Hindawi
Journal of Advanced Transportation
Volume 2020, Article ID 7523423, 12 pages
https://doi.org/10.1155/2020/7523423

Research Article

Development and Validation of Improved Impedance Functions for Roads with Mixed Traffic Using Taxi GPS Trajectory Data and Simulation

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Received 12 June 2019; Revised 1 December 2019; Accepted 14 January 2020; Published 21 February 2020

Academic Editor: Rakesh Mishra

This paper proposes an improved impedance function for roads with mixed traffic. It is known that only limited studies consider the impact of nonmotorized traffic on travel impedance of a road segment, and a comparison of the impedance considering nonmotorized traffic with the classic BPR function, which does not consider the former, is scarce. Most of the previous studies targeted road conditions in developed countries, where the presence of nonmotorized traffic is negligible, and therefore limited efforts have been invested to develop improved impedance function considering mixed traffic. To overcome this limitation, this paper develops an improved impedance function and carries out a case study for a road in the city of Wuhan, China. The improved impedance function explicitly considers the interaction between motorized and nonmotorized traffic. Taxi GPS data from the case study road is used to extract and analyze the travel time of the "probe vehicles" running through the sampled segment at any time during a sampling day. The capacity of the road segment is measured, and the traffic flow of motorized vehicles and nonmotorized vehicles on the segment is counted. Based on the above data, the classic BPR function and the improved one proposed in this paper are calibrated. After comparing and analyzing the observed road impedance based on both analytical and simulation results, the classic BPR function and the proposed impedance function, the proposed impedance function is found to be more accurate to simulate the observed road impedance, with the error reducing from 14.83 s with the classic BPR impedance function to 6.50 s with the improved function. The proposed impedance function possesses a simple structure and high flexibility, and the parameters calibrated in this paper can be applied to similar roads to provide more realistic impedance than the previous ones based on the classic BPR function. The calibrated improved impedance function's transferability to other similar roads is validated by applying it to another road and the results show that the percentage error between the predicted travel times and the observed ones is only 3.8%.

1. Introduction and Background

The determination of impedance function is the foundation of traffic assignment and urban transportation network analyses based on transportation demand forecasting models, where estimating travel time based on other traffic flow parameters is critically important. There are many impedance function models that have been developed so far, and the most popular one is the classic Bureau of Public Roads (BPR) impedance function. The BPR function has been calibrated with the data collected from the US where mixed traffic is rare and therefore may not be applicable in developing countries such as China where traffic conditions with two or more modes of travel coexist on the same road are very common. Most of the previous research [1–4] has mainly focused on model development and algorithm design using the classic BPR function. Within a mixed traffic environment, however, the classic BPR function cannot be applied directly, especially under scenarios that the interferences between motorized and nonmotorized vehicles prevail. Therefore, it is of great significance for urban road design, traffic operation, and management to study the capacity of roads under complex road conditions and develop road impedance functions that are suitable for mixed traffic condition.

While most of the previous studies on road traffic impedance functions [5–10] have focused on the classic BPR function or its derivatives, there are also efforts in the different parts of the world developing their road impedance models according to the local traffic environment. For example, the Transport and Road Research Laboratory (UK) has found that the speed based on measured data is usually higher than the traditional model and thus established an impedance function applicable to new roads in urban central areas, other urban roads, or roads with higher speed [11]. The linear section impedance function is adopted by the ministry of communications of Japan and Germany [12]. In general, the impedance functions developed are targeted to a relatively single-mode (mainly motorized) traffic environment. But in many developing countries, such as China, the traffic environment is much more complex, where motorized vehicles and nonmotorized vehicles are often sharing roads. The classic BPR function and its derivatives are not perfect choices for such traffic environments and the development of improved impedance functions should be considered.

Calibrating impedance functions need a field survey of vehicle travel times under different traffic flow conditions. Previous studies usually need to collect the travel time data manually by using devices such as stopwatches, which is very inefficient and costly. This paper develops an efficient computing tool to estimate the travel times through road sections using GPS trajectory data of taxis and the volume of different traffic modes are extracted from the videos taken on site. A new impedance function with six parameters is proposed by considering the relationship between travel time and the volume of three types of traffic participants, including cars, buses, and nonmotorized vehicles. The Broyden method is used to solve the nonlinear equation in the proposed model. Travel time and traffic volume data of a two-lane collector street in the City of Wuhan in China are collected for calibrating the proposed model. The same dataset is also used to calibrate the classic BPR function. The calculated travel times from the calibrated models are compared with the actual travel times estimated from GPS trajectory data. The result shows that the calibrated road impedance function proposed in this paper matches the observed road impedance more accurately by comparing with the classic BPR function. Microscopic simulation of the traffic flow on this road section is carried out to verify the results. Through analyzing the simulation results, it is found that the travel time with the consideration of the interference of nonmotorized vehicles is much closer to the observed travel time. Besides, to validate the calibrated new impedance function, data of another road section with a similar traffic environment in Wuhan is also collected. The estimated travel times based on the proposed impedance function are compared with the actual travel times.

The remainder of this paper is organized as follows: Section 2 is a literature review related to impedance function and data analysis. Section 3 briefly introduces the data and research methods. Section 4 presents results and discussions. Section 5 is the simulation and verification. Section 6 validates the proposed impedance function by using data of another road. The last section provides the conclusions and future research of this study.

2. Literature Review

2.1. Classic BPR Function and Its Development. The US Highway Bureau [13] conducted a traffic survey on a large number of road sections in 1964. Then the BPR function was obtained through regression analysis. The function takes the actual driving time of the vehicle on the road segment as the measurement parameter of the traffic impedance and reflects the relationship between the actual driving time of the road segments and the traffic volume of the road segments. It is defined as follows.

