trucks (km/h);
 $V_{85,pc}$ = 85th percentile of the distribution of speeds of the preceding horizontal curve (km/h);
 L = tangent length (m);
 g = grade (%); and
 $CCR_{C\_T\_C}$ = Curvature Change Rate of the tangent and its adjacent horizontal curves (gon/km).

Mehrabani and Mirbaha [27]: Multiple Linear Regression

$V_{85} = 93.567 + 3.220\ LN - 0.485\ SLP + 6.249\ MTRSC - 4.307\ AD - 8.041\ LULN$ $R^2_{adj} = 0.730$

Where:

  LN = Segment length (km);

  SLP = Slope (%);

  $MTRSC$ = Median and roadside type (1 if guardrail and flat; otherwise);

  AD = Access density; and

  $LULN$ = Adjacent land use length (km).

Maji et al. [28]: Forward Multiple Linear Regression

Three models were developed:

- Model 1—85th percentile speed for lower speed limit highways ($PSL \leq 45$ mil/h):

  $V_{85} = 16.539 + 0.678\ PSL$ $R^2_{adj} = 0.27$

- Model 2—85th percentile speed for higher speed limit highways ($PSL \geq 50$ mil/h):

  $V_{85} = 10.960 + 0.840\ PSL + 0.067\ SN - 0.028\ IRI$ $R^2_{adj} = 0.71$

- Model 3—85th percentile speed for all highways:

  $V_{85} = 4.395 + 0.889\ PSL + 0.084\ SN$ $R^2_{adj} = 0.85$

Where:

  PSL = posted speed limit;

  SN = skid number; and

  IRI = international roughness index.

Zedda and Pinna [29]: Forward Multiple Linear Regression

Two models were developed:

- Model 1— space mean speed for all roads

  $V_{ms} = 14.21 - 0.05\ F - 0.64\ F_{in,out} - 11.84\ C + 0.03\ TL + 3.84\ O + 4.07\ LW$ $R^2_{adj} = 0.810$

- Model 2— space mean speed for two lane roads

  $V_{ms} = 21.80 - 0.60\ F_{in,out} + 4.11\ M + 0.05\ TL$ $R^2_{adj} = 0.845$

Where:

  F = flow (vehicle/ 5 min intervals);

  $F_{in,out}$ = number of vehicles entering and leaving traffic stream aggregated in 5 min intervals;

  C = presence of crosswalk;

  TL = tangent length (m);

  O = type of left-lateral obstacle; and

  LW = lane width (m).

Abbondati et al. [30]: Multiple Linear Regression

$V_{85} = 15.45\ \log_{10}(L_T) + 0.57\ V_{85Cp}$ $R^2 = 0.73$

Where:

  L_T = tangent length (m); and

  V_{85Cp} = operating speed on preceding curve (km/h).

Thiessen et al. [31]: Ordinary Least-Squares Applied to Panel Data (OLS-PD)

Three models were developed:

  1- A&C Model: for arterial and collector locations

  Operating Speed $= f(x_1, x_2, x_3, x_4)$ $R^2 = 0.78$

Three models were developed:

  2- A Model: for arterials only

  Operating Speed $= f(x_1, x_2, x_3, x_4)$ $R^2 = 0.84$

Three models were developed:

  1- C Model: for collectors only

  Operating Speed $= f(x_1, x_2, x_3, x_4, x_5)$ $R^2 = 0.77$

Where:

  x_1 = General road features: Median width (m); Length (m); Posted Speed Limit (km/h); and number of ways.

  x_2 = Roadside features: Access density, Pole density, and Tree density (per km); and Average object offset.

  x_3 = Traffic composition: Average vehicle length (m).

  x_4 = On-road features: Road width (m); Pedestrian crossing; Bus stop; and Bike Route.

  x_5 = Roadside treatment.

