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Vehicle Routing for Dynamic Road Network Based on Travel Time Reliability

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ABSTRACT Vehicle path selection follows the shortest path principle, while taking the shortest travel time as the optimization goal. In the real road network, affected by signal control, the travel time of the vehicle path has significant uncertainty. The shortest path algorithm with static road indicators as the weights has obvious defects in path selection. In order to solve this problem, according to the theory of distributed wave, the operating state of the vehicle under the influence of the downstream signal control is classified. The travel time of the vehicle on the road segment is classified and predicted, and the travel time prediction value set is further transformed into the travel time reliability. For the vehicle route selection of a dynamic road network, the path travel time reliability determined by the product of the road segment travel time reliability is logarithmically converted, and the Dijkstra algorithm is used to find the most reliable path as the target solution. Then, a simulation model is constructed to verify the validity of the algorithm. The experimental results prove that using the reliability of travel time as the weight of path selection and solving by Dijkstra algorithm can reflect the actual vehicle path selection more accurately. This method is a beneficial improvement to the problem of static path selection.

INDEX TERMS Dynamic road network, path selection, signal control, traffic engineering, travel time reliability.

I. INTRODUCTION

In the increasingly congested urban roads, the travel time of vehicles is becoming more and more uncontrollable. Drivers and passengers have paid great attention to the problem of optimal path selection.

We attributed the solution of vehicle routing problem to the acquisition of the shortest path of travel distance. However, the shortest path selection in the dynamic road network [1] can't meet the requirements of drivers and passengers because of the great fluctuation of vehicle travel time caused by signal control.

For the problem of vehicle routing in a dynamic road network, related studies have analyzed the difference between the dynamic road network and the static road network, and established a variety of dynamic road network vehicle routing methods for specific situations. Psaraftis [2] compared the fundamental differences between the static and dynamic models of the vehicle routing problem; Orda and Rom [3] studied the dynamic routing problem in complete state and compared the travel time of the vehicle on the road section and the time at the intersection. The waiting time is all taken into consideration, and the concepts of dynamic edge weights and dynamic node weights are established, respectively. Michael *et al.* [4] proposed a queuing theory model for solving traffic congestion based on route selection. Michael *et al.* [5] studied and analyzed the model of a single vehicle dynamic routing problem, and regarded the arrival time of the task as subject to a Poisson distribution, and the aim function was to minimize the total time of customer service. Chabini and Lan [6] found that when the driving behavior of the vehicle on the route meets the first in first out criterion (FIFO), the Dijkstra algorithm can solve the dynamic path planning problem without increasing the complexity of problem solving. Ma *et al.* [7] developed a tabu search heuristic algorithm for vehicle routing problems with time window requirements and capacity restrictions caused by the weight of dangerous goods. Bulhões *et al.* [8] proposed a branch price algorithm and hybrid genetic algorithm for the vehicle routing problem with service level restrictions, and established an adaptive balance penalty mechanism between service level and cost. Yanqiu *et al.* [9] established an integer

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linear programming model with the objective of minimizing the sum of vehicle call cost, vehicle transportation cost and third-party logistics transportation cost, constructed a new variable dimension matrix coding structure, and proposed a new intelligent optimization algorithm. Liucheng *et al.* [10] established a mixed integer-programming model with the optimization goal of maximizing the economic benefits of the enterprise, and proposed an accurate segmentation algorithm for chromosome coding of the vehicle routing problem with order selection to get a workable solution structure.

However, in the above research, the travel time prediction of key variable of the dynamic shortest path's study mostly solidifies the delay in the intersection. The predicted travel time is a fixed value and lacks response to the dynamic road network conditions, so that the volatility of travel time dynamics is not considered enough in route selection. Dynamic travel time has uncertainty, so it is not suitable to be directly used in route selection. This paper plans to use travel time reliability as a key variable for path selection, which can reflect the dynamic changes of travel time and extract a relatively fixed value for path selection.

The travel time reliability is studied based on the equilibrium model. If there is no difference in the behavior of travelers in the equilibrium model, a homogenous model is established [11], and if the behavior of travelers is different, a heterogeneous model is established [12]. This kind of research is based on LOGIT or Probit proposed. Bell *et al.* [13] analyzed the problem of path flow estimation for stochastic user equilibrium with and without delay. Herman and Prigogine [14] used fluid models to analyze the characteristics of two types of traffic flow in the city: vehicles in motion and vehicles stopped due to traffic conditions. Inouye [15] proposed a model to estimate travel time reliability assuming a stochastic user equilibrium. Clark and Walting [16] proposed a method to estimate the probability distribution of the total travel time of the road network according to the daily change rate of the travel demand matrix in the road traffic network. Iida [17] outlined the basic concepts, remaining problems and future directions of road network reliability analysis and gave a method for estimating the reliability of links within road networks. Sheffi [18] described the equilibrium analysis methods with mathematical program in urban transportation networks. Li *et al.* [19] set a reliability evaluation method for stochastic networks with multiple parking facilities. Taylor [20] used Fosgerau's valuation method to calculate travel time reliability in cost-benefit analysis. Zhao *et al.* [21] used optimal control theory to optimize intersection travel time. Reliability estimation model of travel time based on stochastic user equilibrium allocation model. The common idea of this model is to assume that the travel time of road sections and paths conform to a logical distribution or a normal distribution, and the traffic state between road sections is irrelevant. Using Monte Carlo simulation method, the random user optimal traffic allocation is repeatedly performed to get the mean and variance of travel time of all paths on the road network, and then calculate the reliability of the road network.

