



Research Article

Travel Time Prediction Model of Freeway Corridor Based on Real-Time Safety Reliability

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Received 15 June 2020; Revised 9 July 2020; Accepted 24 July 2020; Published 6 August 2020

Academic Editor: Kun Wang

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By considering the feature of vehicle driving on the event management unit of the freeway corridor, according to the system target, a method to divide the management unit of the road network was put forward. The relative safety braking deceleration was taken as the evaluation index of single-vehicle driving risk. The reliability graph relationship and structure-function between the management unit and subunit were analyzed. Then, dynamic safety reliability and real-time safety reliability were determined on the basis of driving risk. In addition, the queuing and dissipating characteristics of the management unit under traffic incidents were analyzed based on the wave theory. The incident duration and dissipation time were also calculated. At the same time, the travel time prediction model of the incident management unit was set up when the real-time safety reliability was taken as a road resistance function. Finally, an improved travel time prediction model established in this paper is of great significance to improve traffic safety and efficiency, and the research results will provide an important theoretical foundation in the freeway corridor route decision.

1. Introduction

1.1. Background. With the rapid development of the freeway, people need higher information service and quality, which include safety, economy, punctuality, and reliability. According to the survey, travel time reliability is one of the most important factors in the residents' travel choice. The time and location of the traffic incidents can be affirmed by the traffic administrators according to the change of the travel time, who make reasonable traffic policies; the researchers of the traffic can evaluate the level of the service according to the travel time; traffic travelers can choose the reasonable travel route according to the travel time. Although the freeway corridor network has quick access to most traffic flow, its running state is vulnerable to contradictions of supply and demand, bad weather, accidents, and so on. This leads to increased time volatility. Therefore, it is urgent to use effective methods to estimate and forecast the current freeway sections' travel time information.

1.2. Related Work. Many scholars had researched the travel time prediction models abroad from the 1990s [1–5]. However, in recent years, with the frequent occurrence of traffic congestion and incidents, the uncertainty of vehicle travel time increases [6–8]. Accurate prediction of travel time plays an important role in providing better service for high-speed service system. In order to effectively predict travel time, scholars have carried out a lot of research. Yang and Zhu [9] established a real-time travel time prediction model based on BP neural network and used the traffic data of Changchun city for real-time prediction of travel time. Chang et al. [10] proposed a travel time prediction algorithm based on data classification. In this algorithm, naive Bayes classification and multiple rules classification were used to obtain the speed range of road sections and estimate the travel time. The results show that the method based on rule classification can be applied to accurately predict travel time under different traffic flow states. Nam et al. [11] established the freeway travel time prediction model, which applies the

random queuing theory and the traffic volume on the road section and has good practicability. Son and Oh [12] studied the travel time estimation model of urban road sections. It is pointed out that traffic behavior and traffic control characteristics of signalized intersections should be paid special attention to when estimating travel time. Alexander and Nikolaos [13] predicted the travel time of urban roads. The model is based on the shock wave theory in physics. Considering the influence of traffic signal control on the arrival of vehicles at the intersection, the queuing situation of vehicles arriving at the signalized intersection is modeled in time and space. Dharia et al. [14] combined the data of detection vehicle and vehicle inspection and predicted short-term freeway travel time based on reverse neural network method. Shen and Hadi [15] used sensor data to compare and analyze the influence of different interpolation methods on road travel time estimation. Coifman et al. [16] and Hoogendoorn et al. [17] studied the travel time estimation method based on traffic flow theory. With the in-depth study of travel time, the factors to be considered and the model to be set up are more and more perfect, and applications are increasingly widespread. Research and application of domestic freeway travel time started late and there was some research on the influence of fog, rain, and other factors on freeway travel time reliability and evaluation model [18–23].