In the study of the impedance function, the most widely used model is the US Federal Highway Administration's [13] road resistance function (BPR). The BPR function takes the actual travel time of the vehicle on the road section as the measurement parameter of the traffic impedance, reflecting the relationship between the actual travel time and the traffic volume. It is defined as follows:

$$t = t_0\left(1 + \alpha (q/c)^{\beta}\right), \tag{1}$$

where t—the actual travel time required to pass the road segment (s); t_0—free-flow travel time of the road (s); q—the amount of traffic passing the road (pcu/h); c—actual traffic capacity of the road segment (pcu/h); α, β—coefficient; the recommended value is $\alpha = 0.15$, $\beta = 4$.

The Traffic and Road Research Laboratory (TRRL, UK) pointed out that the classic BPR function may not be universally applicable based on measured data and proposed a modified version of impedance function [14]. The TRRL recommended the following model for urban sections or higher speed road:

$$V_q = 67.6 - \frac{0.123\,(q + 1000)}{W - R}, \quad 32 < V_q < 56\,\text{km/h}, \tag{2}$$

where V_q—the speed of the road section when the traffic volume is q (km/h); W—the width of the traffic lane (m); R—the reduction in the width of the traffic lane (m).

The above formula is based on noncongested conditions; the results cannot accurately reflect the actual traffic situation.

Many scholars made efforts to improve the accuracy of the BPR function. Davidson [15] applied queuing theory to propose a progressive impedance function, which adopted the data of the road segment in the US highway capacity manual (HCM).

Sheffi [16] pointed out that the BPR function proposed by the Federal Highway Administration is too simple and does not consider the impact of intersections on the road impedance function. Therefore, the road impedance function may have low accuracy and occasional problems such as infinity values. Sheffi's research mainly focuses on the theoretical level of the road impedance function and lacks investigation and research on the actual traffic situation.

Spiess [17] established a new road impedance function because the β value in the BPR function is excessively high and BPR function has the low accuracy in the travel time at a low saturation situation. The relationship between the parameters α and β is shown as $\alpha = (2\beta - 1)/(2\beta + 1)$.

Akcelik [18] established a road impedance function considering the impact of intersection on speed and calculated a parameter table by survey. Skabardonis and Dowling [19] improved the BPR function by studying road containing traffic signal control and validated the model in both congested and noncongested situations. He found that the improved road impedance function is more accurate than the unmodified road impedance function. According to the characteristics of Chinese urban roads, Wang et al. [20] recalibrated the BPR function and established a model of road capacity. Wang and Zhang [21] established a theoretical model of speed and traffic flow. Based on the three-parameter relationship in traffic flow theory, a new theoretical model of traffic flow and bicycle crossing is proposed, and the calculating speed of the traffic demand model is also improved. Since the BPR function has been widely used in China and many developing countries, many scholars improved it to adapt to more complicated traffic conditions, including the mixed traffic environment.

2.2. Improved Impedance Functions considering Nonmotorized Traffic. Based on traffic flow theory, Yang and Qian [8] constructed the road impedance functions that were suitable for different cross-sections and road classes. Zhang [22] used VISSIM (micro simulation software) to simulate the traffic flow of urban road sections and obtained the data such as travel time and free-flow speed and then calibrated and analyzed the parameters of BPR function. Wang [20] studied travel time and toll stations by considering the characteristics of transportation network. Considering the impact of various nodes in the transportation network on the road impedance, a better model of road impedance was constructed by the actual road data. Highway Planning and Design Institute of the Ministry of Communications adopted a large number of traffic survey data to construct road impedance functions between road length and traffic flow and calibrated parameters of different road classes. However, these impedance functions did not consider the characteristics of mixed traffic flow. The characteristics of different modes of transportation and the interferences among the different modes are not considered, especially the influence of nonmotor vehicles flow on the impedance function.

Guo and Wang [23] analyzed the mixed traffic characteristic based on urban roads. Considering the distributions of medium and large vehicles in terms of lanes and locations, a practical BPR model of speed and flow is developed. The proposed model can reflect the actual impedance of the road sections with the consideration of the ratio of vehicle types. The results showed that the modified model can adapt to various traffic components with high accuracy. It can be used to accurately predict the traffic flow parameters of road sections without investigation data. In this research, they set the proportion of various transportation modes and simulated the traffic flow, and the model of traffic flow transformation was obtained. The model was theoretically applicable to various traffic conditions. The model can be expressed as $v/vf = \lambda/[1 + \alpha(q/c)\beta]$, where λ, α, β are functions of $\gamma_1 - \gamma_3$, and γ_1 and γ_3 are the ratios of small and large vehicles, respectively.

Si et al. [24] and other scholars analyzed the main modes of transportation on the urban mixed traffic road sections, including the characteristics of the traffic flow of cars, buses, and nonmotorized vehicles. Irawan et al. [25] improved the impedance function and established a model for Q/C under Indonesia's traffic conditions. The model could accurately describe the relationship between speed and traffic volume but it did not consider other factors. Besides, the function's constant is free-flow travel time and the stability needs to be improved [26].

2.3. Extraction of Travel Time Using GPS Trajectory Data. Previous studies have shown that the travel time, average speed, and road congestion coefficient can be obtained by calculating and processing the taxi trajectory data [27]. For example, the model developed by Castro can automatically calculate the capacity of each road segment by using the taxi GPS trajectory data, which can accurately predict traffic conditions and alleviate traffic congestion [28]. In this study, the taxi GPS data was used to extract the travel time of taxi through the Tieji Road. The data was preprocessed by reformatting and cleaning to make it more convenient for analyzing the travel time of the taxi.