Hashim et al. [32]: Multiple Linear Regression

maximum operating speed at the independent tangent (tangent length $T_L > 200$ m):

$$V'_{85} = 84.34 + 0.593 \sqrt{T_L}$$ $R^2 = 0.851$

Where:

T_L = tangent length (m).

Cvitanić and Maljković [33]: Stepwise Multiple Linear Regression

the maximum operating speeds on tangent section

$$V_{85}^T = 13 + 6.92 \ln R_{bef} + 3.69 \ln R_{aft} + 2.97 \ln T$$ $R^2 = 0.85$

Where:

R_{bef} = radius of the previous curve;

R_{aft} = radius of the following curve; and

T = tangent length.

Boroujerdiana et al. [8]: Multiple Linear Regression

Mean and standard deviation speed models for Downgrade sections:

$$Mean = 2.596 + 6.442 \frac{1}{G} + 0.014\, G^3 + 0.687\, V_0 - (9.360 \times 10^{-6})V_0^3 - 0.017\, fr_1 + 5.993\, VHC_1 + 0.423\, PSL$$ $R^2 = 0.69$

$$Lnstdev = 1.491 + 0.695 \frac{1}{G} + 0.0574\, G + 0.003\, V_0 - (6.2 \times 10^{-4})L - 0.035\, SHW + 0.108\, VHC_1 + 0.203\, SHT$$ $R^2 = 0.20$

Mean and standard deviation speed models for Upgrade sections:

$$Lnmean = 1.938 + 0.012\, V_0 - (9.8 \times 10^{-12})V_0^5 + 0.215 \frac{1}{G} + 0.201 \ln L - (7.47 \times 10^{-7})L^2 + 0.007\, SHW^2$$
$$+ (3.3 \times 10^{-4})fr_1 + 0.086\, VHC_1$$ $R^2 = 0.67$

$$Lnstdev = 0.434 + 0.270\, W + 0.075\, G + 0.335 \frac{1}{G} - 0.104\, VHC_1 + 0.012\, mean - (4.2 \times 10^{-4})L$$ $R^2 = 0.33$

Where:

mean and *stdev* = speed normal distribution parameters (km/h);

G = slope of tangent (%);

V_0 = the initial speed of vehicle at the start point of tangent (km/h);

fr_1 = flow rate in same direction (veh/h);

PSL = posted speed limit (km/h);

VHC_1 = 1 if the vehicle is a passenger car and 0 otherwise;

L = the length of tangent (m);

W = lane width (m);

SHW = right shoulder width (m); and

SHT = 1 if the right shoulder is paved and 0 otherwise.

Eboli et al. [34]: Simple Regression

$$V_{85} = 0.762\, V_{85,i-1} + 13.994 \log_{10}(L) - 10.721$$ $R^2_{adj} = 0.902$

Where:

L = tangent length; and

$V_{85,i-1}$ = operating speed for previous segment.

Montella et al. [35]: Multiple Linear Regression

$$V_{85\_tangent} = 137.076 - \frac{2.480}{R_{cb}}$$ $R^2 = 0.620$

Where:

R_{cb} = radius of the curve preceding the tangent (km).

Bella et al. [36]: Multiple Linear Regression

$$V_{85T>200m} = 102.711 - 2.183\, i + 0.006\, L_T$$ $R^2 = 0.78$

Where:

$V_{85T>200m}$ = 85th percentile speed at the midpoint of the independent tangent (km/h);

i = local longitudinal grade (%);

L_T = length of the tangent (m).

Montella et al. [37]: Multiple Linear Regression

$$V_{85\_tangent} = 139.543 + 1.751\, L_t - \frac{4.983}{R_{cb}} - 2.507\, G_u - 0.068\, CCR_2$$ $R^2 = 0.804$

Where:

L_t = Length of tangent (km);

$1/R_{cb}$ = Horizontal curvature of the curve preceding tangent (1/km);

G_u = Equivalent upgrade (%); and

CCR_2 = Curvature change ratio of the 2 km preceding the curve.