To sum up, a large number of scholars have carried out a lot of research on travel time prediction and considered the impact of weather and traffic congestion. However, there are still some deficiencies in the above research. Although Nam and Drew [11] have established a freeway travel time prediction model, the model is based on the ideal situation and does not make necessary assumptions on the actual traffic conditions. In addition, Alexander and Nikolaos [13] and Son's and Oh [12] prediction of travel time mainly focused on urban roads, without further study on freeways. At the same time, the current research on urban road travel time is more, while the research on freeway travel time prediction is less. Finally, most of the current researches on travel time prediction do not consider the impact of traffic incidents, and few scholars consider the differences brought by different regions. Because the traffic situation is more complicated and special in China, some methods of the determined travel time are a lot different among the urban road network and the overseas freeway, leading to a large deviation in the practical application.

In this paper, on the basis of the division of the freeway management unit, the travel time on the freeway is studied. Considering the influence of traffic incidents, real-time safety reliability is proposed, and two travel time prediction models under different traffic conditions are established. This improved travel time prediction model can accurately predict the travel time and lay a foundation for freeway guidance and control management.

1.3. Management Unit Division of Freeway Corridor.

Freeway access management road network consists of the main trunk road, side road, a variety of import and export, and transport hub nodes. In establishing a network security

management system, a road network bypass, emergency auxiliary routes, traffic demand control points, and other factors are anticipated. In addition, we need to divide the management unit of the freeway. Cell division's merits will not only affect the content of the real-time security management strategies but also determine whether the results of the analysis system are correct or not and its application results in a large scale. Recently, a complete systemic approach of freeway management unit division has not been formed [24, 25], because the travel time studies mainly serve the freeway route guidance and traffic management and control under disastrous conditions. Therefore, according to the system objectives we raised the management unit division method and steps as follows:

- (1) According to different road names, different levels, and different directions, we divided the network into different sections and determined the starting point and terminal point of every road.
- (2) According to different travel directions, freeway sections were divided, respectively, from the end of the freeway, interchange, entrances and exits, toll station, back to the turn lane from the end of the tunnel, and the service area which can turn around. Then, the management unit can be obtained.

2. Methodology

2.1. Real-Time Safety Reliability of Management Unit. The operating safety of the freeway network management unit is affected not only by the dynamic climate environment and traffic flow situation but also by the static factors of road facilities and monitor system. Therefore, the real-time safety of the management unit can be divided into static safety reliability and dynamic safety reliability which can be calculated by fuzzy comprehensive evaluation method and driving risk index evaluation, respectively.

2.1.1. Driving Risk Evaluation Index. There are two main risks on the freeway which are following risk and changing lane risk. According to the principle of driving dynamics, the safety braking deceleration is usually used as the vehicle risk evaluation index. When the current car takes emergency braking, it is the minimum brake deceleration which is taken by the rear vehicle to ensure the following safety after reaction time T. Under different climate conditions, the driver may have different driving risk even when the safety braking decelerations of two vehicles are complete. For example, the driving risk with the same braking deceleration is smaller in normal climatic conditions (road adhesion coefficient is larger). But in a wet or icy environment, it may lead to slip. As a result, the relative safety braking deceleration $\bar{a}(t)$ is proposed as the real-time safety index. The larger $\bar{a}(t)$ is, the smaller the driving risk is.

2.1.2. Dynamic Safety Reliability of Management Unit Based on Driving Risk. According to the above analysis, the safety reliability of a single vehicle can be defined as

$$r(t) = \begin{cases} 1, & a(t) \leq 0, \\ \bar{a}(t) = \frac{a_c(t) - a(t)}{a_c(t)}, & 0 < a(t) \leq a_c(t), \\ 0, & a_c(t) < a(t). \end{cases} \quad (1)$$

where $v(i, t, m, n)$ is the speed of management unit i at vehicle detector n of lane m ; $h(i, t, m, n)$ is space headway of management unit i at vehicle detector n of lane m ; a is emergency braking deceleration; $T(i, t)$ is the reaction time of management unit i at time t .

The real-time safety reliability of management unit i at vehicle detector n of lane m is

$$r(i, t, m, n) = \frac{\varphi(i, t) \times g - a(i, t, m, n)}{\varphi(i, t) \times g}, \quad (3)$$

where $\varphi(i, t)$ is the adhesion coefficient of management unit i at time t .

The real-time safety reliability of the management unit can only be expressed by real-time safety reliability of several vehicle detector sections. These sections can be referred to as the subunits of the management unit.

