Free-Flow Speed Profile Prediction for Tangent Segments on Urban Roads

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Abstract. The free-flow speed profile is one of the essential elements in the design and operation of the roads. The speed profile is employed to improve road design, traffic emissions models, fuel consumptions models, evaluate the consistency, among others. Speed profiles are built with speed, acceleration, and deceleration models. Therefore, understanding how different factors affect speed, acceleration, and deceleration is a critical research question. Many studies have focused on rural roads and only a few on urban roads. In urban environments, studies did not yet reach conclusive results. This research attempted to address these limitations by developing speed, acceleration, and deceleration models in urban tangents under free-flow conditions in the city of Loja, Ecuador. Three different tangents were selected: before stop-controlled intersections, before signal-controlled intersections, and before roundabout intersections. Speeds of light vehicles, equipped with GPS, were collected in 13 tangents with 45 drivers. Geometric and operation characteristics were also collected: geometric elements of the street, street environment, driver, and vehicle-related. Forty-five speed, acceleration, and deceleration regression models were calibrated and validated. This research expands the knowledge of the most influential variables on speed in various urban settings, offering useful information for city planners and designers.

Keywords: Free-flow speed profile · Speed models · Acceleration and deceleration models · Urban tangents

1 Introduction

The free-flow, operating, or 85th percentile speed profile is one of the elements that improve the design and operation of streets and highways. This profile allows determining traffic emissions [1], fuel consumption [2], evaluating consistency [3], among others. The speed profile can be used during the highway project or in its operation. When the road is already in operation, speed is collected on-site, and in projects, it must be calculated indirectly using prediction models. These models must find the relationship between speed, acceleration, and deceleration with the characteristics related to the driving. This relationship is a critical research question and is complicated to answer, so the studies have not yet reached conclusive results. Answering this question

C. Klein et al. (Eds.): SMARTGREENS 2021/ VEHITS 2021, CCIS 1612, pp. 371–391, 2022.
https://doi.org/10.1007/978-3-031-17098-0_19

also would help controlling vehicle speed [4–7]. In general, five parameters influencing speed, acceleration, and deceleration in free-flow conditions: driver, vehicle, roadway, environment, traffic operation and control [8].

Driver characteristics impact their vehicle speed choice, such as personality [7, 9, 10], age [11–14], gender [14], driving experience [14], speeding intention [15], among others [16–19]. Speed choice also is influenced by the vehicle characteristics, such as the age of the vehicle [7], vehicle class [7, 16, 20, 21], or vehicle length [22]. Also, roadway impacts on the speed choice, such as number of lanes [16, 23, 24], roadway width [23, 25], lane width [14, 25, 26], length of the street [16, 23], road grade [27], road surface condition [8, 16, 24], or pavement markings [27, 28]. Environment also plays an important role on the driver speed choice, specially, access density [16], roadside objects density [16, 23, 29], parking presence [7, 16, 24], crash barriers [29], bus stop presence [29], adjacent land uses [7, 16, 22], lighting conditions [30–32] weather conditions [33, 34], day of the week [24, 33]. On the other hand, traffic operation and control could also affect speed choice, for instance, the speed limits [14, 35] or the posted speed [36], speed enforcement system [37], speed cameras [36], photo-radar presence [38]. Despite the effort to build prediction models with these parameters, the results have been mixed. Furthermore, little research focused on urban streets that are complex to study.

Therefore, the present study aims to analyze the relationship between various parameters that affect the choice of speed, acceleration, and deceleration in free-flow conditions. Urban tangents were analyzed in three types of intersections: stop-controlled, signal-controlled, and roundabouts. Preliminary results of this study on signalized intersections can explore it in [39] and free-flow speeds [40]. The article is organized as follows: materials y methods, pattern analysis, results, and conclusions. The materials and methods sections describe the sample size, measurement site, equipment, and driver selection. Also, it details the data collection and processing. Then the pattern analysis is shown, which evaluates the parameters and their influence on the variables of speed, acceleration, and deceleration. Subsequently, in the result section, the calibration of the prediction models and their respective validation are shown. And finally, the principal conclusions are presented.

2 Materials and Methods

2.1 Sample Size

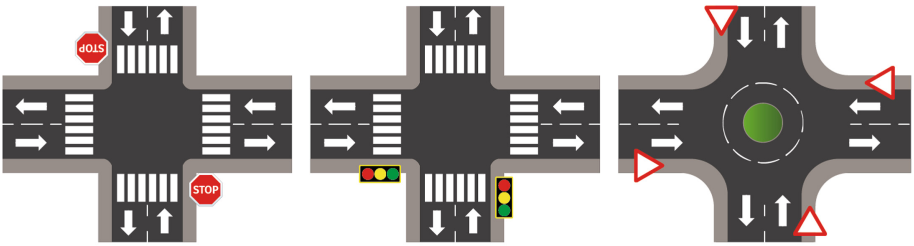
Equation 1 [41] allowed to calculate the study sample size. A standard deviation of 13 km/h [42] and an error of 5 km/h were assumed. With a confidence level of 95% (K = 1.96) and a value of U = 1.04 (for operating speed), the minimum number of observations in every tangent was 40. Then, 45 observations were collected in this study, thereby reducing the error or the confidence level of the results is increased.

$$\mathrm{n} = \frac{\mathrm{K}^2 \times \sigma^2 \times \left(2 + \mathrm{U}^2\right)}{2 \times \mathrm{el}^2} \tag{1}$$

where: n = sample size, K = constant based on the chosen confidence level, σ = standard deviation, U = normal deviation corresponding to the desired speed percentile, el = precision or maximum permissible error.