Bella et al. [38]: Multiple Linear Regression

$$V_{85TD>200m} = 88.984 - \frac{801.717}{R_P} + 0.012\,L_T \qquad\qquad R^2 = 0.85$$

Where:

$V_{85TD>200m}$ = 85th percentile speed during daytime for tangents longer than 200 m (km/h);

R_P = Radius for the previous curve (m); and

L_T = tangent length (m).

Dinh and Kubota [39]: Three-stage Least Square (3SLS) Analysis

Two models were developed:

Dependent variable in the first model is logarithm of 85th percentile speed of tangent (km/h):

$$\log V_{85T} = 3.5383 + 0.0323\,NL + 0.0005\,L + 0.0269\,S - 0.0082\,RSD + 0.0285\,W \qquad R^2 = 0.559$$

Dependent variable in the second model is logarithm of mean speed of tangent (km/h):

$$\log V_{meanT} = 3.4484 + 0.00039L + 0.0125\,RSW - 0.0269\,RSD + 0.0313\,W \qquad R^2 = 0.577$$

Where:

NL = Number of lanes;

L = Length of street section (m);

S = Sidewalk indicator (1 if sidewalks are available on both sides; 0 otherwise);

RSW = Right safety strip width (m)

RSD = Roadside object density (per 100 m); and

W = Carriageway width (m).

Semeida [40]: Stepwise Multiple Linear Regression and Artificial Neural Networks (ANN)

The best regression model:

$$V_{85} = 44.6 - 25.3\,SA + 12.3\,SW + 0.273\,PSL \qquad\qquad R^2 = 0.761$$

For ANN model: It is found that the independent variables are: *PW*, *MW*, *SA*, and *PSL*. $\qquad R^2 = 0.978$

Where:

SA = Existence of side access (1 if exiting; 0 otherwise) (m);

SW = Right shoulder width (m);

PSL = Posted speed limit (km/h);

PW = Pavement width in one direction (m); and

MW = Median width (m).

Jacob and Anjaneyulu [9]: Nonlinear Regression

$$V_{Car} = 47.50 + 3.6\,PTLS^{0.312} \qquad\qquad R^2 = 0.89$$

$$V_{Two-wheeler} = 44.10 + 3.6\,PTLS^{0.300} \qquad\qquad R^2 = 0.87$$

$$V_{Bus} = 45.00 + 3.6\,PTLS^{0.281} \qquad\qquad R^2 = 0.90$$

$$V_{Truck} = 37.50 + 3.6\,PTLS^{0.335} \qquad\qquad R^2 = 0.95$$

where

$PTLS$ = Length of approaching tangent up to the point of speed observation (m).

Singh et al. [10]: Neural Networks Analysis

Four models were developed:

Model 1: with posted speed but without accident data.

Model 2: without posted speed and without accident data.

Model 3: with posted speed and with accident data.

Model 4: without posted speed but with accident data.

Dell'Acqua and Russo [22]: Ordinary Least-squares (OLS)

$$V_{85T>500\,m} = 79.67 + 2.8 \times 10^{-3}\,L + 0.011R_{PC}^{3/2} - 0.23R_{PC} + 0.15\,V_{85PC} - 2.40\,INT - 4.94\,PD \qquad R^2 = 0.83$$

$$V_{85T<500\,m} = 61.65 + 2.4 \times 10^{-4}\,R_{PC}^{2} - 0.11R_{PC} + 0.017\,D + 0.30\,V_{85PC} - 3.29\,INT - 3.41\,PD \qquad R^2 = 0.89$$

Where:

$V_{85T>500\,m}$ = predicted operating speed on tangent segment with lengths greater than 500 m (km/h);

$V_{85T>500\,m}$ = predicted operating speed on tangent segment with lengths less than 500 m (km/h);

L = total tangent length (m);

R_{PC} = radius of the preceding curve (m);

V_{85PC} = operating speed in the middle section of the preceding curve (km/h);

INT = intersection indicator, equal to 1 if the intersection is located 150 m before or after the surveyed location and 0 otherwise;

D = the distance from the survey point to the end section of the preceding horizontal curve (m); and

PD = pavement distress indicator.