2.4. Methods for Calibrating Impedance Functions. Many researchers have discussed the calibration of the traffic impedance function and proposed calibration methods to several different parameters [29, 30]. Based on the characteristics of urban traffic in China, Meng and Li [31] and others believed that the travel time should be regarded as a cost. The maximum likelihood method is used to calibrate the generalized traffic impedance function model of travel time, travel cost, and traffic volume. Meng and Li [31] and others focused on the calculation of the intersection delay and established a generalized model for evaluating the delay of various intersections. They also proposed the calculation method of delay and the method was validated by actual traffic data. Finally, the impedance function of the highway and arterial road was determined. Wang et al. [32] studied the relationship between the traffic flow and the travel time. The relationship can well reflect the impedance for noncongested roads. Si et al. [24] considered the interaction between the main transportation modes of different road scenarios and constructed the traffic impedance model for mixed traffic network and calibrated the parameters. After analyzing the advantages and disadvantages of the function, Wang et al. [33] established a new function to obtain a monotonically increasing function; the results showed that the road capacity is limited to reflect the road impedance.

3. Data and Methodology

3.1. Study Site and Data. For this study, the Tieji Road in Wuhan city of China was selected as the study site (from the intersection of Youyi Avenue and Tieji Road to the intersection of Heping Avenue and Tieji Road), which serves as the middle road connecting the two main roads (Figure 1). The length of this road section is 660 m. There is a primary school at 380 m from the initial point of the road section and a hospital at the end of the road. Parents often drive the car to pick up or drop off their children. There is no physical barrier between the motorized vehicle and the nonmotorized vehicle lane. Peak traffic is very congested. Pedestrians walk on the isolated pedestrian walkway and therefore would not affect the road impedance significantly.

There are two types of data needed in the study, i.e., the travel time and the traffic flow. The travel time is estimated by the time of "probe cars" traveling through the road segment, and the traffic flow is the number of traffic entities passing through the Tieji Road during this time. The traditional method uses a stopwatch or other machines to obtain the travel time while the travel time is calculated from the GPS data in this study. The traffic flow data comes from the video taken on the Tieji Road.

3.1.1. Taxi GPS Data Collection and Preprocessing. The GPS data comes from the GPS device installed in each taxi by the Taxi Company in Wuhan. For monitoring and management purposes, all taxis in Wuhan are mandatorily equipped with GPS tracking devices. The taxi trajectory data can be collected by the taxi GPS monitoring service system in real time. One day's historical taxi trajectory data with 800,000 lines of records provided by the taxi GPS monitoring service system were used in this study. Table 1 shows a sample of the original GPS data. Information in the trajectory data in each line of record includes car ID, time, latitude, longitude, speed, angle, status, and OD.

It can be seen from Table 1 that each taxi has a unique ID, which can be used conveniently and accurately to search corresponding GPS data. The latitude and longitude indicate the location of each taxi. The detection time is used to calculate the travel time. The four states of the taxi change from 0 to 3. The state "0" means the taxi is out of service; "1" means the taxi is not carrying passengers, but the GPS module has started working; "2" means the taxi is carrying passenger, but the GPS module does not work; "3" means the taxi is carrying passenger and the GPS module is working.

Information from the data provider (the Taxi Company) indicates that the GPS devices can reach a locating accuracy of around 3–5 meters at open area (e.g., on streets). And the data were recorded almost in real time (there is almost no time delay during data recording). Since the urban road studied in this paper is such type of open area, it is believed that the GPS data used in this paper has the same accuracy.

The taxi GPS monitoring system collects more than 800,000 lines of GPS trajectory data records every day in Wuhan which has far beyond the handling ability of common single-thread data processing tools and systems. Therefore, in this study the taxi trajectory data is preprocessed and analyzed by Pandas (a data analysis package in Python) in a cloud computing station environment, which can improve the efficiency of processing. Then the GPS trajectory data of the desired road sections could be extracted from the original database and formatted as shown in the data sample in Table 1.

3.1.2. Traffic Flow Data on Tieji Road. Traffic flow is used to calibrate the impedance function. There are three main types of vehicles on the Tieji Road, including private cars, buses, and nonmotorized vehicles (bike, electronic bike). In this study, the motorized vehicles and nonmotorized vehicles are counted from the recorded video. Videos are recorded from the intersection of the Tieji Road in three periods, 23:00–0:00 (free flow), 7:00–8:00 (morning peak), and 17:00–18:00 (evening peak). Cars and buses are converted to equivalent Passenger Car Unit (PCU), and nonmotorized vehicle is bike unit. Table 2 shows the traffic flow at the evening peak of Tieji Road.

3.2. Methodology

3.2.1. Extraction of Travel Time from GPS Trajectory Data. As mentioned above, GPS data include the attributes of segmentation time and location (longitude and latitude), which can be used to calculate the travel time of any road segment. The taxi GPS data track consists of a series of points. All GPS tracks are imported into ArcMap. The longitude and latitude of each point can be displayed in the panel. ArcMap can show the four vertices of the two selection areas (A and B in Figure 2). It should be noted that there is a special case in the calculation of the travel time. If the taxi trajectory is A-D-E-B, the taxi will also be detected in two areas (A and B), but this travel time is not the actual time of the Tieji Road (AB). Therefore, it is necessary to add a point C on the Tieji Road between A and B when calculating the travel time. If the trajectory of each taxi is detected in three areas (A, B, and C), the calculated travel time is regarded as the real travel time of Tieji Road.

Before the calculation, the time stamps of all records were converted from "string" to "int." The taxi IDs in the three selection areas (A, B, and C) are matched by all GPS data, and then the time of each point is processed.