2.2 Road Test Section

The road test sections had to have grades less than 3%, have pavement in good condition, and a maximum speed limit of 60 km/h. Thus, thirty-four urban streets were selected in the city of Loja (Ecuador). Of these 34 sections, 13 were tangents before stop-controlled intersections, 12 were tangents before signal-controlled intersections, and 9 were tangents before roundabout intersections. Figure 1. Shows the typical configuration of these intersections. In the first intersections, the tangent lengths were between 47–226 m, up to 2 traffic lanes, and the roadway width was between 7 to 9 m, and one-way or two-way direction. In signal-controlled intersections, the length of the tangents had 94 to 121 m, up to 3 lanes, the roadway width between 7 to 10 m, and both directions. In the roundabouts, the tangent lengths were between 63–830 m, up to 3 traffic lanes, the roadway width had seven up to 13 m. Additionally, the length traveled within the circle was between 17–118 m, the internal diameter was between 11.5 to 25 m, the external diameter was between 26–61 m, the width of entrance and exit of the roundabout was between 7–11 m, and the width of the road within the roundabout was between 9 to 14 m.



Typical stop-controlled intersections | Typical signal-controlled intersections | Typical roundabouts intersections

Fig. 1. Typical studied two-lane intersections in this research.

2.3 Research Instruments

Two types of instruments were used for data collection: traditional and GPS-based. The traditional tools (such as tape measure, paper, pencil) were used to measure the width of the lane, distance to fixed objects, among others. The GPS-based instrument was employed to measure the speed, acceleration, and deceleration of the vehicle. However, it was also used to estimate the length of the tangent. In addition, the GPS equipment has an integrated camera helping to count the number of trees, number of power poles, and others. The GPS equipment, called Video VBOX Lite, was installed inside each driver's vehicle. It has an accuracy of 0.02 km/h in speed and 0.05% in the traveled distance. This equipment has previously been used for speed studies.

2.4 Driver Selection

The participants were drivers who have a valid driver's license, have a light vehicle, and have driven regularly in the last two months. Forty-five drivers participated in this study, of which twenty-three were men. The main requirement was that drivers had to have their light vehicles, to eliminate the effect of out of habit.

2.5 Driver and Car Data Collection

After driving the circuit, the drivers answered two principal surveys: MDSI-S [43] to estimate their personality traits and ZKPQ-50-cc [44] to estimate their driving style. The ZQPK-50-cc survey has 50 questions related to the five traits of personality: aggression - hostility, impulsive sensation seeking, neuroticism - anxiety, sociability, and activity. MDSI-S survey (41 questions) estimates the driving style that prevails in the driver: risky and high-velocity style, dissociative style, angry style, careful and patient style, anxious style, or distress reduction style.

Additionally, drivers answered another survey about their characteristics and their vehicles. Thus, drivers had an average age of 30.5 years and a driving experience of 9.3 years. The year of manufacture of the vehicles was on average 2008, the mean cylinder capacity was 1850 cm^3, and the last revision was on average 52 days before the day of data collection.

2.6 Speed Data Collection

The Video VBOX Lite was installed in light vehicles, taking care not to interfere with the driver's visibility. The GPS antenna was placed in the central part of the vehicle roof. The camera was on the front windshield facing the street. During the data collection, a researcher operated the equipment and notified in advance the study streets. Speeds were collected in good weather conditions, dry pavement, and during daylight.

2.7 Data Processing

The position, distance traveled, and speed were exported every second from the data collected by the Video VBOX Lite. The profiles that were not in free-flow were eliminated, as shown in Fig. 2. In tangents before stop-controlled intersections, there were 21 free-flow profiles for each section and 423 speed profiles in total. In the signal-controlled intersections, 67 profiles in free-flow condition were in a green light, 45 in red, and 13 in amber. On the other hand, the free-flow speed profiles in tangents before roundabout intersections were 90, while inside the roundabout were 125.

It calculated in each street the operating speed, mean free-flow speed, and the standard deviation of free-flow speed in the middle of the tangent. Acceleration and deceleration were estimated based on the recorded speeds data by Eq. (2). The 85th percentile of the acceleration and deceleration, their mean values, and their standard deviations were estimated by using the individual results from Eq. (2).

$$a = \frac{V_f^2 - V_i^2}{25.92 \times d_{i,i-1}} \tag{2}$$

where: a = acceleration or deceleration in m/s^2, V_f = final speed in km/h, V_i = initial speed in km/h, $d_{i,\ i-1}$ = distance between points "i" and "i-1" in m.

