

Knowledge-Based and Data-Driven Highway Vehicle Speed Calculation Methods and Models: Postprint

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Abstract

Due to the currently insufficient positioning accuracy of cellular base stations and the inherent uncertainties in signaling data, accurately estimating traffic information parameters from mobile phone signaling data remains a formidable challenge. Highway vehicle speed parameter constitutes one of the most frequently studied metrics for evaluating road service quality. Currently, the fundamental procedure for traffic parameter estimation based on mobile phone signaling data encompasses data collection and preprocessing, map matching, user route matching determination, and traffic information parameter estimation. Building upon this foundation and leveraging principles from physical kinematics, we propose an enhanced vehicle speed calculation method incorporating distance weighting to address the uncertainties inherent in mobile phone signaling data and the susceptibility to contamination by noise from parallel highway user data. Furthermore, we develop an additional vehicle speed calculation method that eliminates interference data from parallel highways, thereby enhancing computational accuracy. Case validation was conducted utilizing a platform provided by a mobile network operator, with Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and Mean Absolute Percentage Error (MAPE) employed as performance metrics. The proposed method demonstrates superior performance across all metrics compared to conventional approaches, with the Mean Absolute Percentage Error reduced by approximately 10% relative to traditional methods, thereby possessing significant practical application value.

Full Text

Preamble

Research on Model of Highway Vehicle Speed Calculation Based on Knowledge and Data Driven

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Abstract: Due to insufficient positioning accuracy via cellular base stations and the inherent uncertainty of signaling data, estimating traffic information parameters accurately from mobile phone signaling data remains a significant challenge. Highway vehicle speed is one of the most frequently studied parameters for evaluating road service quality. Current traffic parameter estimation based on mobile phone signaling data typically involves four basic steps: data collection and preprocessing, map matching, user route matching determination, and traffic information parameter estimation. Building upon this foundation and drawing from physical kinematics principles, this paper addresses the uncertainty of mobile signaling data generation and the influence of noise user data from parallel highways. We propose an improved vehicle speed calculation method that incorporates distance-weighted fusion, and further develop a parallel highway interference elimination method to enhance calculation accuracy. Experimental validation using a platform provided by a mobile operator demonstrates that our method outperforms traditional approaches across all performance metrics, including Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and Mean Absolute Percentage Error (MAPE), with MAPE reduced by approximately 10% compared to conventional methods, indicating significant practical value.

Keywords: intelligent transportation system; mobile phone signaling data; vehicle speed; parallel road; noise data

0 Introduction

In recent years, economic growth and technological advancement have led to increasing demands for traffic services in Intelligent Transportation Systems (ITS). Real-time traffic information systems have become increasingly important. Currently, highway traffic flow data are primarily collected through detectors such as inductive loops, geomagnetic sensors, video cameras, radar, and infrared devices. These methods require installing equipment on roads, consuming substantial human and material resources. Alternatively, vehicle information can be collected via GPS, but this approach requires installing GPS devices in ve-

hicles, resulting in high initial investment costs and incomplete data collection with inherent limitations.

With the comprehensive dense coverage of cellular networks and the widespread adoption of mobile phones, using mobile phone signaling data to obtain traffic information parameters has become an effective and feasible approach. This method offers low cost, comprehensive coverage, and the ability to acquire traffic parameter information accurately and in real-time, around the clock. Consequently, estimating traffic parameters and conditions based on cellular phone signaling data has emerged as a popular alternative to traditional methods.

Numerous domestic and international studies have investigated the acquisition of highway traffic flow parameters and road condition information through mobile phone signaling data. Key traffic flow parameters include vehicle speed, density, travel time, and traffic volume, among which vehicle speed is one of the most critical parameters for highway traffic information and is most frequently studied in road service quality evaluation. Current highway vehicle speed calculation methods based on mobile phone signaling data fall into two main categories: first, calculating speed using the ratio of travel distance difference to travel time difference between two points ($V_k = \frac{S_2 - S_1}{T_2 - T_1}$); second, calculating speed using the ratio of traffic flow (veh/h) to traffic density (veh/km) ($V_k = \frac{q}{k}$).

Previous research has validated the significant value of signaling data for traffic congestion identification by analyzing mobile phone signaling data, using handover events between base stations during user movement to calculate travel distance and time differences for vehicle speed estimation and congestion state identification, demonstrating feasibility and practicality. When a mobile user moves from cell 1 to cell 2 during a call, a handover signal is generated and recorded. As the user continues moving from cell 2 to cell 3, another handover signal is recorded. Analyzing these two handover signals yields the cell residence time in cell 2 and the vehicle travel distance, enabling highway speed estimation. Other studies have proposed location handover-based traffic speed estimation methods using longest common subsequence algorithms for map matching between user trajectories and target road segments, achieving reasonable results but with significant speed fluctuations and interference data that limit calculation accuracy. Alternative approaches have estimated traffic density through location updates and call arrivals, and traffic flow through periodic updates, subsequently calculating vehicle speed. While feasible, these methods suffer from low accuracy in density and flow estimation and computational complexity, leading to substantial errors.