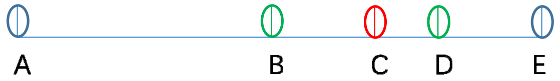


FIGURE 1. Diagram of the relative position of key points on the road section.

This paper aims to get a convenient and effective travel time reliability algorithm for dynamic road network vehicle routing. This research proposes to classify the states of the relative position relationship between the vehicle position and the end of the queue at the time of signal conversion under the influence of the downstream intersection signal control based on the principle of distributed wave. The complex changes between the vehicle delay caused by the signal control, the dissipating speed of the traffic flow and the length of the signal period are deeply studied. We get a set of travel time prediction values. This paper introduced the reliability of travel time as the characteristic variable of vehicle path selection. By thus, we convert the shortest path problem into the most reliable path problem. Then, for the path selection problem under the dynamic road network, a new alienation weight Dijkstra algorithm is proposed to solve it, and a real road network simulation model is constructed to verify the effectiveness of the algorithm.

It organize the rest of this paper as follows. The second chapter proposes a new dynamic travel time prediction method. The third chapter proposes the corresponding travel time reliability algorithm. Chapter 4 presents the path selection algorithm of dynamic complex road network. Chapter 5 uses the simulation model for algorithm verification and analysis. Chapter 6 is the conclusion of the full text.

II. DYNAMIC TRAVEL TIME PREDICTION

According to the theory of collecting and dispersing waves [22], as shown in Figure 1, section AE represents the intersection of road section a and downstream signals, and the driving state of the vehicle on it is based on the interface C of the assembled wave as the key point, and divide the travel time $T_a(t)$ of the vehicle at time t into two segments [23], [24]. The AC segment vehicle runs at a certain stable speed as a non-congested segment, and the travel time is $r_a(t)$. The CE segment vehicle decelerates to a standstill and waits for a period before accelerating and leaving as the queuing section. The travel time is $d_a(t)$.

$$T_a(t) = r_a(t) + d_a(t) \tag{1}$$

Overall:

$$r_a(t) = \frac{2L - v_a^f k_a^j r}{2v_a(t)} \left[1 \pm \sqrt{1 - \frac{4x_a^{up}(t)}{v_a^f k_a^j}} \right] s_a \tag{2}$$

$$d_a(t) = \frac{v_a^f k_a^j r}{2Q_a(t)} \left[1 \pm \sqrt{1 - \frac{4x_a^{up}(t)}{v_a^f k_a^j}} \right] \tag{3}$$

where: L is the length of the road section, in km; v_a^f is the free flow speed, in km/h; k_a^j is the congestion density, in veh/km/lane; $v_a(t)$ is the road section driving in an uncongested state speed, in km/h; r is the duration of the red light, in s; $x_a^{up}(t)$ is the upstream flow in veh/h; s_a is the intersection influence coefficient; $Q_a(t)$ is the traffic capacity of the intersection, in veh/h.

To clarify the influence of signal control on vehicle travel time, this study assumes that the vehicle enters the road section when the downstream red light signal is on. If the vehicle will catch up with the downstream queuing traffic during the nth green light signal period, the travel time classification analysis is performed based on the relative position of the vehicle and the tail of the downstream queuing line at the end of the nth red light signal period.

A. THE VEHICLE DID NOT REACH THE END OF THE QUEUE

At this moment, the vehicle is at point B. After n red light r, a queue is generated. The length of the queue is CE segment. The vehicle travels from A to B without reaching the end of the queue C. In the next green light period, the car may face four situations:

All queued traffic has disappeared

(1) The vehicle passes directly through the intersection and passes through the entire journey at speed $v_a(t)$. Now:

$$T_a(t) = \frac{L}{v_a(t)} \tag{4}$$

(2) The vehicle did not pass through the intersection and only stopped at the parking line at the last moment, waiting for a red light to pass. Now:

$$T_a(t) = \frac{L}{v_a(t)} + r \tag{5}$$

Queuing traffic is partially dissipated

When the car arrived at the end of the queue, it experienced n red lights and n green lights.

