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Research Article

A Data-Driven Functional Classification of Urban Roadways Based on Geometric Design, Traffic Characteristics, and Land Use Features

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The functional classification system (FCS) of roads means categorizing roads based on their service characteristics. The two primary considerations in classifying highway and street networks are accessibility and mobility, where by increasing the role of one, the other's role is reduced. In this paper, besides the conventional variables such as geometric design characteristics, parking lots, land use features, and accessibility; the Sydney Coordinated Adaptive Traffic System (SCATS) data following the real-time traffic flow and average speed of vehicles collected by Location-Based Services (LBS) are considered as new variables for estimating the FCS. Linear regression is used to model the importance of the variables. The chi-square test compared the observational and predicted speeds in the five categories of roads in Tehran, the capital of Iran. Results show that on-street parking has the highest impact and the land use variable has the lowest impact on speed that changes the FCS. Moreover, the presented classification was one to two categories compared with the conventional FCS presented in manuals in the case of Tehran's transportation network as a developing city.

1. Introduction

Various functional classification systems (FCS) are defined based on different criteria including road geometry design, volume and type of traffic, and origin-destination (OD) of trips. These are beneficial in developing the standard road network. Roads can have a functional classification that expresses their functional importance in the whole network. Classifying volume and type of roads can be presented as a result of traffic assignment. Moreover, sometimes an environmental classification could be considered heavy vehicles and transportation's harmful impacts on the environment [1].

According to the two types of services that roads carry out, two main criteria are used to classify them, which are accessibility and mobility level. In fact, these are two criteria by which different types of roads are created based on changes in each of them [2]. The two criteria of accessibility and mobility are inversely related, so increasing accessibility means reducing mobility and vice versa.

The conflict between providing mobility for traffic movements and spreading origins and destinations in a city requires countless roads with different functions to respond to the generated demand [3]. The leading purpose of the highway is to provide mobility that is defined at different levels. For example, mobility on the highway can mean riding comfort and privation of speed changes. However, due to the importance of sustainable transportation, attention to accessibility has become more important in these days and it can be used as an indicator to define the reliability of services in the transportation system [4]. Of course, it should be noted that access is not the only factor in achieving sustainable transport, and the public transport network must also support it [5]. In this regard, balancing mobility based on accessibility concerns is essential for managing the urban traffic network.

Many factors describe accessibility. Generally, it consists of traffic characteristics and geometric design features such as volume, angle of access, the distance of access points from each other, access control and access management, turning radius of the access point, entering speed from the access point to the roadway, location of bus and taxi stations, total ramp density, number of lanes, lane widths, type of median, on-street parking, the distance between intersections, deceleration and acceleration lanes, and types of land use [3, 6].

In addition to those conventional attributes, we consider more recent data source including Location-Based Services (LBS) and Sydney Coordinated Adaptive Traffic System (SCATS) to investigate the accurate classification of roadways by fusion of their data to conventional on-field attributes. LBS are applications on mobile portable devices (e.g., smartphones) that provide information depending on the location of the device and the user through mobile networks [7, 8]. Rapid advances in LBS with the continuous evolution of mobile devices and telecommunication technologies were presented just in a few years. Thus, LBS became more popular in outdoor and indoor environments (shopping malls, museums, airports, and big transport hubs). Moreover, LBS was applied in services like emergency services, tourism services, navigation guidance, intelligent transportation systems (ITS), entertainment (gaming), assistive services, healthcare/fitness, and social networking [9–11]. This service could be used as a tool for investigating and comparing traffic patterns [12], evaluating the Origin-Destination (OD) trips [13], and even verifying the accuracy of conventional traffic assignment methods [14]. In addition to this data, traffic volumes are gathered by installed detectors based on SCATS. SCATS is a traffic management system designed to optimize traffic flow [15] and metering the internal/external traffic during the rush hour to minimize the queue lengths at intersections [16].

2. Material and Methods

In this study, the variables extracted from the accessibility were selected as independent variables, and the effect of these variables on the spot speed was evaluated using linear regression. Furthermore, the data of real-time traffic characteristics have been used in addition to the conventional data like roadway's geometric design features. The roadway data for geometric design features are the angle of access, total ramp density, number of lanes, on-street parking, deceleration and acceleration lanes, and types of land usage. In addition, the traffic characteristics data for the roadway are spot speed and volume. In this study, each independent variable's effect on the dependent variable is measured using linear regression, and the effects of all variables on each other are measured by using the correlation matrix. Then the observed and predicted speeds were compared by the chi-square test.