3.2.2. Capacity of the Tieji Road. According to the Highway Capacity Manual, the capacity of a motorway is determined

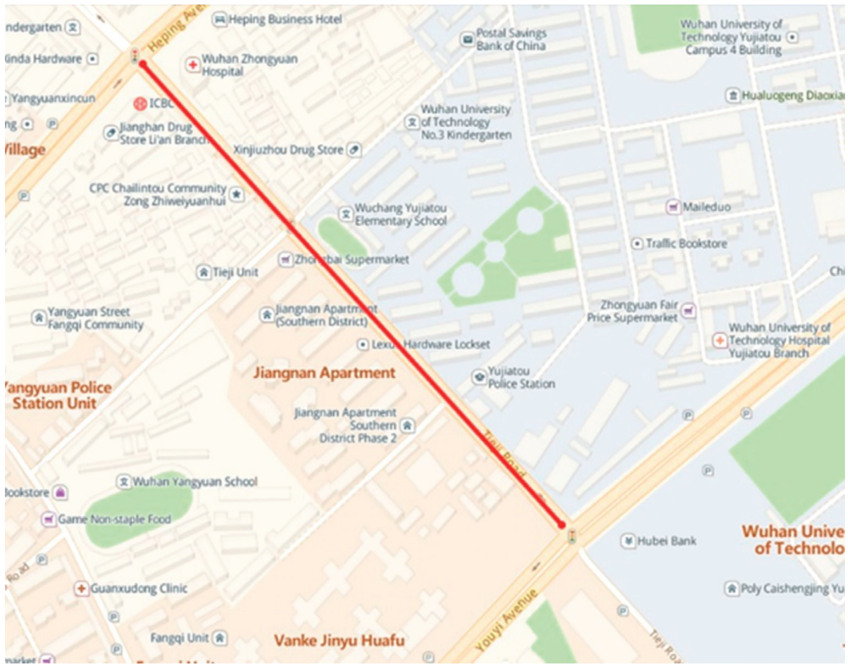

Figure 1: Details of the Tieji Road section.

Table 1: Sample of the extracted GPS data preprocessed by pandas.

Car ID	Time	Latitude	Longitude	Speed	Angle	Status	OD
3342849	1002230149	30.58293	114.2628	0	0	1	
3342849	1002230238	30.58371	114.2667	32.93	163.13	3	0
3342849	1002230325	30.58036	114.2656	54.87	243.42	3	
3342849	1002230405	30.57784	114.2599	31.78	242.24	3	
3342849	1002230445	30.57642	114.2565	23.99	260.14	3	
3342849	1002230503	30.57619	114.2559	0	0	3	
3342849	1002230602	30.57316	114.2561	25.38	171.17	3	
3342849	1002230619	30.57226	114.2561	0	0	1	1
3342849	1002230625	30.57225	114.2561	0	0	1	
3342849	1002230741	30.5755	114.2559	26.79	357.55	1	

Table 2: Traffic flow survey data for Tieji Road.

Traffic direction	Traffic flow			Percentage (%)
	Car (pcu/h)	Bus (pcu/h)	Nonmotorized vehicle (bu/h)	
Turn left	181	0	0	25.80
Straight forward	240	3	70	34.18
Turn right	281	18	200	40.02

by the number of lanes and the width of the lane and is affected by intersections and nonmotorized vehicles. The capacity of the Tieji Road is defined in formula (3), N_a is the design capacity of the road (pcu/h), γ is the correction factor of nonmotorized vehicle, η is the correction factor of road width, and C and n' are the correction factor of crossroad and lane number, respectively. There are details of these factors in the highway capacity manual. Tieji Road has two motorized lanes in each direction. The width of the motorized lane is 3 meters and nonmotorized lane is 1.5 meters. There is no barrier between the motorized lanes and the nonmotorized lane. The split of Tieji Road is 0.55. Through these parameters, the capacity of the motorized lanes of Tieji Road is calculated to be 1327 pcu/h.

$$N_a = N_0 \cdot \gamma \cdot \eta \cdot C \cdot n'. \quad (3)$$

The calculation of capacity of the nonmotorized vehicle lane is similar to the calculation of the motorized vehicle lane. C_1 is the class of the nonmotorized lanes, C_2 is the correction factor of intersection, N_t is the number of nonmotorized vehicles, and B is the width of the nonmotorized lanes. These parameters could be found in the urban road design standards. C_1 is 0.9, according to the empirical data collected from Beijing, Tianjin, and Shenyang; C_2 could

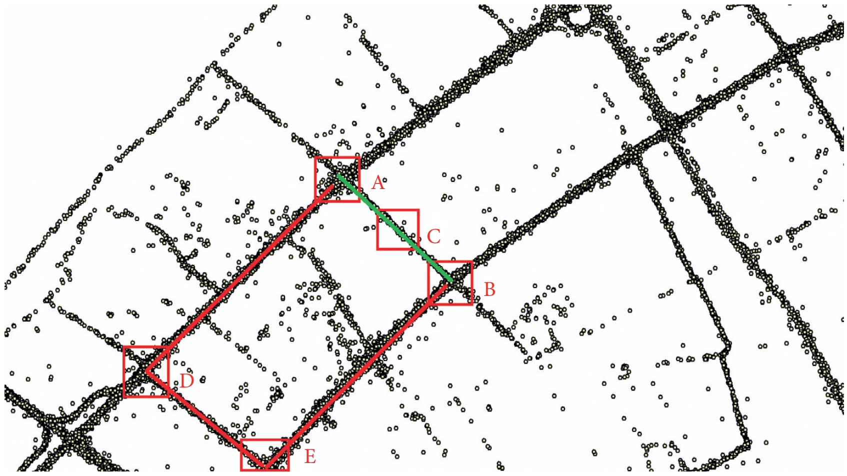

Figure 2: Method for identifying the taxi trajectory on the target road section and the calculation of travel time.