(3) Pass the intersection at the n+1th green light. Now:

$$T_a(t) = n(r+g) + \frac{L - r_a(t) \cdot v_a(t)}{S_a \cdot Q_a(t)} \tag{6}$$

where: g is the duration of the green light, in s.

(4) Pass the intersection at the n+mth green light. Now:

$$T_a(t) = n(r+g) + \frac{L - r_a(t) \cdot v_a(t)}{S_a \cdot Q_a(t)} + mr \tag{7}$$

B. THE VEHICLE ARRIVED AT THE END OF THE QUEUE

The vehicle is at point C. After n red lights r, a queue is generated. The length of the queue is CE segment, and the vehicle travels from A to C at the end of the queue. In the next green light period, the car may face 4 situations:

All queued traffic has disappeared

(1) At the end of the green light, the vehicle just passed the intersection. Now:

$$T_a(t) = nr + (n-1)g + g = n(r+g) \tag{8}$$

(2) Before the end of the green light, the vehicle will pass the intersection ahead of time. Now:

$$T_a(t) = nr + (n-1)g + \frac{v_a^f k_a^j r}{2Q_a(t)} \left[1 \pm \sqrt{1 - \frac{4x_a^{up}(t)}{v_a^f k_a^j}}\right] \tag{9}$$

Queuing traffic is partially dissipated

When the car arrived at the end of the queue, it experienced n red lights and n-1 green lights.

(3) Passing the intersection at the n+1th green light, if n>1, partial dissipated means that the queue formed during a red light cannot dissipate completely during a green light, then the position of the end of the queue after n cycles Reaching point C, it cannot dissipate within a green light time, so n is only 1. Now:

$$T_a(t) = r + \frac{v_a^f k_a^j r}{2Q_a(t)} \left[1 \pm \sqrt{1 - \frac{4x_a^{up}(t)}{v_a^f k_a^j}}\right] + mr \tag{10}$$

(4) Pass the intersection at the n+mth green light. Now:

$$\begin{aligned} T_a(t) = nr + (n-1)g + \frac{v_a^f k_a^j r}{2Q_a(t)} \\ \times \left[1 \pm \sqrt{1 - \frac{4x_a^{up}(t)}{v_a^f k_a^j}}\right] + (m-1)r \end{aligned} \tag{11}$$

C. THE VEHICLE PASSED THE END OF THE QUEUE

The vehicle is at point D. After n red light time r, a queue is generated. The length of the queue is CE segment. The vehicle passes from A to D at the end of the queue C. Next; the vehicle stops at position D and waits until the red light period r ends and the waiting time is $r - r_a(t)$. In the next green light period, the car may face four situations:

All queued traffic has disappeared

(1) n=1, the vehicle passes directly through the intersection. Now:

$$T_a(t) = r + \frac{v_a^f k_a^j r}{2Q_a(t)} \left[1 \pm \sqrt{1 - \frac{4x_a^{up}(t)}{v_a^f k_a^j}}\right] \tag{12}$$

(2) n>1, the vehicle passes directly through the intersection. Now:

$$\begin{aligned} T_a(t) &= nr + (n-1)g \\ &\quad + \frac{L - [nr + (n-1)g] \cdot v_a^f \Big/ \left[1 + J(\frac{\alpha}{1-\alpha})\right]}{S_a \cdot Q_a(t)} \end{aligned} \tag{13}$$

where: J is the service level parameter, it is related to road type, road width and traffic signal timing.

Queuing traffic is partially dissipated

(3) n=1, pass the intersection at the n+mth green light. Now:

$$T_a(t) = mr + \frac{v_a^f k_a^j r}{2Q_a(t)} \left[1 \pm \sqrt{1 - \frac{4x_a^{up}(t)}{v_a^f k_a^j}}\right] \tag{14}$$

(4) n>1, pass the intersection at the n+mth green light. Now:

$$T_a(t) = nr + (n-1)g + \frac{L - [nr + (n-1)g] \cdot v_a^f \Big/ \left[1 + J(\frac{\alpha}{1-\alpha})\right]}{S_a \cdot Q_a(t)} + mr \tag{15}$$

III. DYNAMIC TRAVEL TIME RELIABILITY

A. DYNAMIC LINK TRAVEL TIME RELIABILITY

The predicted value of dynamic travel time is the travel time related to time t considering the actual situation of road network and the randomness of traffic flow. We set a new definition: the probability that the ratio of the predicted travel time to the expected travel time within the acceptable road segment service level is called dynamic link travel time reliability.

$$\begin{aligned} R_a(t) &= P\left\{T_{ai}(t) \big/ T_{\varphi a} \le \gamma, \gamma \ge 1\right\} \\ &= \sum_{i=1}^{n} \left(N = 1 | T_{ai}(t) \big/ T_{\varphi a} \le \gamma, \gamma \ge 1\right) \Big/ n \end{aligned} \tag{16}$$

where: $R_a(t)$ is the reliability of the dynamic travel time of section a, γ is the acceptable service level of section, $T_{ai}(t)$ is the i-th predicted travel time of section a; $T_{\varphi a}$ is the expected travel time of section a, and N is the counting number, n is the number of travel time forecast points.