Esposito et al. [41]: Ordinary Last-Square (OLS)

Two models were developed:

In first Model: V_{85} values were determined at middle sections

$$V_{85} = 98.94 + 8.1 \times 10^{-2}\, CCR_m + 10^{-5}\, L_T^2 \qquad\qquad R^2 = 0.68$$

In second Model: V_{85} values were determined at middle sections and at first and third quarter distance tangent segment

$$V_{85} = 115.48 - 5 \times 10^{-6}\, L_T^2 - 0.12\, CCR_m + 5.83\,|S| - 14.02\, VG \qquad\qquad R^2 = 0.82$$

Pérez-Zuriaga et al. [21]: Multiple Linear Regression

Operating speed model for independent tangent only (tangent length>90 m)

$$V_{85} = V_{85C} + \left(1 - e^{-\lambda L}\right).(V_{des} - V_{85C}) \qquad\qquad R^2 = 0.52$$

Where:

$\lambda = 0.00135 + 7.00625 \times 10^{-6}(R - 100)$

$V_{85C} = 97.4254 - 3310.94/R$

λ = calibration to minimize the mean squared error (MSE);

V_{85c} = 85th percentile speed on previous curves obtained from the proposed speed model for curves (km/h);

V_{des} = desired speed (km/h), [110 km/h];

R = radius of previous curve (m); and

L = tangent length (m).

Dell'Acqua et al. [42]: Multiple Linear Regression

Five points were selected for speeds collecting: center, starting, finishing, and quarters of tangents

$$V_{85T} = 15.45\, \log_{10} L_T + 0.57\, V_{85Cp} \qquad\qquad R^2 = 0.73$$

Where:

L_T = tangent length (m); and

V_{85Cp} = speed on preceding curve (km/h);

Nie and Hassan [43]: Multiple Linear Regression

The lengths of the tangents analyzed ranged between 30 and 200 meters.

Two-Lane Rural Highways:

$$V_{85} = 81.782 + 0.086\, L_T \qquad\qquad R^2_{adj} = 0.661$$

Urban/Suburban Roads:

$$V_{85} = 23.686 + 0.807\, V_P \qquad\qquad R^2_{adj} = 0.698$$

Where:

L_T = tangent length (m); and

V_P = posted speed limit (km/h).

Ali et al. [44]: Multiple Linear Regression

$$FFS_{Mean} = 37.4 + 6.8\, PS_{45} + 2.6\, PS_{40} + 13.5\, SL \qquad\qquad R^2 = 0.87$$

$$FFS_{85th} = 37.4 + 8.0\, PS_{45} + 2.1\, PS_{40} + 3.6\, MT + 13.0\, SL \qquad\qquad R^2 = 0.86$$

Where:

FFS_{Mean} = mean free flow speed (mph);

FFS_{85th} = 85th percentile free-flow speed (mph);

PS_{45} = posted speed limit of 45 mph;

PS_{40} = posted speed limit of 40 mph;

SL = segment length (ft); and

MT = median type.