2.1. Process. Generally, this study's collected data were geometric design features and traffic characteristics by considering roadside land use. In the first step, the functional systems for urban areas used in the American Association of State Highway Officials (AASHTO) were selected. The four functional highway systems for urban areas used in conventional functional classification are principal arterial, minor arterial, collector streets, and local streets [3]. Functional systems for urban areas are schematically shown in Figure 1.

According to the classification of Figure 1, for each of the functional systems, roadways of Tehran were selected as a case study, which is shown in Figure 2 that is gathered from Tehran Trafficþ Maps (https://map.tehran.ir). For the principal arterial, Ayatollah Hashemi Rafsanjani (Niyayesh) was selected (Figure 2(a)). For the minor arterial, Resalat Expressway was selected (Figure 2(b)). In Niyayesh and Resalat expressways, both directions were selected, west to east and east to west. For the collector, two case studies were selected. One of them was Mofatteh Street (Figure 2(c)), and the other one was Motahhari Street (Figure 2(d)). The case study selected for the local street was Mehrdad Street (Figure 2(e)). There are 360 access points in case studies that affected accessibility.

In the next step, each of these roadways was divided into ten segments with equal length. The number of segments in the case study is 61. And then, the required data were collected from the available segments. Finally, modeling was done by selecting the appropriate regression model, and its results were extracted.

Angles of access data were obtained with AUTO CAD, CIVIL 3D, and ENGAUGE DIGITIZER software. The collected number of angles is equal to the number of access points. The geometric design features of the roadways, like the number of lanes and on-street parking, are gathered by observation of field studies and checked by Tehran Trafficþ Maps (https://map.tehran.ir). The deceleration and acceleration lanes data were collected by referencing AASHTO standards and the field study. The ArcGIS software has been used to collect the land use data based on Tehran's spatial land use data. The collected data, deceleration and acceleration lanes, and land use data are qualitative, and other research data have been quantitatively and numerically introduced in the model.

3. Theory/Calculation

Highways' classification methods, Location-Based Service applications, and real-time traffic characteristics are used to find the proposed model in this section.

3.1. Highways' Classification. Highways classify into different operating systems based on functional classes or geometric types. Functional classification, the grouping of highways by the service they provide, was developed for transportation planning purposes. The FCS provides the starting point for assigning highways to different access categories. FCS is applied to categorize streets and highways according to their role [3, 6].

The urban roads have six primary roles:

(i) Providing mobility for motor vehicles (mobility role).

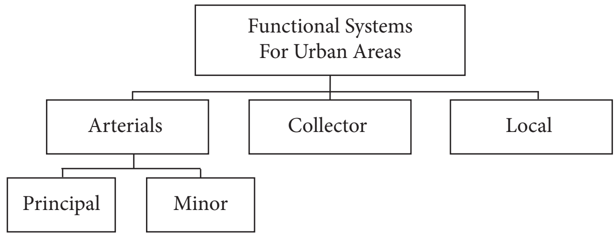


Figure 1: Functional system for urban areas schematic diagram.

Figure 2: Location of case studies-Tehran Trafficþ Maps (https://map.tehran.ir).

(ii) Providing access to motor vehicles and facilities (accessibility role).

(iii) Creating a platform for social communication such as working, traveling, playing, and meeting (social roles).

(iv) Formation of urban architecture (urban architectural role).

(v) Impact on the environment weather surrounding the road (climate effect role).

(vi) Impact on city economics (economic role).

Roads usually take more than one role, and some of these roles conflict with another one. The role of mobility can be measured by the speed and amount of traffic volume. In general, in the six parts, the three roles of mobility, accessibility, and social role are the main criteria for calculating urban roads.

Various classification schemes have been applied for distinct purposes in different rural and urban regions. This research will examine whether traffic characteristics such as volume and speed corresponding to it can be combined with other geometric properties and use statistical methods such as regression to produce a favorable result in urban areas' functional systems. The questions are the following: Is there a meaningful relationship between each of the independent and dependent variables? Is there a simultaneous effect of independent variables with the decreasing effect of the dependent variable's speed value?