B. DYNAMIC PATH TRAVEL TIME RELIABILITY

A single path is a series system, and the product of the dynamic travel time reliability of all sections in the path is taken as the path dynamic travel time reliability.

$$R_{\mathrm{L}}(t) = \prod_{j=1}^{m} \tag{17}$$

where: $R_L(t)$ is the reliability of the dynamic travel time of the path L, and $R_j(t)$ is the reliability of the dynamic travel time of the j-th section of the m sections of the path L.

IV. VEHICLE ROUTING ALGORITHM FOR DYNAMIC COMPLEX ROAD NETWORK

A general travel planning problem with multiple destinations in road network can be regarded as a vehicle routing problem on a dynamic complex network. For dynamic road network vehicle routing problem, its typical application is the routing problem from warehouse to each service point. According to the characteristics of the dynamic complex network, the vehicle is set to meet the FIFO operation rules in the road network, and the single path does not contain loops.

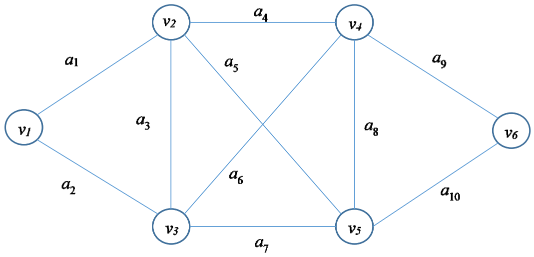


FIGURE 2. **Basic model of complex road network. Note that: 1 Each node represents an intersection in the road network; 2 The connection between each node represents a road section, and all road sections drive in both directions and have the same cross section; 3 Each side weight is the dynamic travel time of the road section (including downstream intersections) reliability.**

For this kind of problem, Figure 2 shows the basic model of the problem, finding the optimal path from the starting point v_1 to each destination point v_j (j=2,3,$\cdots$,p). Considering the influence of intersection signal control, the shortest path algorithm cannot accurately get the optimal path. Use the travel time reliability index proposed in this research to transform the optimal path into the most reliable path.

In this research, the Dijkstra algorithm in the traditional path optimization algorithm is adaptively optimized (alienation weight) to calculate the most reliable path.

According to the logarithmic function operation rule: the logarithm of the product of positive numbers is equal to the sum of the positive logarithms of the same base. Since the path reliability will be equal to the product of the reliability of each component road section in this study, the problem can be transformed into: Finding the logarithm of the path reliability is equal to finding the sum of the logarithm of the reliability of each section. According to the logarithm monotonicity principle, finding the maximum value of the reliability of each path is equivalent to finding the minimum value of the path reliability logarithm based on a positive number less than 1. According to the principle of Dijkstra algorithm, the minimum value can be solved directly by using Dijkstra algorithm to find the shortest path.

The calculation steps of Dijkstra algorithm to find the shortest path are:

Step 1: Start point v_1 as fixed label $v_1^* = 0$ and other points v_j as temporary labels $t_j = \infty$, $V_t = \left\{v_2, v_3, \cdots, v_p\right\}$.

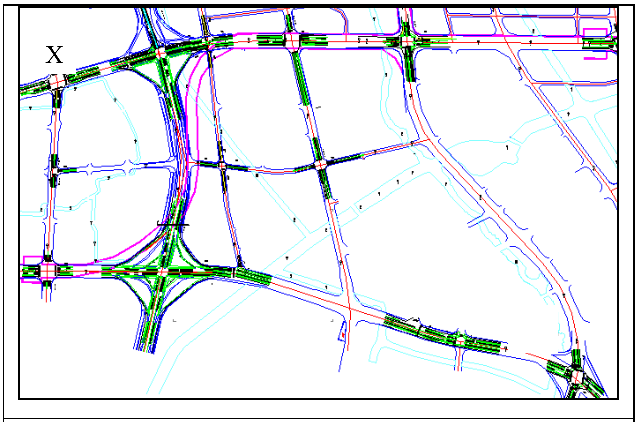
Step 2: Assuming that one or more fixed labels of v_i have been obtained, v_i^*, for $v_j \in N(v_i) \cap V_t$, change the temporary labels of v_j to $t_j = \min\limits_i \left\{t_j, r_i^* + w_{ij}\right\}$, among them, t_j on the right is the original value, t_j on the left is the changed value; w_{ij} is the distance from i to j.

Step 3: For $v_j \in V_t$, set $\min\limits_i t_j = t_i^*$, which is the fixed label of the corresponding point v_j^*, $V_t = V_t - \left\{v_j^*\right\}$.