Wang et al. [45]: Stepwise Multiple Linear Regression

$$V85 = 31.565 + (6.491 \times lane.num) - (0.101 \times roadside) - (0.051 \times driveway) - (0.082 \times intersection) + (3.01 \times curb) - (4.265 \times sidewalk) - (3.189 \times parking) + (3.312 \times land.use1) + (3.273 \times land.use2) \qquad R^2 = 0.67$$

$$V95 = 31.143 + (6.671 \times lane.num) - (0.096 \times roadside) - (0.048 \times driveway) - (0.078 \times intersection) + (3.32 \times curb) - (4.424 \times sidewalk) - (2.864 \times parking) + (3.507 \times land.use1) + (3.379 \times land.use2) \qquad R^2 = 0.67$$

Where:

$V85$ = 85th percentile cruising speed (mph);

$V95$ = 95th percentile cruising speed (mph);

roadside = density of roadside objects divided by their average offsets from roadside [number of objects per mile/offsets (ft)];

driveway = density of driveways (number of driveways per mile);

lane.num = number of lanes;

curb = 0 if there is no curb; otherwise, curb = 1;

sidewalk = 0 if there is no sidewalk; otherwise, sidewalk = 1;

parking = 0 if there is no on-street parking; otherwise, parking = 1;

land.use1 = 0 and *land.use2* = 0 if land use is commercial; *land.use1* = 1 and *land.use2* = 0 if land use is residential; otherwise (was "else"), *land.use1* = 0 and *land.use2* = 1.

Bella [46]: Multiple Linear Regression

The length of tangents range from 150 m to 2200 m. Two models were developed; all tangents were used in the first, while tangents with 150 m long were excluded in developing the second model.

$$V_{85} = 126.4 - 0.073\, CCRs_{(i-1)} + 0.027\, L - 1.61\, i \qquad\qquad R^2 = 0.88$$

$$V_{85} = 127.9 - 0.079\, CCRs_{(i-1)} + 0.026\, L - 1.86\, i \qquad\qquad R^2 = 0.92$$

Where:

$CCRs_{(i-1)}$ = Curvature Change Rate of the curve that precedes the tangent (gon/km);

L = length of the tangent (m); and

i = longitudinal grade of the tangent (%).

Figueroa-Medina and Tarko [47]: Ordinary Least-Squares Applied To Panel Data (OLS-PD)

The model allows calculation of different values for operating speed based on specified percentages.

$$
\begin{aligned}
V_p = {}& 57.137 - 0.071\, TR - 3.082\, PSL_{50} - 0.131\, GR - 1.034\, RES + 2.38 \times 10^{-3}\, SD - 1.67 \times 10^{-6}\, SD^2 - 0.422\, INT \\
& + 0.040\, PAV + 0.394\, GSW + 0.054\, USW - 2.233\, FC + 5.982\, Z_p + 1.428\, (Z_p \times PSL_{50}) \\
& + 0.061\, (Z_p \times GR) + 0.292\, (Z_p \times INT) - 0.038(Z_p \times PAV) - 0.012\, (Z_p \times CLR)
\end{aligned}
\qquad R_{adj}^2 = 0.844
$$

Where:

TR = percentage of trucks;

PSL_{50} = equal to 1 if the posted speed limit is 50 mph, and equal to 0 if the posted speed limit is 55 mph;

GR = highway grade (%);

RES = equal to 1 if the segment has 10 or more residential driveways per mile, 0 otherwise;

SD = sight distance (ft);

INT = equal to 1 if an intersection is located 350 ft before or after the spot, 0 otherwise;

PAV = pavement width, includes the traveled way and both paved shoulders (ft);

GSW = total gravel shoulder width (ft);

USW = total untreated shoulder width (ft);

CLR = roadside clear zone, includes the total gravel and total untreated shoulders (ft);

FC = equal to 1 if the spot is located on a flat curve (radius larger than 1,700 ft), 0 otherwise; and

Z_p = standardized normal variable corresponding to a selected percentile.