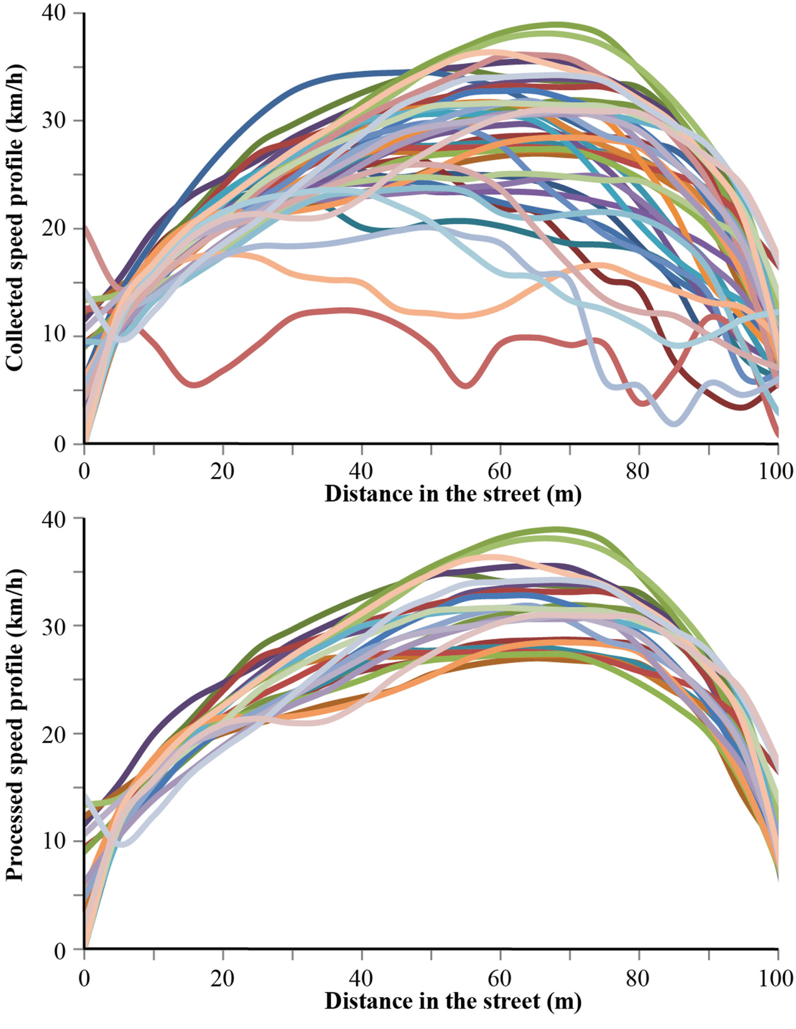


Fig. 2. Example of speed profiles recorded and processed for a street on free-flow condition.

Regarding the results of the ZQPK-50-cc and MDSI-S surveys, most participants had predominant traits such as impulsive sensation-seeking (44.4%) and activity (42.2%). Most drivers were careful and patient style (53.3%) or risky and high-velocity style (26.7%).

3 Pattern Analysis

In this section, a correlation analysis was performed using the independent and the dependent variables. The objective of this section was to detect the most influential variables on speed, acceleration, and deceleration. The variables with a statistically significant effect ($P < 0.05$) will be used in the model calibration. All statistical analyzes were performed with the help of the R program [45].

3.1 Driver and Car Variables

For all intersections, variables related to the driver (driving style scores, personality trait scores, sex, age, and driving experience) and the vehicle variables (type of vehicle, year of manufacture, cylinder capacity, period of previous maintenance, vehicle make, vehicle model) were not statistically significant at 95% level of confidence for the speed, acceleration, or deceleration. This outcome was opposite to previous literature. This result means that the remaining parameters are more influential than the driver or vehicle itself.

3.2 Street and Environmental Variables

Nine independent variables of the street and the environment were evaluated (see Table 1): 1) length of the street, 2) roadway width, 3) lane width, 4) land use in five categories: commercial, industrial, residential, recreational, and productive; 5) density of objects in three categories: poles (right, left or both), trees (right, left or both) and traffic signs (right, left or both); 6) access density; 7) the number of lanes; 8) parking presence (right, left or both) and 9) sidewalk presence (right, left or both). In addition to those variables, the analysis of the acceleration included the speed of the vehicle at the beginning of the tangent (see Table 2), while the decelerations had the speed at the end of the street (Table 3). In roundabouts, the following variables were analyzed: internal circle diameter, external circle diameter, drive curve (calculated according to [46]), entry roadway width, entry deviation angle, and approach/exit speed, but none of them were statistically significant.