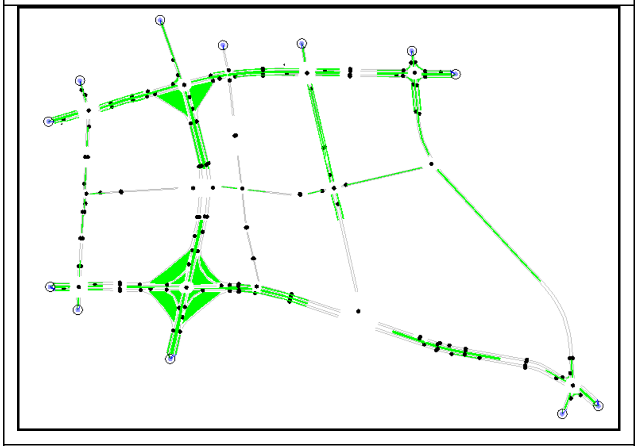
Step 4: When $V_t = \emptyset$, get v_p^*, then start from v_p, trace backward, and determine the shortest path R_p^*. If v_j in R_p^* has been determined, set $r_j^* - w_{ij} = r_i^*$ to determine the previous point v_i; otherwise, go back to Step 2.

After the iteration is finished, according to the final labeling result of each node, the logarithm of the most reliable path from the starting point to all other nodes can be obtained, and the most reliable path can be deduced inversely according to the labeling process.

The validity of the algorithm would be verified by investigation method and enumeration method.



Regional road network



Simulation model

FIGURE 3. Study area road network and simulation model.

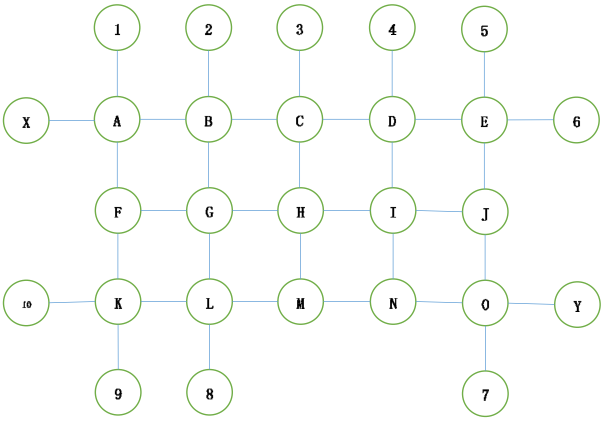


FIGURE 4. Road network abstract coding diagram. Note that: Numbers 1-9 and X and Y represent traffic communities, and letters A-O represent intersections.

V. CASE STUDY

Establish simulation models for actual cases. Calculate the proportion of each path selected through investigation. The path with the highest proportion is used as an alternative to the most reliable path. Extract the travel time of the simulated vehicle on each path and each road segment, and use the alienation weight Dijkstra algorithm and enumeration method proposed in this research to find the theoretical most reliable path. The validity of the algorithm results is verified by comparison of the three. It is assumed that all vehicles running in the road network meet the FIFO operating rules, and there is no loop on the vehicle driving path.

A. CASE PROTOTYPE ANALYSIS AND SIMULATION MODEL CONSTRUCTION

The simulation case takes part of the road network in Ningbo High-tech Zone, Zhejiang Province, as the object to build a simulation model. The road network in this area is shown in Figure 3. The case prototype is abstracted and coded, as shown in Figure 4.

In the complex road network model shown in Figure 4, all vehicles have to reach the other points from point X, and find the path with the most reliable travel time among all paths from point X to each point.

The condition of the car travel path from point X to point Y was investigated, and it was found that there were 15 intersections and 24 road sections between this OD pair, and there were over 30 optional paths. The survey selected the morning peak hours on working days, and there were no emergencies. In the path selection, some representatives of the detour paths are selected, and the paths with too long detour distances are ignored, and 19 paths are finally selected as the research object.

According to the code map, 19 typical paths from point X to point Y are represented by codes, and a one-month survey of regional traffic vehicles is carried out. Among them, there are 96 commuter vehicles (the surveyed vehicles travel frequently in the target area, and their travel route selection relying on the accumulation of experience, choose the path with the highest reliability, rather than the shortest path or the simplest path) and 204 random vehicles (the vehicle under investigation travels less frequently in the target area, and the choice of travel path depends on intuitive feeling or navigation, No experience), as shown in Table 1.

The traffic conditions in this area were recorded and found that the congestion of the KO, AE, and FJ sections of the east-west road gradually increased; the BL section of the north-south road was the most congested, and the CM section had the least traffic pressure. Among the nodes, intersection G, intersection K, and intersection L are prone to congestion.

In each path from X to Y:

1. Route 11: X-A-B-G-H-M-N-O-Y is the shortest distance route, but because of the need to pass intersection G, the proportion of commuter vehicles between the target ODs choosing this route is not high, accounting for only 14% of the commuter vehicles. The total number of vehicles traveling along route 11 accounted for 9.7% of the surveyed vehicles.