Crisman et al. [48]: Multiple Linear Regression

$$V_{85T} = -2.351 + 18.104\, \log_{10} L + 0.585\, V_{85cp} \qquad\qquad R^2 = 0.88$$

Where:

L = tangent length (m); and

V_{85cp} = operating speed of the preceding curve (km/h);

Fitzpatrick et al. [49]: Forward Multiple Linear Regression

Model for all functional classes with posted speed limit of 73 km/h (20% alpha level)

$$FF85 = 25.9 + 0.83\, SL - 0.054\, AD \qquad\qquad R^2 = 0.923$$

Models of operating speed as linear function of posted speed limits by S/U arterial, S/U collector, S/U local, rural arterial

$$FF85\ (S/U\ arterial) = 13.952\ 0.963\, SL \qquad\qquad R^2 = 0.86$$

$$FF85\ (S/U\ collector) = 34.021 + 0.639\, SL \qquad\qquad R^2 = 0.41$$

$$FF85\ (S/U\ local) = 16.607 + 0.776\, SL \qquad\qquad R^2 = 0.14$$

$$FF85\ (rural\ arterial) = 58.689\ 0.517\, SL \qquad\qquad R^2 = 0.81$$

Where:

SL = posted speed limit (km/h); and

AD = access density, number of access points per 1.6 km.

Fitzpatrick et al. [50]: Multiple Linear Regression

$$V_{85}\ (with\ speed\ limit) = 29.180 + 0.701 \times (Speed\ Limit) \qquad\qquad R^2 = 0.543$$

$$V_{85}\ (without\ speed\ limit) = 18.688 + 15.050 \times (Average\ Lane\ Width) \qquad\qquad R^2 = 0.270$$

Polus et al. [19]: Nonlinear Regression

Sites were classified into four groups:

R_1 and $R_2 \leq 250$ m, $TL \leq 150$ m. $\qquad V_{85} = 101.11 - 3420/GM_S$ $\qquad\qquad R^2 = 0.553$

R_1 and $R_2 \leq 250$ m, $150 \leq TL \leq 1000$ m. $\qquad V_{85} = 105.00 - 28.107/e^{0.00108 \times GM_L}$ $\qquad\qquad R^2 = 0.742$

R_1 and $R_2 > 250$ m, $150 \leq TL \leq 1000$ m. $\qquad$ no successful models were identified

$TL > 1000$ m. $\qquad V_{85} = 105.00 - 22.953/e^{0.00012 \times GM_L}$ $\qquad\qquad R^2 = 0.838$

Where:

GM_L = geometric measure of tangent section and attached curves for long tangent lengths (m^2); and

GM_S = geometric measure for short tangent lengths (m).

$$GM_L = \frac{TL \times \sqrt{R_1 \times R_2}}{100}$$

$$GM_S = \frac{R_1 + R_2}{2}$$

TL = tangent length (m);

R_1, R_2 = previous and following curve radii (m);

Andueza [18]: Multiple Linear Regression

$V_{85r} = 100.69 + 3032 \times \dfrac{1}{R_a} + 27.819\,L_a$	$R^2 = 0.79$
$\bar{V}_r = 87.65 + 2064 \times \dfrac{1}{R_a} + 17.353\,L_a$	$R^2 = 0.73$

Where:

V_{85r} = 85th percentile of tangent speed (km/h);

$\tilde{V}_r$ = average speed on tangent (km/h);

R_a = radius of the previous curve (m); and

L_a = length of the tangent (km).

AL-Masaeid et al. [51]: Multiple Linear Regression

$V85T_p = 40.29 + 0.62\,SL - 1.72\,PR$	$R^2 = 0.57$
$V85T_i = 50.36 + 0.28\,SL - 1.21\,PR$	$R^2 = 0.56$
$V85T_t = 56.03 - 0.76\,PR$	$R^2 = 0.48$
$V85T_a = 48.55 + 0.31\,SL - 1.19\,PR + 11.18\,P - 9.36\,H$	$R^2 = 0.82$

Where:

$V85T_p$, $V85T_i$, $V85T_t$, and $V85T_a$ = operating speeds of passenger cars, light trucks, trucks, and all vehicles, in km/h;

SL = posted speed limit for a given type of vehicle (km/h);

PR = rainfall intensity in (mm/h);

P = dummy variable to account for vehicle type (1 for passenger cars, and 0 otherwise); and

H = dummy variable to account for vehicle type (1 for trucks, and 0 otherwise).