be set to 0.55; N_t is 0.51 bikes/(s·m) in the no barrier between motorized lanes and nonmotorized lane road scenario. Through these parameters, the capacity of the nonmotorized lane of Tieji Road is 908 bikes/(s·m).

$$N_b = C_1 \times C_2 \times \frac{N_t}{B - 0.5} \times \frac{3600}{t}. \quad (4)$$

3.2.3. The Improved Impedance Function considering Nonmotorized Vehicles. As mentioned earlier in this paper, the classical BPR function does not consider the nonmotorized vehicle and its disturbances to motorized vehicles. Tieji Road has two motorized lanes and there is no physical barrier between the motorized vehicle lanes and nonmotorized vehicle lane. The influencing factors of the motorized vehicle on Tieji Road include cars, buses, bikes, and electronic bikes with the same driving direction. Therefore, the new improved BPR function considering the impact of bus and nonmotorized vehicles is given by formula (5), where t_a is the travel time of Tieji Road, t_a^0 is the free-flow travel time, q_{car}, q_{bus}, and q_{bike} are traffic volumes of the car, bus, and nonmotorized vehicles (including bikes and E-bikes), respectively, C_{car} and C_{bike} are the capacities of the motorized vehicle lanes and nonmotorized vehicle lane, and $\alpha_1, \alpha_2, \alpha_3, \beta_1, \beta_2, \beta_3$ are the parameters which need to be calibrated.

$$t_a = t_a^0\left[1 + \alpha_1\left(\frac{q_{\text{car}}}{C_{\text{car}}}\right)^{\beta_1}\right]\left[1 + \alpha_2\left(\frac{q_{\text{bus}}}{C_{\text{car}}}\right)^{\beta_2}\right]\left[1 + \alpha_3\left(\frac{q_{\text{bike}}}{C_{\text{bike}}}\right)^{\beta_3}\right]. \quad (5)$$

4. Results

4.1. Calibration of the Improved Impedance Function. According to the aforesaid travel time extraction method, travel time of each taxi in the dataset is calculated and analyzed. The statistics of travel times on this road section shows obvious patterns and can be divided into five time periods (see Table 3 and Figure 3): the time period of 0:00–7:00 is the free-flow period during which the average travel time is the smallest; 7:00–10:00 is the morning peak period during which the traffic flow rises to peak and then decreases. The noon and evening peak have the same pattern, and the evening peak has the largest average travel time; the traffic flow of the period 19:00–0:00 is steady. Table 3 shows the statistics of travel times in the five periods.

Besides, as shown in Figure 3, after regression analysis of the travel time data of the five periods, there would be five regression functions for each period. Table 4 shows the details of the regression function of each period. Then, for each time point between 0:00 and 24:00, the time value can be converted to a value between 0 and 1. Therefore, the regression function can be used to calculate the travel time of the road section at any time.

R-square of the regression function of the travel time for the period 7:00–19:00 is around 0.85, which means the regression function fits well with the actual travel time. While R-square of the regression function of periods 0:00–7:00 and 19:00–0:00 is very small, indicating that the regression function may not be reliable for these two periods. However, since the average travel time between 0:00 and 7:00 is the smallest, it can be used as the free-flow travel time value in the impedance function.

In order to calibrate the α and β parameters in the impedance function (equation (5)) more conveniently, equation (5) can be converted into

$$y^{(i)} = \left(1 + \alpha_1 x_1^{(i)\beta_1}\right)\left(1 + \alpha_2 x_2^{(i)\beta_2}\right)\left(1 + \alpha_3 x_3^{(i)\beta_3}\right), \quad (6)$$

where $y^{(i)} = (t_a^{(i)}/t_a^0) = (t_a^{(i)}/56.67)$, $x_1^{(i)} = (q_{\text{car}}^{(i)}/C_{\text{car}}) = (q_{\text{car}}^{(i)}/1327)$, $x_2^{(i)} = (q_{\text{bus}}^{(i)}/C_{\text{car}}) = (q_{\text{bus}}^{(i)}/1327)$, $x_3^{(i)} = (q_{\text{bike}}^{(i)}/C_{\text{bike}}) = (q_{\text{bike}}^{(i)}/908)$; then the calibration of the impedance function is equal to finding the parameters satisfying with formula (7), where $y^{(i)}$ is the travel time of time period i divided by the free-flow travel time and $x_1^{(i)}$, $x_2^{(i)}$, $x_3^{(i)}$ are the traffic flow of the car, bus, and nonmotorized vehicle divided by the corresponding capacity. The length of time period i can be an arbitrary value theoretically, but 15 mins is used in this study. Table 5 shows the calculated values of x and y in different periods based on the data of Tieji Road.

Table 3: Statistics of taxi travel times of Tieji Road during the five time periods.

Time period	Max (s)	Min (s)	Average (s)	Variance
0:00–7:00	81	33	56.67	58.87
7:00–10:00	99	48	78.90	198.76
10:00–15:00	93	46	71.91	174.30
15:00–19:00	109	60	88.12	148.14
19:00–0:00	103	55	66.92	49.30