TABLE 1. The route classification table of the surveyed vehicles.

Path	Random vehicles	Commuter vehicles	Path	Random vehicles	Commuter vehicles
1:X-A-B-C-D-E-J-O-Y	24	8	11: X-A-B-G-H-M-N-O-Y	16	13
2: X-A-B-C-D-I-J-O-Y	11		12: X-A-B-G-L-M-N-O-Y	17	
3: X-A-B-C-D-I-N-O-Y	10		13: X-A-B-G-L-M-H-I-J-O-Y	1	
4: X-A-B-C-H-I-J-O-Y	13		14: X-A-B-G-L-M-H-I-N-O-Y	1	
5: X-A-B-C-H-I-N-O-Y	9		15: X-A-F-G-H-I-J-O-Y	7	
6: X-A-B-C-H-M-N-O-Y	21	66	16: X-A-F-G-H-I-N-O-Y	10	
7: X-A-B-C-H-M-N-I-J-O-Y	2		17: X-A-F-G-H-M-N-O-Y	13	
8: X-A-B-C-H-M-N-I-D-E-J-O-Y	0		18: X-A-F-G-L-M-N-O-Y	12	
9: X-A-B-G-H-I-J-O-Y	8		19: X-A-F-K-L-M-N-O-Y	20	9
10: X-A-B-G-H-I-N-O-Y	9		Total	204	96

TABLE 2. Critical path length and expected travel schedule (free flow state).

Path	Length（m）	Expected travel time（s）	Path	Length（m）	Expected travel time（s）
1	4249.94	309.31	11（Shortest path）	4003.34	292.96
2	4333.13	313.21	12	4217.50	306.52
3	4284.18	308.78	13	5505.99	400.63
4	4405.94	320.45	14	5407.67	393.99
5	4307.62	313.81	15	4277.88	312.71
6（Most reliable path）	4434.06	310.42	16	4179.56	306.07
7	5642.14	417.68	17	4101.64	303.26
8	6924.78	505.71	18	4250.48	312.04
9	4179.57	302.41	19	4177.20	303.50
10	4081.26	295.77	/	/	/

TABLE 3. Road segment travel time reliability under different acceptable service levels (Dijkstra algorithm).

Road section	XA	AB	BC	CD	DE	EJ	JO	OY	DI	IJ	IN	NO
γ=1.2	0.55	0.3	0.7	0.5	0.7	0.65	0.2	0.95	0.75	1	0.25	0.85
γ=1.4	0.55	0.35	0.9	0.6	0.85	0.85	0.35	1	0.8	1	0.25	1
γ=1.6	0.55	0.4	0.95	0.6	0.85	1	0.45	1	0.95	1	0.4	1
γ=1.8	0.6	0.45	0.95	0.65	0.85	1	0.5	1	1	1	0.45	1
γ=2	0.6	0.55	0.95	0.65	0.9	1	0.55	1	1	1	0.8	1
Road section	CH	HI	HM	MN	BG	GH	GL	LM	AF	FG	FK	KL
γ=1.2	0.29	0.6	0.35	0.65	0.2	0.35	0.2	0.7	0.65	0	0	0.35
γ=1.4	0.47	0.8	0.45	0.8	0.2	0.4	0.2	1	0.75	1	0	0.4
γ=1.6	0.82	0.85	0.75	0.85	0.2	0.4	0.3	1	0.8	1	0.2	0.5
γ=1.8	0.88	0.9	0.95	0.85	0.25	0.4	0.45	1	0.85	1	0.2	0.5
γ=2	0.88	1	1	0.85	0.4	0.45	0.5	1	0.85	1	0.25	0.55

2. Path 6: X-A-B-C-H-M-N-O-Y. As it passes through the CM section with the least traffic pressure in the north-south corridor, this path becomes the absolute first choice for commuter vehicles. Commuter vehicles that choose route 6 account for 69% of all. The total number of vehicles traveling along route 6 also accounted for 27% of the vehicles surveyed.

After the simulation model is constructed, the relevant basic information of the critical path in the target area is obtained, which is consistent with the actual situation, and then the traffic volume running on the road network is allocated. The critical path information is shown in Table 2. Among them, path 11 is the shortest path and its expected travel time is shortest; path 6 is the most reliable path, and its expected travel time is not the shortest one.

B. DYNAMIC ROAD NETWORK PATH SELECTION SIMULATION-DIJKSTRA ALGORITHM OF ALIENATION WEIGHT

Through the simulation of vehicle trajectory detection, the sample travel time of each road section is obtained. Find the reliability of the travel time of each section. The reliability of the travel time of the road section under different acceptable service levels is different. The travel time reliability of each road section under different acceptable service levels γ is shown in Table 3.