Researchers have recognized that vehicle speed estimation using mobile phone signaling data is significantly affected by noise data from pedestrians near highways, vehicles on adjacent roads, and other sources. Methods have been proposed to classify signaling data to distinguish between motorized and non-motorized carriers while filtering noise data, improving speed calculation ac-

curacy. Other studies have introduced handover interval thresholds and time interval thresholds to filter erroneous data and reduce speed calculation errors caused by inaccurate positioning. However, existing methods still face challenges due to the uncertainty of signaling data generation and susceptibility to noise data, particularly from parallel roads, resulting in insufficient accuracy in highway vehicle speed calculation.

This paper addresses the uncertainty of signaling data generation, characterized by varying distance lengths generated within a highway segment, by proposing a vehicle speed calculation method that introduces a distance-related weighting factor function into the ratio of travel distance difference to travel time difference between two points. Additionally, specifically targeting interference from parallel highways, rural roads, and provincial roads adjacent to highways, we propose a parallel highway interference elimination method based on mobile phone signaling data, significantly improving highway vehicle speed calculation accuracy. This approach holds important significance for the application of mobile signaling data in modern ITS and for further improving service quality.

1 Basic Concepts

1.1 Communication Events Generating Mobile Phone Signaling Data

As vehicle-borne mobile phone users travel on highways, they generate mobile signaling data unpredictably at surrounding base stations. This data generation is driven by various communication events. Figure 1 Figure 1: see original paper provides a simplified overview of these communication events.

When a mobile phone user executes a call and moves from cell 1 to cell 2, a handover signal is generated and recorded. As the user continues moving from cell 2 to cell 3, another handover signal is generated and recorded. Analyzing these two handover signals yields the cell residence time in cell 2 and the vehicle travel distance, enabling highway speed estimation.

The mobile signaling data generated by these five types of communication events passes through the mobile operator's raw signaling data collection platform. After preprocessing steps such as data filtering and noise removal, the data is distributed to various processing modules via data transmission pipelines. For this study, we extracted mobile signaling data from base stations monitoring the G85 highway segment. The main fields contained in the mobile signaling data are described in Table 1 .

Table 1 Description of Mobile User Signaling Data Fields

No.	Field Name	Description
1	IMSI	International Mobile Subscriber Identity, unique phone identifier
2	TimeStamp	Timestamp of signaling event, YYYYMMDDHHMMSS, accurate to seconds
3	LAC	Location Area Code
4	CELLID	Cell location area identifier
5	EventID	Communication event type: (1) periodic update, (2) normal location update, (3) SMS send/receive, (4) call handover, (5) handover, (6) power on/off
6	Cause	Handover cause
7	Result	Cell entry/exit identifier

This study primarily uses fields 1, 2, 3, 4, and 5, where LAC and CELLID can be matched to base station longitude (Lng) and latitude (Lat).

1.2 Noise Data in Mobile Phone Signaling Data

Highway networks are complex, with parallel roads, rural roads, and provincial roads in close proximity. Due to insufficient base station positioning accuracy, raw mobile signaling data contains substantial noise user data, including pedestrians near highways, local residents, and users on parallel roads adjacent to highways. This interference noise data severely impacts vehicle speed calculation accuracy. While existing solutions address interference from residents and pedestrians near highways, no specific methods target interference from vehicles on parallel highways and rural roads. Therefore, this paper proposes a parallel highway interference elimination method for vehicle speed calculation. Figure 2 [Figure 2: see original paper] illustrates parallel roads near highways.

2 Highway Vehicle Speed Calculation Method Principles

Current research on obtaining highway traffic flow parameters from mobile phone signaling data has made significant contributions, particularly regarding highway vehicle speed calculation methods. To extract highway vehicle speed parameters from mobile signaling data, the following basic steps are required: signaling data preprocessing; road network matching to align highway and base station sequences; highway user path matching to identify highway-traveling vehicle users; and highway vehicle speed calculation. The overall framework is shown in Figure 3 [Figure 3: see original paper].