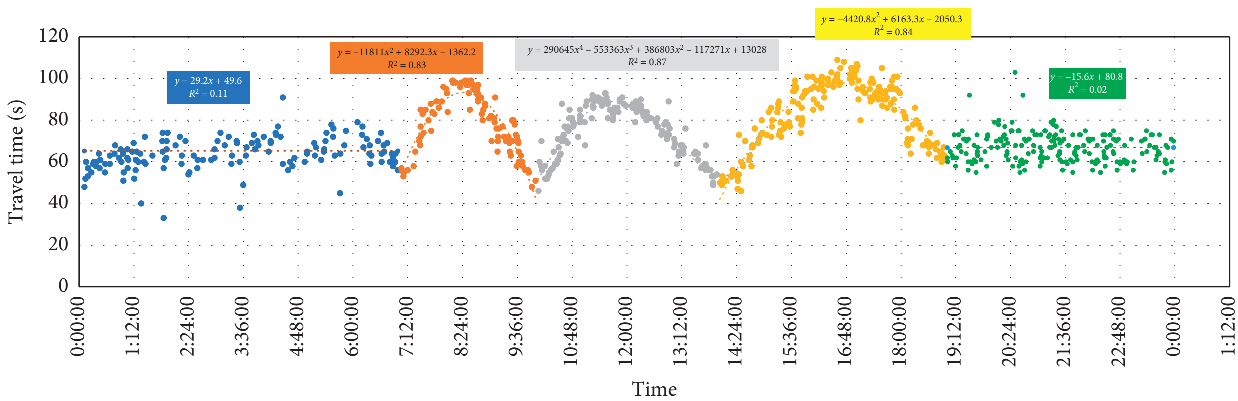

Figure 3: Scatter plot and regression results of travel time for different periods of the day.

Table 4: Details of the regression functions for travel time of different periods of the day.

Time periods	Regression function	R^2
0:00–7:00	$y = 29.2x + 49.6$	0.11
7:00–10:00	$y = -11811x^2 + 8292.2x - 1362.2$	0.83
10:00–15:00	$y = 290645x^4 - 553363x^3 + 386803x^2 - 117271x + 13028$	0.87
15:00–19:00	$y = -4420.8x^2 + 6163.3x - 2050.3$	0.84
19:00–0:00	$y = -15.6x + 80.8$	0.02

$$\min \sum_{i=1}^{N} \left[y^{(i)} - \left(1 + \alpha_1 x_1^{(i)\beta 1}\right)\left(1 + \alpha_2 x_2^{(i)\beta 2}\right)\left(1 + \alpha_3 x_3^{(i)\beta 3}\right) \right]. \tag{7}$$

So far, the parameter calibration problem has been converted into a classic extreme value problem and can be solved through traditional methods easily. For example, one may take partial derivations to these α and β parameters and then convert and solve the nonlinear equation sets after that. In this paper, the Broyden method as mentioned in [34] is used to solve the equations. The "minsearch" tool in Matlab is used to obtain the results. Based on the data of Tieji Road, the calibrated parameters for the improved impedance function are $\alpha_1 = 0.52, \alpha_2 = 0.98, \alpha_3 = 1.0, \beta_1 = 1.2,\quad \beta_2 = 1.2, \beta_3 = 1.3$. Therefore, the improved impedance function considering nonmotorized vehicles for Tieji Road can be given as

$$t_a = 56.67\left[1 + 0.52\left(\frac{q_{\text{car}}}{1327}\right)^{1.15}\right]\left[1 + 0.98\left(\frac{q_{\text{bus}}}{1327}\right)^{1.18}\right] \cdot \left[1 + 1.01\left(\frac{q_{\text{bike}}}{908}\right)^{1.31}\right]. \tag{8}$$

4.1.1. Accuracy of the Improved Impedance Function. To verify the accuracy of the improved impedance function after the calibration of the impedance function, the same traffic volume is used in classic BPR function to compare with the improved impedance function. Besides, the average travel time error of the improved impedance function with the actual travel time is 6.50 s and the average error is 8.24%, while the average travel time error of class BPR function is 14.83 s and the average error is 16.94%. This means the improved impedance function is better than the classic BPR impedance function on describing the impedance of Tieji Road in Wuhan. In addition, for a road with a similar traffic condition as Tieji Road, the parameters of the improved impedance function could also be used.

As shown in Figure 4, the travel time calculated from the improved impedance function is closer to the real travel time calculated by the GPS data, especially in the period after the morning peak.

5. Verification Based on Simulation

In order to validate the applicability of the calibrated impedance function on other similar roads, microscopic simulation of the traffic flow of Tieji Road is carried out. The

Table 5: Calculated values of the dependent and independent variables in the converted equation (6) based on data of Tieji Road.

Time period	$y^{(i)}$	$x_1^{(i)}$	$x_2^{(i)}$	$x_3^{(i)}$
7:00–7:15	0.91	0.63	0.01	0.14
7:15–7:30	1.15	0.73	0.01	0.15
7:30–7:45	1.34	0.61	0.01	0.20
7:45–8:00	1.48	0.72	0.02	0.27
8:00–8:15	1.58	0.67	0.02	0.31
8:15–8:30	1.63	0.61	0.02	0.30
8:30–8:45	1.64	0.47	0.01	0.25
8:45–9:00	1.61	0.43	0.02	0.22
11:45–12:00	1.57	0.48	0.02	0.24
12:00–12:15	1.56	0.49	0.02	0.25
12:15–12:30	1.51	0.52	0.03	0.26
12:30–12:45	1.44	0.46	0.02	0.22
15:30–15:45	1.52	0.64	0.03	0.27
15:45–16:00	1.60	0.64	0.03	0.22
16:00–16:15	1.65	0.73	0.03	0.24
16:15–16:30	1.70	0.77	0.03	0.32
16:30–16:45	1.72	0.60	0.05	0.28
16:45–17:00	1.73	0.53	0.03	0.30
17:00–17:15	1.72	0.74	0.03	0.31
17:15–17:30	1.69	0.77	0.02	0.29
23:30–23:45	0.97	0.13	≤0.01	0.01
23:45–00:00	1.01	0.14	≤0.01	≤0.01

AnyLogic software is used to do the simulation based on observed data and road traffic environment. The effectiveness and accuracy of the improved road impedance function are verified by comparing and analyzing motorized vehicles and nonmotorized vehicles interference with traffic on the road segment.