Regarding the results of the street and environment variables and their influence on the operating speed, mean free-flow speed and standard deviation of free-flow speed are shown in Table 1. In this table, the variables that have a significant statistical relationship are the length of the street, the lane width, the density of objects, and the presence of parking. The analyzed categories of land use were not statistically significant. A similar outcome in previous investigations [7, 23]. In the case of no predictor variables, for example, mean free-flow speed in a green light, the models or equations will be constant or fixed values.

Table 1. Results of the statistically significant relationship between street and environment variables with operating speed, mean free-flow speed, and standard deviation of free-flow speed.

Tangents before		Vehicle Speed	Independent variables*								
			Length of the street (m)	Roadway width (m)	Lane width (m)	Land use	Objects density (n°/100 m)	Access density (n°/100 m)	Number of lanes	Parking presence	Sidewalk presence
Stop-controlled intersections		V_{85}									
		V_{AVG}									
		V_{SD}									
Signal-controlled intersections	Green light	V_{85}									
		V_{AVG}									
		V_{SD}									
	Red light	V_{85}									
		V_{AVG}									
		V_{SD}									
	Amber light	V_{85}									
		V_{AVG}									
		V_{SD}									
Roundabouts intersections		V_{85}									
		V_{AVG}									
		V_{SD}									

*the highlighted box means the statistical relationship between the variables at 95% of the confidence level.
v_{85}: operating speed, v_{AVG}: mean free-flow speed, v_{SD}: free-flow speed standard deviation.

The statistical relationships between the 85th percentile of the acceleration, the mean acceleration in free-flow, and the standard deviation of the acceleration in free-flow with the variables of the street and the environment are shown in Table 2. Most independent variables were statistically significant with at least one or more dependent variables, except the number of lanes. Table 2 also shows that the standard deviation of the acceleration in free-flow, the accelerations in amber light, and the standard deviation in tangents before roundabouts intersections did not have any statistically significant relationship.

Table 2. Results of the statistical relationship between the street and environment variables with the 85th percentile of acceleration, mean acceleration in free-flow, and standard deviation of acceleration in free-flow.

Tangents before		Vehicle Speed	Independent variables*									
			Length of the street (m)	Roadway width (m)	Lane width (m)	Land use	Access density (n°/100 m)	Objects density (n°/100 m)	Number of lanes	Parking presence	Sidewalk presence	Initial speed (km/h)
Stop-controlled intersections		a_{85}										
		a_{AVG}										
		a_{SD}										
Signal-controlled intersections	Green light	a_{85}										
		a_{AVG}										
		a_{SD}										
	Red light	a_{85}										
		a_{AVG}										
		a_{SD}										
	Amber light	a_{85}										
		a_{AVG}										
		a_{SD}										
Roundabouts intersections		a_{85}										
		a_{AVG}										
		a_{SD}										

*the highlighted box means the statistical relationship between the variables at 95% of the confidence level.
a_{85}: 85th percentile acceleration, a_{AVG}: mean free-flow acceleration, a_{SD}: free-flow acceleration standard deviation.

The statistical relationships between the 85th percentile of the deceleration, the mean deceleration of free-flow, and the standard deviation of the deceleration in free-flow with the variables of the street and the environment are shown in Table 3. The independent variables that were not predictors of any deceleration values were: roadway width, land use, access density, and parking presence. It is possible that object density close to the street only affects the drivers 'choice of' lateral position [29]. Likewise, other researchers also found no statistical relationship between the parking presence and speed [25].

Table 3. Results of the statistical relationship of the street and environment variables with the 85th percentile of the deceleration, mean deceleration in free-flow, and standard deviation of the deceleration in free-flow.

Tangents before		Vehicle Speed	Independent variables*									
			Length of the street (m)	Roadway width (m)	Lane width (m)	Land use	Objects density (n°/100 m)	Access density (n°/100 m)	Number of lanes	Parking presence	Sidewalk presence	Final speed (km/h)
Stop-controlled intersections		d_{85}										
		d_{AVG}										
		d_{SD}										
Signal-controlled intersections	Green light	d_{85}										
		d_{AVG}										
		d_{SD}										
	Red light	d_{85}										
		d_{AVG}										
		d_{SD}										
	Amber light	d_{85}										
		d_{AVG}										
		d_{SD}										
Roundabouts intersections		d_{85}										
		d_{AVG}										
		d_{SD}										

**the highlighted box means the statistical relationship between the variables at 95% of the confidence level.
d_{85}: 85th percentile deceleration, d_{AVG}: mean free-flow deceleration, d_{SD}: free-flow deceleration standard deviation.

4 Results

Then it calibrated the speed, acceleration, and deceleration models based on the most influential variables detected in Tables 1, 2, 3. For the calibration, a linear regression analysis was performed with a level of confidence of 95%. When there was no statistically significant variable, fixed values were calculated. After calibration, the models were validated with collected data in other streets with similar characteristics to the initial ones. This validation was carried out by analyzing the prediction errors.