The directed graph relationship between the management unit and the subunit can be seen in Figure 1.

To solve the safety reliability of the management unit, the structure functions of the series model and parallel model are constructed as follows and are shown in Figure 2.

Series system is as follows:

$$\varphi(X_c) = \prod_{a=1}^l x_{e_a}. \quad (4)$$

Parallel system is as follows:

$$\varphi(X_b) = 1 - \prod_{a=1}^l (1 - x_{e_a}), \quad (5)$$

where X is the management unit running state matrix and x_{e_m} is the state variable of the subunit.

The management unit can be composed of the same subunit in series first and then in parallel, as shown in Figure 2. Therefore, the structure function of the management unit i is

$$\varphi(i, X) = \prod_{n=1}^{N(i)} \varphi_n(i, X_b) = \prod_{n=1}^{N(i)} \left\{ 1 - \prod_{m=1}^{M(i)} (1 - x_{e_{m,n}}) \right\}. \quad (6)$$

The real-time safety reliability of the management unit can be given by the expectation of the structure function, i.e.,

It can be seen from formula (1) that braking deceleration should be determined mainly while the safety reliability can be calculated. The required parameters can be obtained by the vehicle detectors which are laid on the freeway. If the vehicle in front keeps the same speed as the rear one at time T , the safety braking deceleration $a(i, t, m, n)$ of management unit i at vehicle detector n of lane m is

$$a(i, t, m, n) = \frac{v^2(i, t, m, n)}{2h(i, t, m, n) + v^2(i, t, m, n)/a - 2v(i, t, m, n) \times T(i, t) - 2L_{safe}}, \quad (2)$$

$$\begin{aligned} SD(i, t) &= E[\varphi(i, t, X)] = E \left[\prod_{n=1}^{N(i)} \varphi_n(i, X_b) \right] \\ &= E \left[\prod_{n=1}^{N(i)} \left\{ 1 - \prod_{m=1}^{M(i)} (1 - x_{e_{m,n}}) \right\} \right] \\ &= \prod_{n=1}^{N(i)} \left\{ 1 - \prod_{m=1}^{M(i)} \left(1 - E[x_{e_{m,n}}] \right) \right\} \\ &\therefore E[x_{e_{m,n}}] = 1 \times P(x_{e_{m,n}} = 1) + 0 \times P(x_{e_{m,n}} = 0) = r_{e_{m,n}} \\ &\therefore SD(i, t) = \prod_{n=1}^{N(i)} \left\{ 1 - \prod_{m=1}^{M(i)} (1 - r_{e_{m,n}}) \right\}. \end{aligned} \quad (7)$$

If static safety reliability is recorded as $SS[i]$, so the real-time safety reliability of management unit under nonfree flow can be expressed as

$$S[i, t] = w_s \times SS[i] + w_D \times SD[i, t], \quad (8)$$

where w_s is static safety reliability weight, w_D is dynamic safety reliability weight, and $w_s + w_D = 1$.

2.2. Wave Analysis of Queuing-Dissipating Process of Incident Unit. The freeway travel time refers to the time which a car spends passing through a section. It is an important basis for traffic management guidance strategies and decision-making. When we conduct path selection, we can design the travel time, travel distance, congestion, road quality, etc. We can also choose all the resistances or some of the combination into a generalized resistance. This road resistance function is a reaction to many factors, such as time, security, travel costs, traffic flow stability, etc. For managers and users, not only the operator safety is the basic constraints to meet, but also the travel time is the most important resistance factor. The travel time of the section is closely related to traffic flow, and we can use traffic flow function to describe it. The method of the travel time determining under different events is as follows.

Hypothesis management unit “i” represents disaster; the incident management unit travel time, including vehicle travel time spent at upstream sections $t_{i1,1}$ and congestion queuing time spent at queuing length $t_{i1,2}$, is marked as t_{i1} . The travel time spent downstream of the incident point is t_{i2} .