Moreover, the assumptions used in this research are as follows:

(i) The minimum width of the lane is 3.67 m.

(ii) All vehicles in the traffic flow are passenger cars.

(iii) The inclement weather conditions are ignored.

(iv) The level of service in roadways is not *E* or *F*.

The American Institute of Architects (AIA), with ten classes, includes all streets within a city or town based on differing degrees of suitability for traffic movement, pedestrian activity, and building types [17]. The proposed system is shown in Table 1.

In road classification research, Qin et al. [19, 20] presented a straightforward and yet accurate methodology named speed-independent road classification strategy (SIRCS). This method is based on the sole measurement of unsprung mass acceleration. The framework was proposed with two phases named offline and online. In the offline phase, in two stages, the transfer function from acceleration to mobility is first formulated. The frequency range based on the random forest is then classified according to the ISO 8608 road standard definition. In the online phase, first, the mass acceleration and velocity of the vehicle are combined to calculate the appropriate road profile in the area. The second step is to classify the two-stage road mobility based on the power spectral density criterion (PSD) [20]. In this paper, the harmony superposition function generates the road profile in the time domain based on [19, 20]

Table 1: AIA street classification system [18].

Classification	Scale	Speed	Location	Specific feature
Highway	Long-distance	Medium	Open country	Free of intersections, driveways, and adjacent buildings
Boulevard	Long-distance	Medium	Urbanized area	Buildings line, expansive parking, and sidewalk inside and planting trees in center
Avenue	Short-distance	Medium	Urban area	Ends with a significant building or monument
Drive	Edge of the urban area and beside of natural zone	Medium	Along a waterfront, park, or headland	One side of the drive, boulevard, with sidewalk and buildings, while the other has the qualities of a parkway, with naturalistic planting and rural detailing
Street	Small-scale	Low	Access to higher density areas like business zones or rowhouses	Raised curbs, wide sidewalks, closed drainage, parallel parking, trees in individual planting areas, and buildings aligned on short setbacks
Road	Small-scale	Low	Frontage of low-density buildings such as houses	Rural landscape with open areas, plantings and narrow sidewalks
Alley	Narrow access route	—	Servicing the rear of buildings on a street	Usually paved to their edges, with center drainage via an inverted crown
Lane	Narrow access route	—	Access to houses' backyard	Useful for accommodating utility runs, enhancing the privacy of rear yards, and providing play areas for children
Passage	Narrow, pedestrian-only connector	—	Cutting between buildings	Access from the middle of long blocks and connect frontage and backyard of blocks
Path	Narrow pedestrian and bicycle connector	—	A park or the open country	Emerge from the sidewalk network, necessary along highways but not required to supplement boulevards, streets, and roads

$$X_r(t) = \sum_{u=1}^{U} \sqrt{2 \cdot G_q\left(f_{\text{mid}-u}\right) \cdot \frac{f_2 - f_1}{U}} \sin\left(2\pi f_{\text{mid}-u} t + \Phi_{u-l}\right), \tag{1}$$

where U is the total number of the time-frequency components; $f_{\text{mid}-u}$ is u^{th} middle frequency in Hz, $G_q(f_{\text{mid}-u})$ is the PSD of $f_{\text{mid}-u}$ in m^3; Φ_{u-l} is the independent and identically distributed (IID) random phase over (0.2π). f_1 and f_2 are 0.33 Hz and 28.3 Hz, respectively [19].

Adafer and Bensaibi [21] developed a methodology based on determining a numerical indicator called the Vulnerability Index (VI). The vulnerability index also can be used for seismic vulnerability assessment for roads. The main parameters are identified, especially on past Algerian earthquakes and worldwide seismic feedback experiences. To quantify the identified parameters and define an analytical expression of the "VI", Analytical Hierarchy Process (AHP) is used. According to the obtained Vulnerability Index value, the classification of road sections' seismic vulnerability is proposed. This study's analysis and evaluation are number of lanes, pavement type, height, compaction quality, slope, ground type, landslides potential, pavement conditions, and slope protection measures. According to the vulnerability index, landslides potential, pavement conditions, and the number of lanes were the essential components.