4.1 Calibration Models

Tangents before Stop-Controlled Intersections. The speed, acceleration, and deceleration models were calibrated based on the variables detected in Tables 1, 2, 3. Not all the variables were statistically significant in the global model, despite being individually significant. So, the most influential variables were the length of the street, the initial, and the final speed (See Eqs. 3–11). These equations are coherent with what happens in actual driving. For example, in long tangents, drivers have more freedom to choose their speed, and possibly they decide to speed up; and occur the opposite in short tangents. With high initial speeds, drivers have low accelerations since they are approaching the desired speed or a high velocity for the tangent. Likewise, it is coherent that the deceleration is related to the final speed of the maneuver since it is the speed at which drivers wish to reach when they arrive at the intersection.

Proposed Models for Tangents Before Stop-Controlled Intersections.

- Speed in the center of the tangent. Application range: 47–226 m. R^2 adjusted: 0.94, 0.95, 0.79, respectively.

$$v_{85} = 22.4 + 0.114\,L \tag{3}$$

$$v_{AVG} = 20.1 + 0.105\,L \tag{4}$$

$$v_{SD} = 1.99 + 0.0146\,L \tag{5}$$

  where: v_{85} = operating speed in km/h, v_{AVG} = mean free-flow speed in km/h, v_{SD} = free-flow speed standard deviation in km/h, L = length of the street in m, R^2 adjusted = adjusted coefficient of determination.
- Acceleration at the start of the tangent. Application range: 0–45 km/h. R^2 adjusted: 0.86, 0.93, 0.65, respectively.

$$a_{85} = 0.975 - 0.0151\,v_i \tag{6}$$

$$a_{AVG} = 0.807 - 0.0136\,v_i \tag{7}$$

$$a_{SD} = 0.181 - 0.0018\,v_i \tag{8}$$

  where: a_{85} = 85th percentile acceleration in m/s^2, a_{AVG} = mean free-flow acceleration in m/s^2, a_{SD} = free-flow acceleration standard deviation in m/s^2, v_i = entry speed in km/h, R^2 adjusted = adjusted coefficient of determination.
- Deceleration at the end of the tangent. Application range: 0–45 km/h. R^2 adjusted: 0.83, 0.94, 0.57, respectively.

$$d_{85} = -1.84 + 0.0314\,v_f \tag{9}$$

$$d_{AVG} = -1.50 + 0.0301\,v_f \tag{10}$$

$$d_{SD} = 0.310 + 0.010\,v_f - 0.00033\,v_f^2 \tag{11}$$

where: d_{85} = 85th percentile deceleration m/s^2, d_{AVG} = mean free-flow deceleration in m/s^2, d_{SD} = free-flow deceleration standard deviation in m/s^2, v_f = exit speed in km/h, R^2 adjusted = adjusted coefficient of determination.

Tangents Before Signal-Controlled Intersections. The tangents before signal-controlled intersections are more complex than in the previous case. In the proposed models (Eqs. 12–38) for the green, amber and red lights they only have two predictors: a) the initial speed at the 85th percentile of the acceleration and the standard deviation of the free-flow acceleration for the green light, and b) density of objects (trees, traffic signs, and poles) for the speed of operation when the light is red. For the rest of the conditions, constant values were calculated. Based on this, it can be said that the choice of speed, acceleration, and deceleration is conditioned mainly by the presence of the traffic light, and not by the characteristics of the street, environment, vehicle or driver.

Proposed Models for Tangents Before Signal-Controlled Intersections and Green Light. When the light is green, the speeds are slower than when the light is amber, since many drivers tend to accelerate to pass the traffic light in amber light, when they are in the zone dilemma [47].

- Speed in the center of the tangent. Application range: 94–122 m. R^2 adjusted: not available.

$$v_{85} = 52.72 \text{ km/h} \quad (12)$$

$$v_{AVG} = 43.55 \text{ km/h} \quad (13)$$

$$v_{SD} = 4.34 \text{ km/h} \quad (14)$$

where: v_{85} = operating speed in km/h, v_{AVG} = mean free-flow speed in km/h, v_{SD} = free-flow speed standard deviation in km/h, R^2 adjusted = adjusted coefficient of determination.

- Acceleration at the start of the tangent. Application range: 0–45 km/h. R^2 adjusted: 0.86, 0.93, not available, respectively.

$$a_{85} = 1.06 - 0.015\, v_i \quad (15)$$

$$a_{AVG} = 1.13 - 0.021\, v_i \quad (16)$$

$$a_{SD} = 0.21 \text{ m/s}^2 \quad (17)$$

where: a_{85} = 85th percentile acceleration in m/s^2, a_{AVG} = mean free-flow acceleration in m/s^2, a_{SD} = free-flow acceleration standard deviation in m/s^2, v_i = entry speed in km/h, R^2 adjusted = adjusted coefficient of determination.