2.1 Data Cleaning and Preprocessing

Due to insufficient base station positioning accuracy, complex highway environments, and the uncertainty of mobile signaling data generation, raw signaling data collected by mobile operators contains substantial “dirty data.” Therefore, essential preprocessing operations including field extraction, dirty data removal, and ping-pong effect filtering are necessary to facilitate subsequent calculations and improve matching accuracy. The data preprocessing steps are illustrated in Figure 4 [Figure 4: see original paper].

2.2 Road Network Matching

Road network matching involves aligning highway segments with mobile base station coverage. Establishing a mapping relationship table between highway segments and base stations is fundamental for highway user path matching and vehicle speed calculation. This paper considers factors such as distance between road segments and base stations, and base station sector coverage direction, to achieve maximum possible matching between highway segments and base stations. The main steps are as follows:

- a) Establish a rectangular monitoring area based on the highway route that completely encompasses the highway. Using the lower-left corner of the rectangular area as the origin, construct a two-dimensional coordinate system and divide the area into square grids of length L . Record the highway as a road grid sequence:

$$Seg = \{S_{x_1, y_1}(lng, lat), \dots, S_{x_i, y_i}(lng, lat), \dots, S_{x_n, y_n}(lng, lat)\}$$

Record the base stations in the monitoring area as:

$$sta = \{M_{x_1, y_1}(lng, lat), \dots, M_{x_i, y_i}(lng, lat), \dots, M_{x_n, y_n}(lng, lat)\}$$

- b) Match each road grid to its most likely corresponding base station. Calculate the Euclidean distance between each grid in the road grid sequence and each base station in the base station sequence, and determine whether the base station sector covers the road grid. Select the base station with the shortest distance that covers the road grid as the mapping base station for that grid.
- c) Define the ascending order direction of two-dimensional coordinate sequence numbers $\{(x_1, y_1), \dots, (x_i, y_i), \dots, (x_n, y_n)\}$ as the positive direction of the highway, and the descending order direction $\{(x_n, y_n), \dots, (x_i, y_i), \dots, (x_1, y_1)\}$ as the reverse direction. Establish a matching library between highway segments and base stations as shown in Table 2 .

Table 2 Highway and Base Station Matching Table

No.	Field Name	Description
1	Road_ID	Highway road grid sequence number (x_i, y_i)
2	Road_Lng	Road grid longitude
3	Road_Lat	Road grid latitude
4	Station_ID	Base station grid sequence number (x_i, y_i)
5	Station_Lng	Base station longitude
6	Station_Lat	Base station latitude
7	Cover	Whether base station covers road grid (1: yes, 0: no)

2.3 Highway User Path Matching

Highway user path matching identifies highway-traveling vehicle users by comparing preprocessed user mobile signaling data trajectory sequences with the highway grid sequence. The main steps are:

- a) Obtain the user mobile signaling data trajectory sequence set for the monitoring area after data preprocessing. Extract each user's signaling trajectory sequence $\{M_{x_j, y_j}(lng, lat), \dots, M_{x_k, y_k}(lng, lat)\}$ containing N trajectory points. Compare the user's signaling trajectory sequence with the highway base station matching library and count N_1 trajectory points that exist in the highway base station matching library.
- b) Calculate the similarity λ between the user signaling trajectory and the highway road grid sequence. When similarity λ exceeds a certain threshold and exhibits directionality, the user is identified as a highway user. Directionality is determined by the increasing or decreasing order of two-dimensional coordinate sequence numbers (x_i, y_i) .

2.4 Highway Vehicle Speed Calculation

Traditional highway road grid vehicle speed calculation primarily uses the ratio of travel distance difference to travel time difference between two trajectory points:

$$V_i = \frac{dist\{M_{x_i, y_i}(lng, lat), M_{x_j, y_j}(lng, lat)\}}{T_j - T_i}$$

where $M_{x_i, y_i}(lng, lat)$ and $M_{x_j, y_j}(lng, lat)$ are base station location points, $dist$ calculates the Euclidean distance between two base station locations, and $T_j - T_i$ is the travel time difference between the two points.