In another study, Friedrich [22] describes the general methodology of the German Guideline for Integrated Network Planning (GGINP). He presented the approach and its methodology, including the form of transportation networks and the characteristics of the network elements and showed some examples of applying it. Examples of such characteristics are alignment speed, number of lanes, and the control type at intersections. In this research, the relationship between travel time, length, connectivity function level, and length in build-up areas or sensitive areas with impedance was investigated by the regression model. The relationship is [22]

$$w_l = \left(\beta_0 + \beta_1 \cdot CFL_1 + \beta_2 \cdot b_l\right) \cdot t_l + \beta_3 \cdot s_l, \tag{2}$$

where w_l is the impedance of link l, t_l is the travel time of link l, s_l is the length of link l, CFL_l is the connectivity function level of link l $(0 \le \text{CFL} \le 5)$, b_l is the share of link length in build-up areas or sensitive areas $(0 \le b_l \le 1)$, β_0 is the parameter that describes the influence of travel time, i.e., the accessibility, β_1 is the parameter that describes the influence of the road hierarchy, i.e., the bundling of traffic flows, β_2 is the parameter that describes the influence of sensitive areas, i.e., the compatibility of environment, and β_3 is the parameter that describes the influence of length, i.e., the directness [22].

3.2. Location-Based Services (LBS). Compared with other traditional geographic information systems (GIS) and web mapping applications, LBS is more adaptable to the contents and presentation according to its users' context [23]. Thus LBS is more dynamic and more probable to develop other GIS applications and open many research questions beyond the scientific field of geographic information science (GIScience) [24]. Geopositioning smartphones have attracted new application development, which utilizes the user's location information to provide valuable services. These applications are called LBS applications [25].

LBS need infrastructure like an internet network that can provide positioning tools for trough mobile devices [26]. Today, the tool that can supply access to LBS is mobile devices that users can send requests and retrieve results through. LBS need applications that providers develop just for them. These applications would download and install mobile devices like Personal Data Assistants (PDAs),

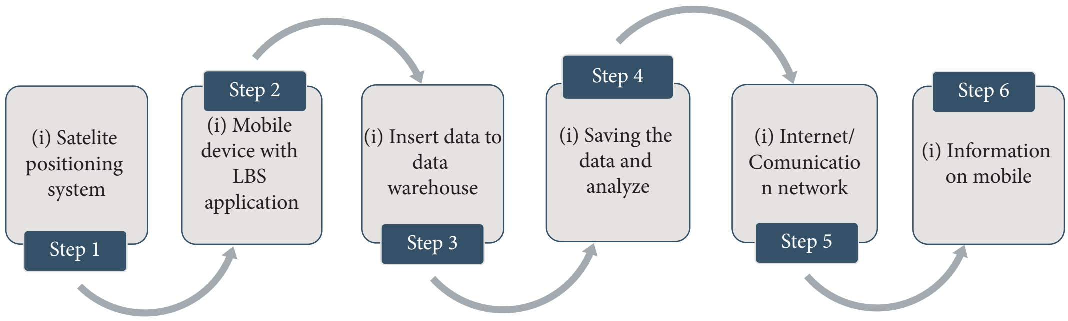
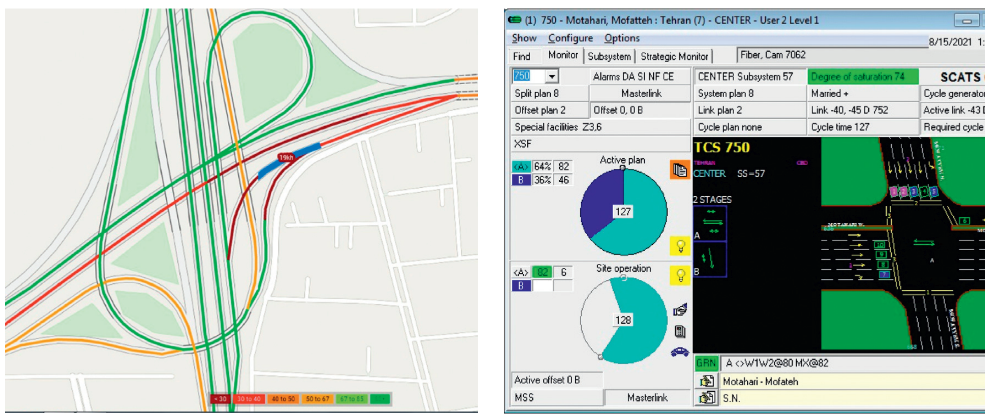


Figure 3: LBS process.