- Deceleration at the end of the tangent. Application range: 94–122 m. R^2 adjusted: not available.

$$d_{85} = -0.07\ \text{m/s}^2 \tag{18}$$

$$d_{AVG} = -0.32\ \text{m/s}^2 \tag{19}$$

$$d_{SD} = 0.18\ \text{m/s}^2 \tag{20}$$

where: d_{85} = 85th percentile deceleration m/s^2, d_{AVG} = mean free-flow deceleration in m/s^2, d_{SD} = free-flow deceleration standard deviation in m/s^2, R^2 adjusted = adjusted coefficient of determination.

Proposed Models for Tangents Before Signal-Controlled Intersections and Amber Light. When the traffic light is in amber, the mean deceleration is higher than the high green light, but its dispersion is high, again a characteristic of the zone dilemma. The same happens with the dispersion of the speed in green and amber light. In green lights, drivers would continue crossing the intersection, and low decelerations are expected, which are seen in these models.

- Speed in the center of the tangent. Application range: 94–122 m. R^2 adjusted: not available.

$$v_{85} = 56.28\ \text{km/h} \tag{21}$$

$$v_{AVG} = 43.31\ \text{km/h} \tag{22}$$

$$v_{SD} = 9.82\ \text{km/h} \tag{23}$$

where: v_{85} = operating speed in km/h, vAVG = mean free-flow speed in km/h, v_{SD} = free-flow speed standard deviation in km/h, R^2 adjusted = adjusted coefficient of determination.

- Acceleration at the start of the tangent. Application range: 94–122 m. R^2 adjusted: not available.

$$a_{85} = 0.55\ \text{m/s}^2 \tag{24}$$

$$a_{AVG} = 0.28\ \text{m/s}^2 \tag{25}$$

$$a_{SD} = 0.24\ \text{m/s}^2 \tag{26}$$

where: a_{85} = 85th percentile acceleration in m/s^2, a_{AVG} = mean free-flow acceleration in m/s^2, a_{SD} = free-flow acceleration standard deviation in m/s^2, R^2 adjusted = adjusted coefficient of determination.

- Deceleration at the end of the tangent. Application range: 94–122 m. R^2 adjusted: not available.

$$d_{85} = -0.10\ m/s^2 \tag{27}$$

$$d_{AVG} = -0.73\ m/s^2 \tag{28}$$

$$d_{SD} = 0.74\ m/s^2 \tag{29}$$

where: d_{85} = 85th percentile deceleration m/s^2, d_{AVG} = mean free-flow deceleration in m/s^2, d_{SD} = free-flow deceleration standard deviation in m/s^2, R^2 adjusted = adjusted coefficient of determination.

Proposed Models for Tangents Before Signal-Controlled Intersections and Red Light. In red light, the speeds are lower than the previous two conditions. This behavior is because drivers already know to stop at a red light, and the high values of decelerations confirm that. However, the acceleration values are higher than the two previous conditions, maybe due to the impulsive sensation-seeking detected in the sample of drivers. Even though the drivers know they must stop at the intersection, they accelerate with a higher value, possibly to cross the intersection.

- Speed in the center of the tangent. Application range: 5.3–29.1 u/100 m. R^2 adjusted: 0.49, not available, and not available, respectively.

$$v_{85} = 33.4 + 0.533\ OD \tag{30}$$

$$v_{AVG} = 39.71\ km/h \tag{31}$$

$$v_{SD} = 4.45\ km/h \tag{32}$$

where: v_{85} = operating speed in km/h, v_{AVG} = mean free-flow speed in km/h, v_{SD} = free-flow speed standard deviation in km/h, OD = Object density in units per each 100 m, R^2 adjusted = adjusted coefficient of determination.

- Acceleration at the start of the tangent. Application range: 0–45 km/h. R^2 adjusted: 0.66, 0,65, and not available, respectively.

$$a_{85} = 1.40 - 0.024\ v_i \tag{33}$$

$$a_{AVG} = 1.33 - 0.024\ v_i \tag{34}$$

$$a_{SD} = 0.32\ m/s^2 \tag{35}$$

where: a_{85} = 85th percentile acceleration in m/s^2, a_{AVG} = mean free-flow acceleration in m/s^2, a_{SD} = free-flow acceleration standard deviation in m/s^2, v_i = entry speed in km/h, R^2 adjusted = adjusted coefficient of determination.

- Deceleration at the end of the tangent. Application range: 94–122 m. R^2 adjusted: not available.

$$d_{85} = -0.75\ m/s^2 \tag{36}$$

$$d_{AVG} = -1.50\ m/s^2 \tag{37}$$

$$d_{SD} = 0.54\ m/s^2 \tag{38}$$

where: d_{85} = 85th percentile deceleration m/s^2, d_{AVG} = mean free-flow deceleration in m/s^2, d_{SD} = free-flow deceleration standard deviation in m/s^2, R^2 adjusted = adjusted coefficient of determination.