5.1. Simulation Model Setup. The simulation model was set up with the same parameters and road environment setup as the road section studied for the improved impedance function. The microscopic simulation model was constructed in Anylogic software.

5.1.1. Traffic Flow Data. Selecting the intersection of Tieji Road and Heping Avenue as the study object, the signal timing scheme and the traffic flow of each entrance road were investigated and counted. As the simulation verified the travel time of vehicles in this section, the traffic flow of the south entrance road at the intersection was investigated and counted, mainly divided into two periods: morning peak and evening peak. At the same time, there are traffic lights around the school for signal control; the traffic flow near the school needs to be investigated and counted during the evening peak hour from 16:30 to 17:10. At last, the traffic volume calculated is shown in Tables 6–9.

5.1.2. Vehicle Parameters. The average length of cars in the model is set as 5.036 meters, and the speed limit of Tieji Road is 50 km/h. The average speed of vehicles is 32.3 km/h by processing of taxi GPS data and the average size of buses is 8.54 meters and the average speed of buses is 17 km/h.

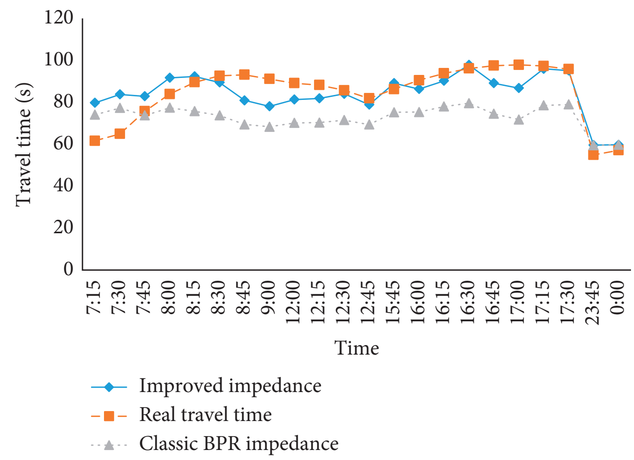

Figure 4: Comparison of travel time predicted by the improved impedance function, the classic BPR function, and the real travel time estimated from GPS data.

5.1.3. Signal Timing Setup. According to the observed signal timing plan, the signal timing plan of school intersection and the intersection of Tieji Road and Heping Avenue were used directly as inputs into the signal control module in the simulation.

6. Simulation Result and Analysis

Through processing the taxi GPS trajectory data, the actual travel time of the Tieji Road is obtained. AnyLogic is used to run the simulation and the travel time during the three periods with the consideration of nonmotorized vehicle interference and without the consideration of nonmotorized vehicles interference is extracted from the simulation results. The simulation results are shown in Table 10. The following can be seen: (1) during the free-flow period, the observed travel time is 56.7 s and the travel time is 40.5 s and 52.1 s, respectively, without considering the interference of nonmotorized vehicles and without considering the interference of nonmotorized vehicles. The travel time extracted from the simulation runs considering the interference of nonmotorized vehicles is much closer to the observed. (2) During the morning peak hour, the average observed travel time is 78.9 s, the travel time without considering nonmotorized vehicles is found to be 62.4 s, and the one with considering nonmotorized vehicles is 71.1 s. (3) During the evening peak hour, the average travel time is 88.1 s, the travel time without considering nonmotorized vehicles is 105.9 s, and the one with considering nonmotorized vehicles interference is 93.3 s. When the interference of nonmotorized vehicles is not considered, the error goes from 16.8% to 21.0%, whereas when the interference of nonmotorized vehicles is considered, the error goes down from 5.5% during the evening peak up to 9.9% for the morning peak period.

The result shows that the error of considering the nonmotorized vehicle travel time is much smaller and the improved impedance function conforms more to the

Table 6: Morning peak hour traffic flow at the intersection of Tieji Road and Heping Avenue.

South entrance	Traffic flow (1 hour)		Proportion of traffic flow (%)
	Car (pcu/h)	Bus (pcu/h)	
Left	230	0	26.84
Straight	133.5	5	15.99
Right	481.5	17	57.17

Table 7: Evening peak hour traffic flow at the intersection of Tieji Road and Heping Avenue.

South entrance	Traffic flow (1 hour)		Proportion of traffic flow (%)
	Car (pcu/h)	Bus (pcu/h)	
Left	400	0	38.24
Straight	334	5	31.93
Right	312	12	29.83

Table 8: Morning peak hour traffic flow near the school.

South entrance	Traffic flow (1 hour)		Proportion of traffic flow (%)
	Car (pcu/h)	Bus (pcu/h)	
Left	12	0	2.2
Straight	614	22	94.68
Turn around	25	0	3.60

Table 9: Evening peak hour traffic flow near the school.

South entrance	Traffic flow (1 hour)		Proportion of traffic flow (%)
	Car (pcu/h)	Bus (pcu/h)	
Left	23	0	2.24
Straight	960	17	93.75
Turn around	41	0	4.00

observed traffic time. Compared with the classic BPR function, the proposed method can more accurately reflect the observed traffic operation state at the Tieji Road.

7. Validation by Applying to Other Roads

7.1. Validation Site and Data. To validate the improved impedance function, the Jianshe Road in Wuhan City which possesses similar features to Tieji road was selected. This road section also serves as the middle road connecting the two main roads (Figure 5). The length of this road section is 897 m. There is an elementary school and a middle school at around 200 m of this road section (starting from the southeast intersection). There is no physical barrier between the motorized vehicle and the nonmotorized vehicle lanes. Traffic demand is large especially during the morning peak. Similar to Tieji Road, there are three main types of vehicles, including cars, buses, and nonmotorized vehicles (bike and electronic bike). Pedestrians walk on the isolated pedestrian walkway and therefore would not affect the road impedance significantly.