FIGURE 5. Data fitting curve of path travel time reliability under different acceptable service levels (Dijkstra algorithm).

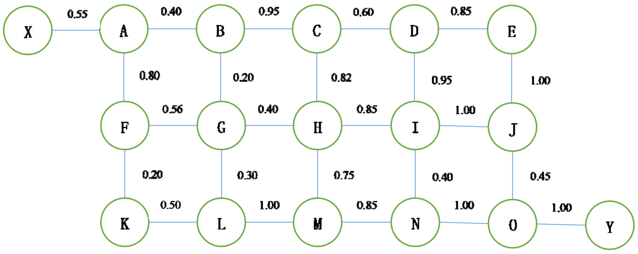


FIGURE 6. Road network model of road section reliability weight.

The acceptable level of service γ is the ratio scale of $T_{ai}(t)$ and $T_{\varphi a}$. When $\gamma = 1.6$ indicates that the predicted travel time exceeds the expected travel time, and the excess part reaches 60% of the expected travel time, while $\gamma = 2.0$ indicates that the excess part reaches 100% of the expected travel time. Under the same road service level, with the increase of acceptable level of service (the margin of predicted travel time exceeding the expected travel time increases), the travel time reliability of road section at time t increases.

In Table 3, when $\gamma = 1.2$, it is the strictest acceptable level of service; when $\gamma = 2.0$, it is the most relaxed acceptable level of service. Under different acceptable levels, the reliability of each section shows a trend of nonlinear change.

To find the appropriate acceptable service level according to the range of reliability changes, the data in Table 3 is transformed into a reliability fluctuation curve, as shown in Figure 5.

Analyzing Figure 5 finds that when the acceptable service level is 1.6, the reliability discrimination of different road sections is the largest. The road network model of road section reliability weights is shown in Figure 6.

According to the calculation requirements of the Dijkstra algorithm of the alienation weight to find the most reliable path, the reliability of the weight of the road section is converted into a logarithmic value with a base of 0.1, as shown in Figure 7.

Applying Dijkstra's algorithm to inspect and calibrate each node, we can get the path with the smallest sum of weights from point X to each point, the most reliable path. The calibration result is shown in Figure 8.

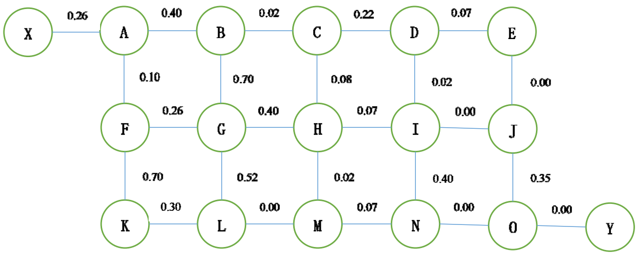


FIGURE 7. Road network model of road section reliability alienation weights.

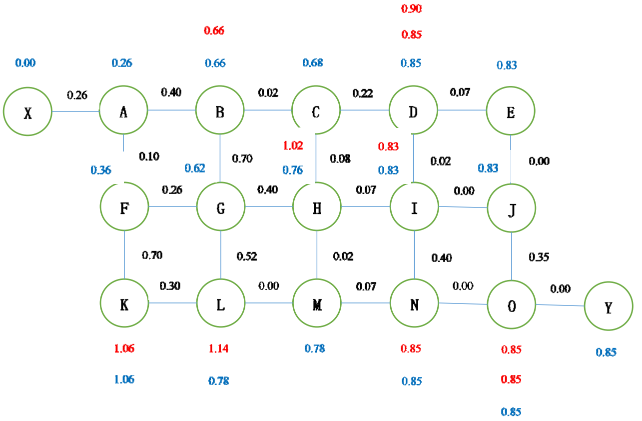


FIGURE 8. Calibration results of road network nodes. Note that: the blue text is the final calibration result.

TABLE 4. The most reliable path table from X point to each vertex.

Number	OD	Most reliable path
1	XA	X-A
2	XB	X-A-B
3	XC	X-A-B-C
4	XD	X-A-B-C-H-I-D
5	XE	X-A-B-C-H-I-J-E
6	XF	X-A-F
7	XG	X-A-F-G
8	XH	X-A-B-C-H
9	XI	X-A-B-C-H-I
10	XJ	X-A-B-C-H-I-J
11	XK	X-A-F-K
12	XL	X-A-B-C-H-M-L
13	XM	X-A-B-C-H-M
14	XN	X-A-B-C-H-M-N
15	XO	X-A-B-C-H-M-N-O
16	XY	X-A-B-C-H-M-N-O-Y

According to the operation rules of the Dijkstra algorithm, the final label of each vertex in Figure 8 is the logarithm of the most reliable path of the vehicle from point X to each vertex in the road network with the base 0.1, and the most reliable path is obtained, as shown in Table 4. The most reliable path from point X to point Y is path 6: X-A-B-C-H-M-N-O-Y, which is consistent with the actual survey results. The most reliable path from point X to other destinations can also be verified by actual investigation.