Tangents before Roundabouts Intersections. Models 39 to 47 were calibrated based on the variables in Tables 1, 2, 3 The speed values are higher than those recorded in the previous intersections. Also, the acceleration values of the models are slightly higher than the values of the acceleration models at tangents before stop-controlled intersections, since they are tangents with similar starting conditions. Additionally, equation values are closer to the deceleration models in tangents before signal-controlled intersections with amber light. This trend is because there is also a dilemma zone in the circle. The driver may doubt whether to continue or stop the vehicle before the approach of vehicles within the ring. The most statistically significant variables were the length of the tangent, entry or initial speed, and traffic signs density. Speed choice in previous studies were related to entry width [46, 48], internal circle diameter [46, 48], drive curve [46], entry deviation angle [46] and approach/exit speed [48].

Proposed Models for Tangents Before Roundabout.

- Speed in the center of the tangent. Application range: 63–321 m. R^2 adjusted: 0.98, 0,90, and not available, respectively.

$$v_{85} = 28.3 + 0.091\ L \tag{39}$$

$$v_{AVG} = 20.5 + 0.080\ L \tag{40}$$

$$v_{SD} = 5.38\ km/h \tag{41}$$

where: v_{85} = operating speed in km/h, v_{AVG} = mean free-flow speed in km/h, v_{SD} = free-flow speed standard deviation in km/h, L = length of the street in m, R^2 adjusted = adjusted coefficient of determination.

- Acceleration at the start of the tangent. Application range: 10–50 km/h. R^2 adjusted: 0.88, 0,77, and not available, respectively.

$$a_{85} = 1.04 - 0.015\ v_i \tag{42}$$

$$a_{AVG} = 0.90 - 0.014\ v_i \tag{43}$$

$$a_{SD} = 0.23\ m/s^2 \tag{44}$$

where: a_{85} = 85th percentile acceleration in m/s^2, aAVG = mean free-flow acceleration in m/s^2, a_{SD} = free-flow acceleration standard deviation in m/s^2, v_i = entry speed in km/h, R^2 adjusted = adjusted coefficient of determination.

- Deceleration at the end of the tangent. Application range: 94–122 m. R^2 adjusted: 0.66, not available, and not available.

$$d_{85} = 0.002L + 0.07\ TSD \tag{45}$$

$$d_{AVG} = -0.70\ m/s^2 \tag{46}$$

$$d_{SD} = 0.55\ m/s^2 \tag{47}$$

where: d_{85} = 85th percentile deceleration m/s^2, d_{AVG} = mean free-flow deceleration in m/s^2, d_{SD} = free-flow deceleration standard deviation in m/s^2, L = length of the street in m, TSD = traffic signs density in units per each 100 m, R^2 adjusted = adjusted coefficient of determination.

Despite trying to find statistical relationships between geometric and operating elements within the circle and speed, none were found. Therefore, the equations had constant values. The calculated values were: mean speed of 28.60 km/h and standard deviation of 4.66 km/h. These values are valid within roundabouts an internal diameter between 11.5–25 m and an external diameter between 26–61 m. The mean speed found was similar to that recorded in other investigations: 30 km/h [49], 17–26 km/h [48], as well as their standard deviation of 4.13–5.21 km/h [48].

4.2 Validation

The calibrated models were validated using information collected from another circuit in the same city. This circuit had similar geometric and operation characteristics to the initial sections. For the tangents before stop-controlled intersections, there were eight sections between 47 to 112 m. Twelve tangents before signal-controlled intersections were collected to validate the models, with 94 and 120 m long. And for the tangents before the roundabout, six sections, between 66 to 287 m, were used.

Six drivers participated in the validation circuit, of which half were men. Drivers had an average age of 26.3 years and driving experience of 7.2 years. The average year of manufacture was 2007, the mean cylinder capacity was 2000 cm^3, and the last average revision was 53 days. The measuring equipment was the same employed in the collection data, and the same data processing was performed for speed, acceleration, and deceleration data.

For the validation of the speed, acceleration, and deceleration models, forecast errors were calculated: mean squared error (MSE), mean absolute error (MAE), the mean absolute percentage error (MAPE), and the Chi-squared test. Table 4 shows these values. Models with constant values were not included in this table; since it is impossible to calculate forecast errors. However, in those cases, an analysis of variance was performed, to determine if the fixed values do not differ from the values found in the validation, at 95% level of confidence.

Table 4 shows that the highest values of MSE and MAE were obtained by the model of the operating speed and the average speed in free-flow for the tangents before roundabouts, so caution should be taken when using these equations. The prediction error will be around 5 km/h (starting assumption). The highest MAPE values were for the equations of the 85th percentile of acceleration and deceleration for the tangents before roundabouts, so caution is also suggested in their use. However, these equations and others in Table 4, the chi-calculated did not exceed the chi-critical; therefore, the equations are valid. All the fixed models were also valid since in the analysis of variance no significant statistical differences were found (p-value > 0.05).

Table 4. Prediction errors and Chi-square values for the equations of speed, acceleration, and deceleration calibrated models.