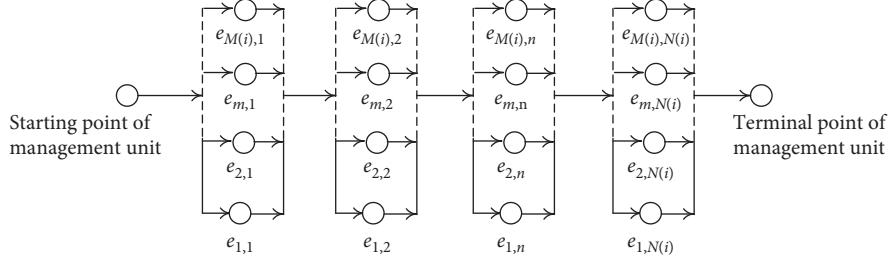


FIGURE 1: Directed graph relationship of subunit and management unit.

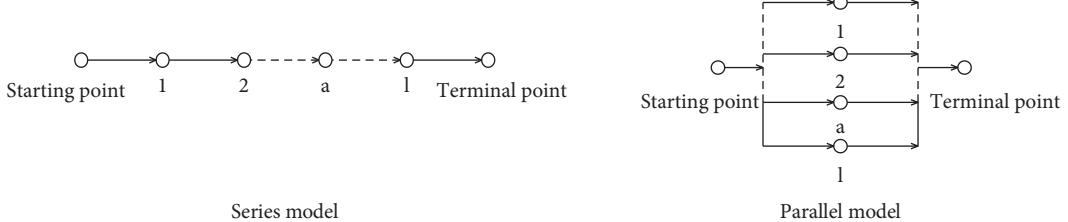


FIGURE 2: Series and parallel model.

According to the traffic flow theory, the capacity of the incident point is lower when the disaster occurs. If it does not meet the upstream sections traffic need, then it will form a traffic queue $y(t)$ and backward “return wave” will appear as shown in Figure 3. When the disastrous event is excluded, there will be “start wave.” At the same time, there are vehicles arriving at wave tail, so two phenomena of “return wave” and “start wave” coexist, both moving backward. The meaning of $t_{i1,1}$ is vehicle traveling time from the upstream node to the tail of the queue, while $t_{i1,2}$ is the time spent in queue $y(t)$ congestion.

After a disastrous event occurs, the hypothesis of the upstream traffic density in this lane is k_r , and the traffic flow needs are q_r . According to the disastrous event hierarchy attribute $LD_{11}(t) = n$, bottleneck point capacity dropped is C_n . Traffic flow density promoted k_2 correspondingly. Disastrous events duration is t_a ; it is the time from disastrous events happening to the traffic flow state recovery normally. This stage includes the time from disastrous events happening to the AID system detecting and confirming the event. Response phase of the event confirms rescue vehicles arriving at incident point; cleanup phase means rescue vehicles that arrived at the incident point leave the scene; traffic flow recovery phase of the incident event means the queues have been completely dissipated. We mark the time from detecting stage to clear stage as t_e , we can see t_e is closely related to the upstream vehicle queue traveling time and waiting time t_{i1} .

2.2.1. Incident Dissipation Process. The time t_e is the time between the incident event detection and clearing. When $q_r \leq C_n$ and $k_1 = k_2 = k_4$, sections usually do not generate traffic congestion as shown in Figure 3(b). But when $q_r > C_n$ and capacity cannot meet with the traffic needs, then the traffic congestion will appear as shown in Figure 3(c).

Figure 4 is the wave distance scheme of traffic jam dissipation process; y and t represent distance and time, y -axis points to the upstream direction of the incident point, and point O corresponds to the incident point. We mark the incident time $t_0 = 0$, and the curve OBCD corresponds to queue length at the incident time.