(a) (b)

Figure 4: RISC Map View by Location-Based Service (LBS) data model (a), and SCATS software environment (b) for one sample (Motahhari-Mofatteh) used intersection.

laptops, and mobile phones [27]. Figure 3 shows the process that an LBS works. In step one, a request is sent through an application on a mobile device. Then in step two, requests and the user's current location data is sent to the server. In steps three and four, the service server gets the necessary information from databases. Finally, in steps five and six, the required information is sent to the user [27].

In this research, eight independent variables and one dependent variable have been defined and counted. The independent variables used were: volume (maximum 15-minute count in hour), angle of access, total ramp density, number of lanes from the access point to the roadway, number of lanes in the roadway, on-street parking, deceleration and acceleration lanes, land use; and the dependent variables used in this research was spot speed as a traffic characteristic.

3.3. Traffic Characteristics. Traffic characteristics in this research included speed and volume data. These data were collected and recorded with the help of Tehran Traffic Control Company (TTCC) based on LBS. Global Positioning System (GPS) tracking data and SCATS data at intersections. LBS collected speed data. Tracking data calibrated by floating car and volume data was collected based on visually counted and rechecked by recorded video and SCATS data, especially for arterials with intersections. An example of LBS's collecting speed data, which Rajman Information Structures Company (RISC) developed, and volume data by SCATS software is shown in Figure 4.

The data collection was started on Monday, February 26, 2018, and was completed on Tuesday, May 28, 2019. These data were collected on Mondays and Tuesdays of each week between 9 a.m. and 11 a.m. for about more than one year in case of typical weather conditions. In this study, about 8600 data points were recorded for speed and volume by data sources.

3.4. Modeling. There are several ways to check the normality of speed data. In this study, skewness, kurtosis, and histogram, Kolmogorov-Smirnov, and Shapiro–Wilk tests were examined [28]. They confirmed the normality of the speed data. The histogram of speed for the normality test is shown in Figure 5.

With linear regression, we can estimate the linear equation's coefficients and for this, we used one or more independent variables to calculate the dependent variable value [28]. The speed data, the dependent variable in this research, is quantitative and numerical and the used model is linear regression. SPSS software was used for modeling and a significant level of 95% was considered. A chi-square test was used to compare observational speed and predicted speeds. Finally, the relationship between all variables is shown in the correlation matrix.

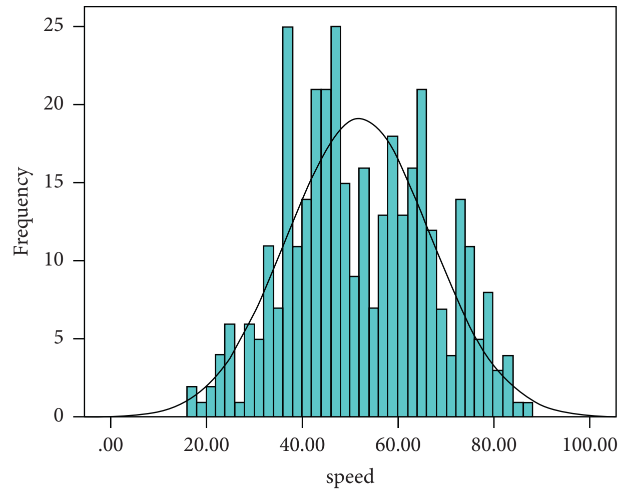


Figure 5: Histogram of gathered speed for normality test.

Table 2: Linear regression model, the effect of independent variables on the dependent variable separately.

Tests	Independent variable	Dependent variable	Standard regression coefficient (β)	Significant level (p-value < 0.05)
1	Angle of access	Spot speed	−0.49	Ok
2	Total ramp density	Spot speed	−0.25	Ok
3	Number of lanes from the access point to the roadway	Spot speed	−0.17	Ok
4	Number of lanes in the roadway	Spot speed	−0.014	Not ok
5	Volume	Spot speed	−0.15	Ok
6	On-street parking	Spot speed	−0.67	Ok
7	Deceleration and acceleration lanes	Spot speed	0.58	Ok
8	Land use	Spot speed	−0.51	Ok

Table 3: Linear regression model, the simultaneous effect of two or more independent variables on the dependent variable.