To calculate the average speed of road grid K, assuming n pairs of trajectory points pass through and include road grid K, the average vehicle speed of road grid K is V_k :

$$V_k = \frac{\sum V_i}{n}$$

1) Proposed Method Model 1 Traditional methods calculate vehicle speed using only the ratio of travel distance difference to travel time difference. However, the uncertainty of mobile signaling data generation results in multiple pairs of trajectory points with varying travel distances within a single road grid. This uncertainty affects highway vehicle speed calculation. Based on physical kinematics principles and statistical analysis, we observe that for trajectory point pairs within a road grid, shorter travel distances contribute more significantly to the grid's average speed. Leveraging this characteristic, we propose an improved vehicle speed calculation method incorporating distance-weighted fusion. The improved method flowchart is shown in Figure 5 [Figure 5: see original paper]. The key steps are:

- a) Calculate the travel distance and travel time for trajectory point pairs containing a specific road grid to determine their speed contribution values.
- b) Select a weighting factor function φ_{ij} that is inversely correlated with travel distance to weight the speed contribution values.
- c) Calculate the weighted values using the distance weighting function, multiply them with individual speed contribution values, and sum the products to obtain the final average vehicle speed for the road grid:

$$V_k = \sum \varphi_{ij} \frac{\text{dist}\{M_{x_i, y_i}(lng, lat), M_{x_j, y_j}(lng, lat)\}}{T_j - T_i}$$

where l represents the l -th user signaling in the k -th road segment, and N_k represents the number of trajectory point pairs in the k -th road segment.

2) Proposed Method Model 2 In addition to the uncertainty of mobile signaling data generation, highway vehicle speed calculation accuracy is significantly affected by noise user data, particularly from vehicles on parallel highways, rural roads, and provincial roads adjacent to highways. Since parallel roads generally exist alongside highway segments, we can eliminate interfering users based on historical user data from preceding road segments without parallel roads. Targeting parallel road interference users and building upon the improved vehicle speed calculation method from Model 1, we further propose a parallel highway interference elimination method to recalculate highway vehicle speeds for segments with parallel roads. The method flowchart is shown in Figure 6 [Figure 6: see original paper]. The main principles are:

- d) Obtain the current number of users N_k on a highway road grid with parallel roads, and simultaneously obtain the historical number of users N_i on preceding highway road grids without parallel roads. Perform intersection

operation $N_k^1 = N_k \cap N_t$, where N_k^1 users are confirmed as highway users, and $N_k^2 = N_k - N_k^1$ represents uncertain users.

- e) Calculate the average speed V_k^1 for the road grid with parallel roads using the confirmed highway users N_k^1 and the vehicle speed calculation method from Model 1. Determine the traffic state based on V_k^1 : smooth state ($V_k^1 \geq 80$ km/h), mild congestion (40 km/h $\leq V_k^1 < 80$ km/h), or congested state ($V_k^1 < 40$ km/h).
- f) Calculate the speed value V_k^2 for each user in the uncertain portion N_k^2 using the travel distance and time difference formula. If a user's speed value V_k^2 falls within the speed range determined by V_k^1 for that traffic state, classify the user as a highway user; otherwise, classify as parallel highway interference user and remove them. Further identify highway users N_k^3 from the initially uncertain user portion N_k^2 .
- g) Apply the vehicle speed calculation method from Model 1 to the N_k^3 portion of users to calculate the average speed value V_k^3 .
- h) Recalculate the road grid's average vehicle speed using the user data after parallel highway noise elimination:

$$V_k = \frac{N_k^1 \times V_k^1 + N_k^3 \times V_k^3}{N_k^1 + N_k^3}$$

3 Experiments

3.1 Experimental Conditions

We selected the G85 Chengdu-Chongqing Expressway segment from Xihuan Interchange to Yongchuan Toll Station in Chongqing as the experimental testbed. The segment spans 56 kilometers, bounded by a rectangular frame as shown in Figure 6 [Figure 6: see original paper]. The mobile signaling data collection system continuously collects signaling data from base stations surrounding the pilot highway segment and distributes it in real-time via ActiveMQ messaging. Raw mobile signaling data examples are shown in Figure 7 [Figure 7: see original paper].

The raw data includes fields such as user ID, generation time, base station location, cell entry/exit criteria, and handover cause. Specifically, “jumpin” indicates a mobile user entering a cell coverage area, “jumpout” indicates leaving the coverage area, and “move” indicates movement within the coverage area.

Using mobile signaling data as the input source, model validation compares results with data from fixed detectors installed alongside the highway. To verify the effectiveness of the parallel highway noise data elimination method, we selected two fixed detectors on highway segments with parallel roads. These

detectors measure instantaneous average speeds within 5-minute intervals. Performance metrics include Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and Mean Absolute Percentage Error (MAPE), calculated as:

$$MAE = \frac{\sum |x_i - x'_i|}{N}$$

$$RMSE = \sqrt{\frac{\sum (x_i - x'_i)^2}{N}}$$

$$MAPE = \frac{\sum \left| \frac{x_i - x'_i}{x_i} \right|}{N} \times 100\%$$

where N is the sample size, x_i is the detector result, and x'_i is the model calculation result.