Field survey of the traffic flow of this road has been conducted and traffic flow data of cars, buses, and nonmotorized vehicles have been obtained. Travel time data have been estimated with the same method as used for Tieji Road. The road impedance function is validated by using the traffic flow and travel time data of the morning peak period of the road. Table 11 shows the traffic flow at the morning peak (8:00-9:00) of the Jianshe Road.

8. Validation Result and Analysis

The traffic flow and travel time of the Jianshe Road are substituted into the calibrated impedance function of the Tieji Road (equation (8)). The calculation results are shown in Table 12.

It can be seen from Table 12 that the improved impedance model proposed can accurately predict the travel time with an average error of only 3.8%.

9. Conclusions, Limitations, and Future Research

In this paper, travel time through a particular road segment is extracted from taxi trajectory data, which emphasizes the possibility of automating the extraction of travel time information for all roads traversed by taxis within a city like Wuhan, China. Such a method can be used to extract travel time for most of the roads and thus makes it useful for potential applications in transportation planning, traffic management and control, and other related transport studies.

Table 10: Comparison of vehicle travel times in three periods.

Time period	Observed travel time (s)	Simulation results (not considering nonmotorized vehicles) (s)	Absolute percentage error	Simulation results (considering nonmotorized vehicles) (s)	Absolute percentage error (%)
Free flow	56.7	40.5	20.4%	52.1	8.1
Morning peak	78.9	62.4	21.0%	71.1	9.9
Evening peak	88.1	105.9	16.8%	93.3	5.5

Figure 5: Details of the Jianshe Road section.

Table 11: Traffic flow survey data for Jianshe Road.

Traffic direction	Traffic flow			Percentage (%)
	Car (pcu/hour)	Bus (pcu/hour)	Nonmotorized vehicle (bu/hour)	
Turn left	103	0	88	15.13
Straight forward	457	42	289	62.44
Turn right	158	0	125	22.43

Table 12: Comparison of the observed average travel time and the predicted travel time calculated from applying the calibrated impedance function on Jianshe Road.

Time period	Observed average travel time (s)	Predicted travel time (s)	Percentage error (%)
8:00–8:05	77.32	82.21	−6.33
8:05–8:10	83.70	86.31	−3.13
8:10–8:15	88.61	91.12	−2.94
8:15–8:20	91.50	95.34	−4.21
8:20–8:25	94.10	96.65	−2.71
8:25–8:30	92.36	93.42	−1.10
8:30–8:35	87.26	86.31	1.11
8:35–8:40	83.71	80.18	4.22
8:40–8:45	81.14	77.78	4.13
8:45–8:50	76.51	72.38	5.39
8:50–8:55	73.37	69.38	5.44
8:55–9:00	70.88	67.10	5.33

Then, an improved impedance function is proposed by considering the interferences between cars, buses, and nonmotorized vehicles. This impedance function is quite different from the classic BPR function, which only considers motorized vehicles on roads and therefore makes their applications in developing countries irrelevant, where roads are often fixedly used by motorized and nonmotorized traffic simultaneously. The proposed improved impedance function is then calibrated based on the travel time data estimated from GPS data and the traffic flow observed through site survey.

Study results prove that the proposed impedance function can more accurately match the observed travel time on the test road segment. When compared with the traditional BPR impedance function, which shows an average error of 16.94%, the average error of the improved impedance function is only 8.24%. Microscopic traffic flow simulations are carried out to verify the applicability of the calibrated impedance function with the same traffic environment setup with the test road segment. The simulation result shows that the error of considering the interference nonmotorized vehicles travel time is much smaller and the travel time of considering the interference nonmotorized vehicles is closer to the observed travel time. Finally, the calibrated impedance function is applied to another road segment with similar traffic flow environment to validate the transferability of the calibrated impedance function. The results show that the predicted travel time of using the impedance function yields only 3.8% percentage error in average by comparing with the observed travel time.

Some questions related to the improved impedance function remain to be solved by future research. In particular, the improved impedance function proposed in this paper does not consider the impact of pedestrians, which is a serious shortcoming for the low-level class roads in developing countries, where a significant amount of pedestrians may interfere with other traffic. The impact of pedestrians on motorized vehicles on roads that pedestrian walkway is not isolated from the motorized lanes should be one of the topics in future research. Besides, the impact of the reverse motorized and the reverse nonmotorized vehicles on the impedance function should also be considered in future research, since these situations are also commonly seen.

The improved impedance function proposed in this paper has only been tested on two particular road sections (the Tieji Road and Jianshe Road, Wuhan City). It is necessary to carry out similar studies on other types of roads, develop different types of impedance functions, and compare their performances under different road conditions. However, it may be difficult to specify a particular impedance function (mathematical form) for each of the roads, as each of them is unique in some aspect (e.g., road configuration, parking regulation, differing in motorized and nonmotorized volumes). As deep learning and artificial intelligence are now becoming more and more practical, they can be trained to capture the relationship between traffic flow of various types (e.g., motorized, nonmotorized, and pedestrian) and travel time for a large number of roads simultaneously.

Data Availability

The data used to support the findings of this study have not been made publicly available because these data relate to personal privacy and there is a data confidentiality agreement with the data provider.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This study was supported by National Natural Science Foundation of China (51778510 and 51678461), a research fund from the Wuhan Transportation Planning Institute (WHTPI), and start-up grants from Wuhan University of Technology. The funding from National Key Research and Development Program of China (no. 2018YFB1600900) is also appreciated.

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