Tests	Independent variable	Dependent variable	Standard regression coefficient	R^2 adjust (%)
9	• Angle of access • Volume	Spot speed	−0.48–0.116	26
10	• Angle of access • Volume • Total ramp density	Spot speed	−0.46–0.091–0.12	27
11	• Volume • Total ramp density • On-street parking	Spot speed	0.10–0.12–0.64	47
12	• Total ramp density • On-street parking • Deceleration and acceleration lanes	Spot speed	−0.13–0.48 0.24	50
13	• Total ramp density • Angle of access • Volume • On-street parking	Spot speed	−0.1–0.14–0.099–0.56	50

4. Results

Initially, the independent variables were fitted separately to the linear regression model's spot speed-dependent variable. The results are presented in Table 2.

Then, using the multiple linear regression analysis, the simultaneous effect of independent variables on speed was measured. In this test, two to four independent variables' simultaneous effect is shown on the dependent variable. The number of independent variables causes an increasing number of prediction models. The results of the test are shown in Table 3.

In the final multiple regression analysis, which is the purpose of the research, the simultaneous effects of all

Table 4: Results of the final regression model.

Factors		Standard regression coefficient	t	P-value	VIF
Angle of access		$\beta = -0.059$	−1.13	0.26	1.9
Total ramp density		$\theta = -0.069$	−1.58	0.11	1.3
Number of lanes from access point to the roadway		$\gamma = 0.039$	−0.88	0.37	1.4
Number of lanes in roadway		$\delta = 0.072$	1.57	0.11	1.5
Volume		$\mu = -0.099$	−1.97	0.049	1.9
On-street parking		$\pi = -0.5$	−8.2	<0.001	1.2
Deceleration and acceleration lanes	0	—	—	—	—
	1	$\tau = -0.23$	−4.06	<0.001	2.2
Land use	Commercial or administrative	—	—	—	—
	Residential	$\rho = 0.019$	0.27	0.7	2.9

Table 5: ANOVA table.

Model	Sum of square	df	Mean square	F	Sig
Regression	42039.87	8	5254.98	46.97	<0.001
Residual	39269.41	351	111.87	—	—
Total	81309.28	359	—	—	—
$R^2 = 0.52$; R^2 adjust = 0.5; Durbin-Watson = 1.4					

Table 6: The correlation matrix.

Correlation matrix	A	B	C	D	E	F	G	H	L
A	1	−0.49	−0.25	−0.66	−0.16	−0.01	−0.15	0.57	−0.51
B	−0.49	1	0.23	0.56	0.17	0.12	0.07	−0.65	0.47
C	−0.25	0.23	1	0.16	−0.12	−0.39	0.22	−0.14	0.22
D	−0.66	0.56	0.16	1	0.35	0.15	0.03	−0.65	0.64
E	−0.16	0.17	−0.12	0.35	1	0.42	−0.08	−0.3	0.22
F	−0.01	0.12	−0.39	0.15	0.42	1	−0.06	−0.21	0.13
G	−0.15	0.07	0.22	0.03	−0.08	−0.06	1	−0.07	0.53
H	0.57	−0.65	−0.14	−0.65	−0.3	−0.21	−0.07	1	−0.54
I	−0.51	0.47	0.22	0.64	0.22	0.13	0.53	−0.54	1

Table 7: Chi-square test based on design speed.

Functional systems	Local frequency (percent)	Collector frequency (percent)	Minor arterial frequency (percent)	Major arterial frequency (percent)	Total frequency (percent)	Chi-square test result
Observed	8 (2.25%)	109 (30.25%)	142 (39.45%)	101 (28.05%)	360 (100%)	$\chi^2 = 291.5$
Predicted	186 (51.67%)	45 (12.5%)	129 (35.83%)	0 (0%)	360 (100%)	$P < 0.001$

Table 8: Chi-square test based on permissible speed.