3.2 Results and Validation Analysis

The mobile signaling data stream for the test segment monitoring area was provided by a mobile operator and distributed in real-time via ActiveMQ. After receiving five minutes of signaling data, the data stream is distributed to the processing model. Following the procedures described in Sections 2.1, 2.2, and 2.3, the processed data is fed into three highway average speed calculation models:

- a) Reference [11] model: Traditional vehicle average speed calculation model
- b) Proposed Method Model 1: Distance-weighted fusion vehicle average speed calculation model
- c) Proposed Method Model 2: Distance-weighted fusion + parallel highway interference elimination vehicle average speed calculation model

In Method Model 1, selecting an appropriate distance-inverse weighting function is crucial for optimal results. Common weighting functions include inverse distance function $\frac{1}{S}$, inverse squared distance function $\frac{1}{S^2}$, and Gaussian weighting function $e^{-(S^2)}$, where S represents vehicle travel distance. Using data from May 17, 2017, between 6:00 and 22:00, we tested these three weighting functions in the vehicle average speed calculation models alongside the traditional model. Results from two fixed detector locations were compared with model outputs, yielding the performance comparison shown in Table 3 .

Table 3 Performance Error Comparison for Method Model 1

Speed Detector	MAE	RMSE	MAPE
Reference [11] method model	11.35	13.56	19.8%
Method Model 1 ($\frac{1}{S}$ weighting)	9.87	11.98	17.2%
Method Model 1 ($\frac{1}{S^2}$ weighting)	9.12	11.23	15.6%
Method Model 1 ($e^{-(S^2)}$ weighting)	8.45	10.67	14.3%

The results demonstrate that Method Model 1 outperforms the reference [11] method across all metrics, validating the effectiveness of the proposed distance-weighted improved vehicle speed calculation method. The Gaussian weighting function $e^{-(S^2)}$ yields the optimal results and is therefore selected as the weighting function.

To further address parallel highway interference data, we incorporated the parallel highway interference elimination method into the distance-weighted vehicle average speed calculation model, creating the distance-weighted + parallel highway interference elimination vehicle average speed calculation model (Method Model 2). Comparing this model's results with Method Model 1 and two fixed speed detectors yields the performance comparison shown in Table 4.

Table 4 Performance Error Comparison for Method Model 2

Speed Detector	MAE	RMSE	MAPE
Method Model 1	8.45	10.67	14.3%
Method Model 2	6.78	8.93	12.1%

Table 4 shows that incorporating parallel highway interference elimination further improves MAE, RMSE, and MAPE, effectively eliminating noise user data from parallel highways and preventing interference from adjacent parallel roads on highway vehicle speed calculation.

Using the Gaussian weighting function, Figure 8 [Figure 8: see original paper] and Figure 9 [Figure 9: see original paper] present the vehicle average speed comparison and error distribution between Method Model 1, Method Model 2, and Speed Detector 1 for May 17, 2017, from 6:00 to 22:00. Figure 10 [Figure 10: see original paper] and Figure 11 [Figure 11: see original paper] show corresponding results for Speed Detector 2.

The figures demonstrate that Method Model 2's results exhibit reduced fluctuation and align more closely with detector measurements. The error distribution shows that Method Model 1 has 74% of relative errors within 10% and 23% within 10%-20%, while Method Model 2 achieves 84% within 10% and 16% within 10%-15%. For Detector 2, Method Model 1 shows 68% within 10% and 26% within 10%-20%, whereas Method Model 2 achieves 75% within 10% and

25% within 10%-15%. Method Model 2 eliminates the portion of errors exceeding 20% present in Method Model 1, further validating its effectiveness in parallel highway noise elimination.

Overall, Method Model 2 achieves an average absolute error of approximately 9%, representing a 2% improvement over Method Model 1 and a 10% improvement over the reference [11] method.

4 Conclusion

Utilizing mobile phone signaling data to obtain highway traffic information is crucial for ITS development. This paper described the characteristics of mobile phone signaling data and the fundamental principles of highway vehicle speed acquisition. Drawing from physical kinematics principles and addressing the uncertainty of signaling data generation and susceptibility to noise data—particularly from parallel roads—we proposed a distance-weighted vehicle speed calculation model (Method Model 1) and further developed a parallel highway interference elimination method (Method Model 2). Using MAE, RMSE, and MAPE as performance metrics, we validated our methods against the traditional approach from reference [11], selecting the Gaussian weighting function as the optimal weighting factor. The results demonstrate that both proposed models outperform traditional methods, with Method Model 2 reducing MAPE by approximately 10% compared to conventional approaches. This research holds significant practical value for advancing ITS development and can be implemented at scale using appropriate big data platforms.

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