It means the incident event has been cleared when $t = t_e$. Traffic congestion occurs in FA section. We remember the congestion density is k_i and the low rate is q_i . If the upstream vehicle of point A arrived at an average flow rate q_r , traffic density is maintained at k_r . When a disastrous event occurs, road vehicle traveled at q_s , k_s , and we think the traffic flow gradually reaches the maximum capacity in the incident point; the traffic flow $q_s = C_n$ at that time. After a period of time, the sections of the incident event will completely block, just as Figure 2 describes. Slash of the coordinate plane yet represents the traffic flow characteristic curve. For example, throughout the OAF segment, the characteristic curve is negative, its tangent curve is consistent with flow density at point 2(q_i, k_i), and point 3 belonging to the curve is the flow-density curve of the incident section. When $t = t_e$, density of point F then from k_i becomes the maximum capacity corresponding to traffic density k_m in a short time. Characteristic curve fanned out at point B (i.e., the slope of all possible values from $(dq/dk)_{k_2}$ to 0), in accordance with this approach, drawing the rest of the characteristic curve as shown in Figure 3.

It can be seen from Figure 4 that the coordinate plane was divided into three different areas in flow density along the border by the characteristic curve. The characteristic curve of intersecting lines is the traffic wave curve (OABCD), that is, the track of the congestion team; in this time, the distance between the nodes A, B, C, and D and the t axis means the length of the vehicle queue; use $y(t)$ instead.

The traffic wave produced in section OF spread back relative to the accident point and ended at point B; point B

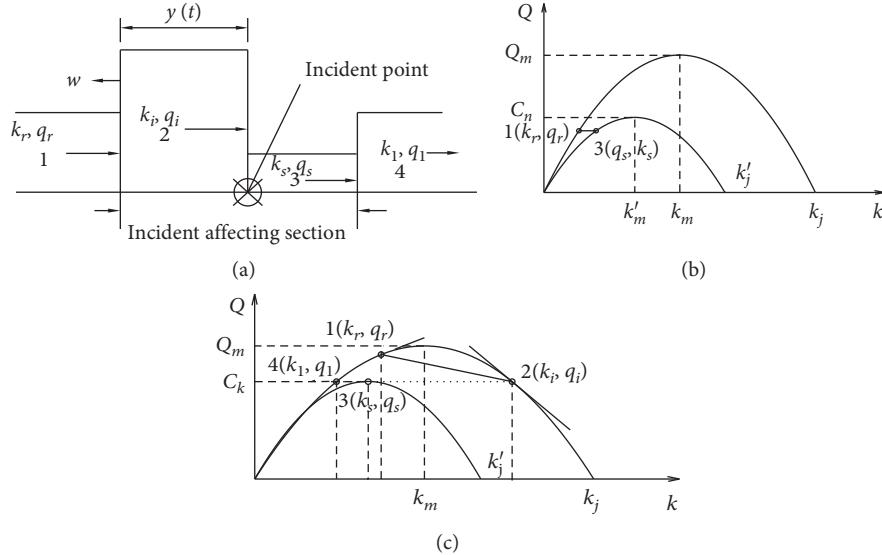


FIGURE 3: Incident point traffic wave spread and flow-density signal. (a) Traffic wave spread signal. (b) $q \leq C_n$. (c) $q > C_n$.

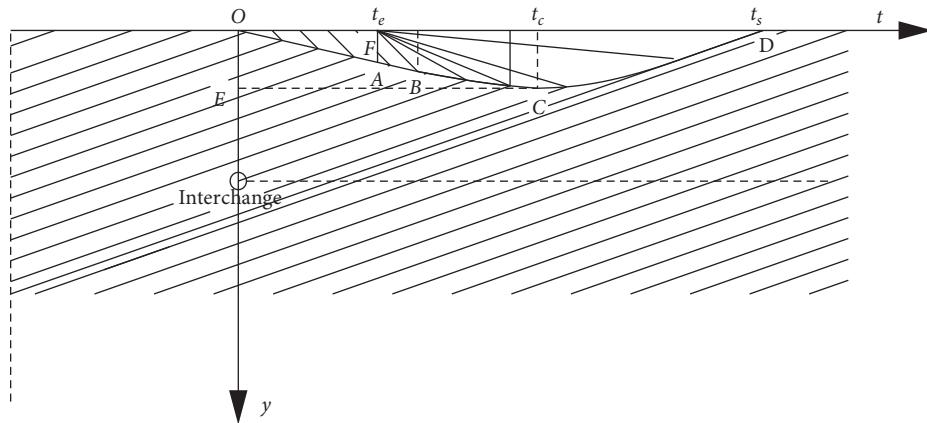


FIGURE 4: Traffic jam dissipation process of waveform headway figure.

represents the last issue by the incident point which has a density k_i of characteristic curve. After point B, because the fan-shaped radiation characteristics curve has different densities in the regions FBD and the traffic wave propagation downstream has changing densities, the traffic wave density constant is k_r from the interchange to the incident point, so BCD shows nonlinear change and spreads at varying speeds.