Tangents before		Prediction equation	Error estimator				
			MSE	MAE	MAPE (%)	χ^2 calculated	χ^2 critic
Stop-controlled intersections		V_{85}	3.83	1.27	4.04	0.95	14.07
		V_{AVG}	5.85	2.13	7.69	1.68	14.07
		V_{SD}	0.82	0.70	22.84	2.11	14.07
		a_{85}	0.02	0.14	17.52	0.13	9.49
		a_{AVG}	0.02	0.14	22.01	0.16	9.49
		a_{SD}	0.00	0.02	11.36	0.01	9.49
		d_{85}	0.01	0.10	6.85	0.05	9.49
		d_{AVG}	0.01	0.10	8.57	0.05	9.49
		d_{SD}	0.00	0.03	8.52	0.02	9.49
Signal-controlled intersections	Green light	a_{85}	0.04	0.13	22.23	0.68	14.07
		a_{AVG}	0.02	0.08	16.75	0.30	14.07
	Red light	V_{85}	8.77	2.44	5.70	1.41	12.59

(*continued*)

Table 4. (*continued*)

Tangents before		Prediction equation	Error estimator				
			MSE	MAE	MAPE (%)	χ^2 calculated	χ^2 critic
		a_{85}	0.01	0.09	17.02	0.16	9.49
		a_{AVG}	0.01	0.06	15.56	0.11	9.49
Roundabouts intersections		V_{85}	36.79	5.44	11.60	4.54	11.07
		V_{AVG}	26.60	5.11	14.39	4.44	11.07
		a_{85}	0.04	0.17	34.29	0.54	12.59
		a_{AVG}	0.01	0.10	28.84	0.27	12.59
		d_{85}	0.03	0.16	36.39	0.41	9.49

V_{85} = operating speed in km/h, V_{AVG} = mean free-flow speed in km/h, V_{SD} = free-flow speed standard deviation in km/h, a_{85} = 85th percentile acceleration in m/s^2, a_{AVG} = mean free-flow acceleration in m/s^2, a_{SD} = free-flow acceleration standard deviation in m/s^2, d_{85} = 85th percentile deceleration in m/s^2, d_{AVG} = mean free-flow deceleration in m/s^2, d_{SD} = free-flow deceleration standard deviation in m/s^2, MSE = mean squared error in (km/h)^2 for the speed and (m/s^2)^2 for the acceleration or deceleration, MAE = mean absolute error in km/h for the speed and m/s^2 for the acceleration or deceleration, MAPE = mean absolute percentage error in percentage, χ^2 calculated = Chi-squared calculated, χ^2 critic = Chi-value where if the χ^2 calculated is greater than χ^2 critic the model is not valid.

5 Conclusions

The objective of this article was to investigate the influence of several urban street, driver, and vehicle characteristics on speed, acceleration, and deceleration in free-flow conditions. Three scenarios were analyzed: tangents before stop-controlled intersections, tangents before signal-controlled intersections, and tangents before roundabout intersections. After the presented results, the following conclusions are presented:

In stop-controlled intersections, the length of the tangent, the speed at the start and the end of the maneuver were the most influential variables on speed, acceleration, and deceleration, respectively. In signal-controlled intersections, there were only two sporadic predictors: the initial speed and the object density. Regarding roundabout, the length of the street influenced the operating speed and mean free-flow speed, the initial speed influenced the 85th percentile of the acceleration, and the traffic sign density impacted the 85th percentile of the deceleration. All models were valid, and they can use to get speed profiles on these types of streets. These profiles can be used to analyze the consistency of streets, calculate fuel consumption, calculate polluting gas emissions, or in macroscopic traffic modeling.

In conclusion, the most influential parameters in the driver's speed choice in urban streets are the street characteristics and its environment. Neither the type of vehicle, year of manufacture, cylinder capacity, period of previous maintenance, vehicle brand, vehicle model; or the values of personality traits, values of driving styles, age, or sex of the driver were statistically significant variables. For the drivers, the physical elements of the road scene are more important than their characteristics or their vehicles. This outcome is because an urban environment is limited space, where drivers do not have enough freedom/space to accelerate or decelerate. Thus, on rural roads, drivers should have different behavior; therefore, the prediction models of one type of road cannot be employed in another one different from the calibration data. This issue can be explored in future research.

This study has several limitations. First, the speed in the middle of the tangent was representative; however, the highest speed (for safety reasons) could be found in another spot in the tangent. The models should be used in the range where they were calibrated and validated. The local and geographic characteristics could influence the values of the models. Despite these limitations, the study helps to understand the complex relationship between the knowledge about the speed profile in free-flow conditions. The calibrated models were coherent with the actual driver behavior. Additionally, it covers three types of intersections, that previous research only studies one intersection. Finally, this study would help designers and urban planners.

Acknowledgements. The authors thank the National Secretariat for Higher Education, Science, Technology and Innovation (SENESCYT) of the Republic of Ecuador and the Universidad Técnica Particular de Loja for their support in this research.

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