Functional systems	Local frequency (percent)	Collector frequency (percent)	Minor arterial frequency (percent)	Major arterial frequency (percent)	Total frequency (percent)	Chi-square test result
Observed	8 (2.25%)	109 (30.25%)	142 (39.45%)	101 (28.05%)	360 (100%)	$\chi^2 = 139.6$
Predicted	5 (1.38%)	225 (62.5%)	129 (35.82%)	1 (0.3%)	360 (100%)	$P < 0.001$

independent variables on speed are measured, and the final result is shown in (3) and Tables 4 and 5. The prediction rate of the model is 52%.

$$y = \alpha + \beta x_1 + \theta x_2 + \gamma x_3 + \delta x_4 + \mu x_5 + \pi x_6 + \tau x_7 + \rho x_8, \quad (3)$$

where y is the dependent variable, which is Spot speed, x_1 is the angle of access, x_2 is the total ramp density, x_3 is the number of lanes from the access point to the roadway, x_4 is the number of lanes in the roadway, x_5 is the volume (maximum 15-minute count in an hour), x_6 is the on-street parking, x_7 is the deceleration and acceleration lanes, and x_8 is the land use.

The effect of all the variables used in this study on each other is shown in the correlation matrix. The correlation matrix is shown in Table 6. In this matrix, A is the spot speed, B is the angle of access, C is the total ramp density, D is the on-street parking, E is the number of lanes from the access point to the roadway, F is the number of lanes in the roadway, G is the volume, H is the deceleration and acceleration lanes, and L is the land use.

To compare the criteria before and after modeling, chi-square test was used. A comparison of speed frequencies has been made based on the design speeds and permissible speed, and the results are shown in Tables 7 and 8.

5. Discussion and Conclusion

According to the tests, it can be concluded that the most influential independent variable is the on-street parking, which, due to the negative standard coefficient, has an inverse effect on the dependent variable. Among the independent variables, land use had the lowest impact on the dependent variable. The standard regression coefficient of this variable is positive. It had a direct impact on the dependent variable. In multiple linear regression models, the number of lane variables from the access point to the roadway, the number of lanes in the roadway, and land use were variables that directly correlated with other variables. The relationship of the dependent variable with other variables was indirect.

By analyzing the on-street parking data, an unexpected result was obtained. In the parts of the roadway where there was on-street parking but was not being used, the speed was increased compared to the previous one and one of the reasons is that users use these lanes as passing lanes.

The observational speeds before the study were compared with the predicted speeds after modeling using the chi-square test. According to Table 7, at first, these values were compared with the design speed, with the initial values for local streets equal to 8 (2.25%), for collector streets equal to 109 (30.25%), for minor arterial streets equal to 142 (39.45%), and for *s*, 101 (28.05%). After modeling and comparing with design speed, their values were as follows: 186 (51.67%) for local streets, 45 (12.5%) for collector streets, 129 (35.83%) for minor arterial streets, and zero for principal arterials. Then, these values were compared with the permissible speed. According to Table 8, the results of the chi-square test based on permissible speed are as follows: for local streets it is equal to 5 (1.38%), for collector streets it is equal to 225 (62.5%), for minor arterial streets it is equal to 129 (35.82%), and for principal arterials it is equal to one (0.3%).

The predicted and the Nash–Sutcliffe test measured observational speeds to measure the modeling's prediction accuracy. The Nash–Sutcliffe model efficiency coefficient value was obtained at 96.8%. This means that the predicted speeds were close to the observational speeds, and the regression model's prediction has been corrected. However, in Tehran, the actual function of the roadways differed from their nominal function. All speed numbers entered in the chi-square test were coded. Finally, only one number among the speeds was in the design speeds range and the principal arterials' permissible speeds.

According to the chi-square test results, two general results can be extracted: Firstly, in Tehran, as our case study, each of the urban FCS does not match the current situation of traffic characteristics and geometric design features by considering roadside land use. The actual functional classification is remarkably different from the conventional functional classification named in the references. In most cases, the obtained classification was one to two categories less than the conventional nominal classification. Secondly, considering the SCATS and LBS data encode the real-time traffic flow and average speeds, it can be used as a new method to determine the more accurate FCS of each segment in the urban transportation network.

Data Availability

The datasets are available from the corresponding author on reasonable request.

Conflicts of Interest

There are no conflicts of interest.

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