Cardoso [52]: Multiple Non-Linear Regression

$Vt15 = 29.56 - \dfrac{329.138}{Rp} + 4.15\,LW + 2.64\,SW + 0.0016\,L + 0.0119\,Rf + 0.0102\,Rp$	$R^2 = 0.84$
$Vt85 = 41.67 - \dfrac{548.892}{Rp} + 5.95\,LW + 5.28\,SW + 0.0165\,L + 0.0207\,Rf + 0.0238\,Rp$	$R^2 = 0.90$

Where:

$Vt15$ = 15th percentile of tangent speed (km/h);

$Vt85$ = 85th percentile of tangent speed (km/h);

Rp = radius of the preceding curve segment (m);

LW = combined lane width (m);

SW = shoulder width (m);

L = length of the tangent segment (m); and

Rf = radius of the next curve segment (m).

Krammes et al. [53]: Multiple Linear Regression

On long tangent (>244 m): the statistically significant variables were the geographic region and the terrain.

AL-Masaeid et al. [23]: Multiple Linear Regression

$V_P = 115.0 - \dfrac{3.772}{LT} - 0.70\left(\dfrac{DF_1 \times DF_2}{DF_1 + DF_2}\right)$	$R^2 = 0.68$
$V_L = 106.0 - \dfrac{3.391}{LT} - 0.73\left(\dfrac{DF_1 \times DF_2}{DF_1 + DF_2}\right)$	$R^2 = 0.71$
$V_T = 99.3 - \dfrac{3.099}{LT} - 0.75\left(\dfrac{DF_1 \times DF_2}{DF_1 + DF_2}\right)$	$R^2 = 0.72$
$V_A = 108.3 - \dfrac{3.498}{LT} - 0.71\left(\dfrac{DF_1 \times DF_2}{DF_1 + DF_2}\right)$	$R^2 = 0.72$

Where:

V_P, V_L, V_T, and V_A = 85th percentile speed of passenger cars, light trucks, trucks, and all vehicles (km/h), respectively;

LT = length of common tangent (m) [$LT \leq 300$ m]; and

DF_1 and DF_2 = deflection angles of first and second curve (degrees), respectively.

5. Conclusion

This paper aimed to provide a comprehensive review of studies that have developed operating speed prediction models on straight sections of various types of roads in different geographic regions of the world. The information included the classification of the studied roads, the types of vehicles, the techniques and devices used in data collection, the number of study sites, the principle adopted in extracting the free-flow speed, the terrain that the road path passes through, as well as the grades of the studied sections. The previous literature review showed that Tangent grade and length were essential factors for the researcher in the operating speed approach and most studies have focused on two-lane rural roads, while studies on other types of roads were limited. In addition, the majority of the studies were concerned with the speeds of passenger cars. Moreover, most of the study sites were located in flat terrain areas or with a slight slope. On the other hand, Speed guns and laser guns were the most commonly used to measure vehicle speed, and some research used video image analysis to calculate speed. However, driving simulators were adopted by three researchers for their high efficiency and ease of data collection. According to Operating Speed Models, the multiple linear regression method (MLR) was the preferred approach by most researchers in developing speed prediction models. By reviewing the models developed in various previous studies, it can be concluded that tangent length is the most variable shown in speed models as a predictor, and the independent variables in rural road models are less than in urban roads. This study provides data and information about straight-segment operating speed to save time and effort for researchers. The author recommended a further study of the impact of highway geometric characteristics on the free-flow speeds of vehicles on long tangent sections.

6. Declarations

6.1. Data Availability Statement

Data sharing is not applicable to this article.

6.2. Funding

6.3. Acknowledgements

6.4. Conflicts of Interest

The author declare no conflict of interest.

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