When the vehicles enter the upstream interchange and gradually travel near the incident point, if the congestion is not over yet, its departure of the incident point time is $t_{i1} = t_s$. If the congestion has ended, the vehicles will not be affected by the congestion, and travel time can be expressed by the function of the upstream flow.

2.2.2. Analytical Calculation of Incident Dissipation Time. In order to obtain the analytical results of OABCD curve segments and BCD coordinates, we assumed the Green-shields flow-density model is as Figure 3 shows.

OB is the track of return wave after the incident event happens, so the wave velocity is

$$w_{OB} = \frac{q_i - q_r}{k_i - k_r} = v_f \left(1 - \frac{k_r + k_i}{k_j} \right). \quad (9)$$

By solving the triangular relationship we can get t_B and make $h(k) = (dq/dk)$, so

$$t_B = \frac{(k_j - 2k_i)t_e}{k_r - k_i}. \quad (10)$$

Hypothesis k_R represents the traffic density at any point on the BCD curve segment; the wave velocity of this point is

$$\frac{dy}{dt} = \frac{q_R - q_r}{k_R - k_r} = \frac{v_f}{k_j} (k_j - k_r - k_R),$$

$$y_R = -h(k_R) \times (t - t_e) = -v_f \left(1 - \frac{2k_R}{k_j} \right) \times (t - t_e), \quad (11)$$

$$\frac{dy}{dt} = -\frac{v_f}{2} + \frac{y}{2(t - t_e)} + \frac{v_f k_r}{k_j}.$$

Solving differential equations can be obtained as

$$y_{BCD}(t) = (-h(k_i) + h(k_r)) [(t - t_e)(t_B - t_e)]^{1/2} - h(k_r)(t - t_e). \quad (12)$$

Making $y_{BCD}(t) = 0$, disastrous event dissipation moment t_s is

$$t_s = \left[1 - \frac{h(k_i)}{h(k_r)} \right]^2 (t_B - t_e) + t_e$$

$$= \frac{4(k_r - k_i)(k_j - k_r - k_i)}{(k_j - 2k_r)^2} t_e + t_e. \quad (13)$$

In this function, k_i is the traffic density near the incident event; it can be detected by the detector. When $q_r > C_n$, the calculation function is as follows:

$$k_i = \frac{1}{2} k_j \left(1 + \sqrt{1 - \frac{C_n}{C}} \right). \quad (14)$$

The event duration time is

$$t_a = t_s = t_e \times \left[\frac{4(k_r - k_i)(k_j - k_r - k_i)}{(k_j - 2k_r)^2} + 1 \right]. \quad (15)$$

3. Results and Discussion

3.1. Travel Time Prediction Model Based on Real-Time Safety Reliability. It is assumed that the moment is $t = t_0$, the incident event occurs at a distance L_{i1} from the start of the road management unit i , the dissipation time is t_{i1} , so the dissipation moment is $(t_0 + t_{i1})$. With the event handling and dissipation, because the vehicles enter the management unit at different times, it takes different travel time at the incident event road section. When the vehicles reach the management unit i vicinity of the incident point at t moment, if the event is completely dissipated, the traffic flow returns to normal and the vehicles are not affected by the disastrous event. If the disastrous event is not completely dissipated, the vehicles will experience some dissipation time. The model of management unit i travel time calculation is

$$T(i, t) = \max \left\{ \frac{L_i \times k_j}{v_f(k_j - k_i)}, t_e \times \left[\frac{4(k_r - k_i)(k_j - k_r - k_i)}{(k_j - 2k_r)^2} + 1 \right] + \frac{L_{i2} \times k_j}{v_f(k_j - k_i)} - (t - t_0) \right\}. \quad (16)$$

In this function, L_i is the length of management unit i , k_m ; k_i is the traffic density of management unit i , pcu/km; k_j is the jam density, pcu/km; t_e is the event clear time, min; v_f is the freedom velocity, km/h; k_r is the upstream traffic density of management unit i , pcu/km; L_{i2} is the distance between the incident point and management unit i , km; t_0 is the incident happening time, min; t is the time when the vehicle enters the management unit i , min.

Using management unit-attribute expressed in function (16), k_r , k_i , and k_l , respectively, refer to the traffic density upstream, at incident section of, and downstream the management unit. When the n th vehicle detector belonging to the management unit i detects disastrous event, the travel time can be expressed under this condition as follows:

$$T(i, t) = \max \left\{ \left[\frac{4(LD_1(i-1, t) - LD_1(i, t))(LS_{35}(i) - LD_1(i-1, t) - LD_1(i, t))}{(LS_{35}(i) - 2LD_1(i-1, t))^2} + 1 \right] t_e \right. \\ \left. \cdot \frac{L_{i2} \times LS_{35}(i)}{LD_5(i, t)(LS_{35}(i) - LD_1(i+1, t))} - (t - t_0), \frac{LS_{31}(i) \times LS_{35}(i)}{LD_5(i, t)(LS_{35}(i) - LD_1(i, t))} \right\}. \quad (17)$$

In this function, t_e means the three stages' total time of disastrous events detection, response, and cleanup, in which event type, event severity, the level of joint management, and other freeway management center will affect the event

clearance time. Currently, the event clearing time statistical methods are mainly linear regression, analysis of variance, decision tree method, nonparametric regression, hazard duration method, fuzzy logic method, etc.

3.2. Model Modification. When the mainline freeway management unit disastrous event occurs, traffic managers can provide two pieces of traffic guidance recommended strategy. Firstly, choose to wait or slow through the incident unit on the freeway. Secondly, choose a feasible path that bypasses the incident unit in front of the incident point and return back a node after the incident point. For all the start and endpoint of induction programs, in order to meet the real-time, security, and reliability needs of the management unit, we can make the following amendment to the road barrier function:

$$T_{(i-k)to_i, t} = \max \left\{ \sum_{m=i-k}^i \frac{L_m \times k_j}{v_f(k_j - k_m)}, t_e \left[\frac{4(k_1 - k_2)(k_j - k_1 - k_2)}{(k_j - 2k_1)^2} + 1 \right] + \frac{L_2 \times k_j}{v_f(k_j - k_4)} - (t - t_0) \right\}. \quad (19)$$

The parameter meaning is the same as the former.

4. Conclusion

Travel time of the freeway network is the most important, widespread concern, which best reflects the operational status of the traffic information. Get real-time estimates of travel time and accurately predict the future travel time of the road section. It has great practical significance for improving the effectiveness of traffic management and travel decision.

Considering the characteristic of a vehicle traveling on the road network, in accordance with the road name, road grades, driving directions, and the position of road network node and other factors, the method of management unit division has been put forward. Then, real-time safety reliability of the freeway network was divided into static safety reliability and dynamic safety reliability. Method of reliability graph analysis is applied to determine dynamic safety reliability on the basis of single-vehicle driving risk. Then by analyzing the queuing and dissipating process of the incident events, an analytical solution to event dissipation and the calculation method of the event duration time were obtained. Taking real-time safety reliability into consideration, the travel time prediction model was established and modified. The research provides a good theoretical basis and reasonable solution to travel time prediction engineering of the freeway. At the same time, it increases the safety level and comfort of road users as well as traffic operation efficiency.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

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

$$c(i, t) = \begin{cases} \frac{L_i * k_j}{v_f(k_j - k(i, t))}, & S[i, t] \geq SC, \\ +\infty, & S[i, t] < SC. \end{cases} \quad (18)$$

If a disastrous event occurs in the management unit i , the calculation function of the travel time from upstream management unit $(i-k)$ to the end of the management unit i can be expressed as

Acknowledgments

This research was funded by the National Natural Science Foundation of China (nos. 51978069 and 71673201).

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