TABLE 5. Travel time reliability of each path under different acceptable service levels (enumeration method).

Path / γ	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1.2	0.12	0.00	0.14	0.20	0.24	0.33	0.10	0.31	0.04	0.00	0.09	0.13	0.00	0.05	0.05	0.00	0.18	0.19	**0.48**
1.35	0.19	0.05	0.43	0.40	0.44	**0.58**	0.20	0.31	0.08	0.00	0.26	0.29	0.14	0.14	0.18	0.28	0.45	0.43	0.52
1.5	0.27	0.19	0.62	0.70	0.72	**0.92**	0.30	0.44	0.17	0.29	0.48	0.58	0.24	0.36	0.59	0.60	0.77	0.67	0.78
1.6	0.42	0.29	0.62	0.80	0.84	**1.00**	0.30	0.63	0.21	0.52	0.65	0.63	0.43	0.50	0.64	0.72	0.95	0.76	0.93
2	0.73	0.86	**1.00**	0.85	**1.00**	**1.00**	0.50	0.75	0.58	0.90	**1.00**	0.96	0.57	**1.00**	0.82	**1.00**	**1.00**	**1.00**	**1.00**

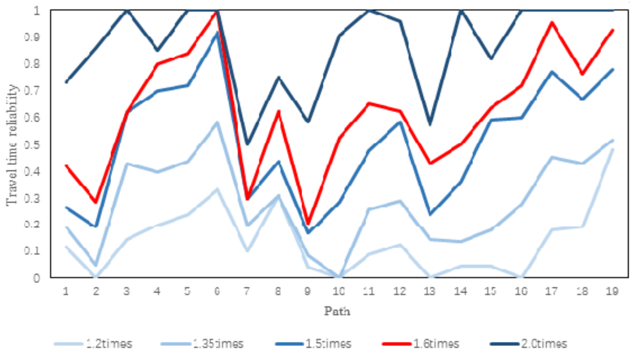


FIGURE 9. Data fitting curve of path travel time reliability under different acceptable service levels (enumeration method).

TABLE 6. Reliability ranking table of path travel time when $\gamma = 1.6$.

Sort	Travel time reliability	Path	Sort	Travel time reliability	Path
1	1.00	6	11	0.63	12
2	0.95	17	12	0.62	3
3	0.93	19	13	0.52	10
4	0.84	5	14	0.50	14
5	0.80	4	15	0.43	13
6	0.76	18	16	0.42	1
7	0.72	16	17	0.30	7
8	0.65	11	18	0.29	2
9	0.64	15	19	0.21	9
10	0.63	8			

C. DYNAMIC ROAD NETWORK PATH SELECTION SIMULATION-ENUMERATION METHOD

Taking the route selection from point X to point Y as an example, over 20 simulated vehicles are investigated for each path and the vehicle journey process is recorded. Select the vehicle is completely on the target path as the target vehicle. Exclude vehicles that choose other routes or end points because of long queues.

Comparing the travel time of the simulated vehicle with the expected travel time of the path can obtain the travel time reliability of each path under different acceptable service levels, as shown in Table 5. When the acceptable service level γ is at different levels, the reliability of the travel time of each path has a different performance. When $\gamma = 1.2$, the travel time reliability of path 19 is the highest. When γ rises to 1.35, the travel time reliability of path 6 is always at the highest level. When $\gamma = 2.0$, the travel time reliability of multiple paths reaches 1, the travel time reliability of each path cannot be effectively distinguished.

Draw the above path travel time reliability data fitting curve under different acceptable service levels, as shown in Figure 9. It is found that when the acceptable service level $\gamma = 1.6$, the travel time reliability level of each path has the highest separation and good discrimination.

When the acceptable service level $\gamma = 1.6$, the travel time reliability of path 6 is up to 1, and the travel time reliability of path 17 is 0.95, ranking second. The reliability of the travel time of other paths gradually decreases. Sort the paths in descending order according to travel time reliability, as shown in Table 6.

Route 6: X-A-B-C-H-M-N-O-Y, its path length and expected travel time are higher than the shortest distance path 11. However, from the perspective of travel time reliability, the travel time reliability of route 6 (first) is much higher than that of route 11 (eighth). Therefore, using the enumeration method to get path 6 as the most reliable path from the starting point X to the end point Y, the result is consistent so of the Dijkstra method and the result of the actual vehicle survey.

VI. CONCLUSION

Aiming at the uncertainty of road travel time caused by signal-controlled intersections, this paper conducts a detailed classification analysis and establishes a dynamic travel time prediction method. On this basis, in order to further improve the efficiency of vehicle routing in the road network, the dynamic travel time prediction set is transformed into travel time reliability. This reliability is used as the weight of the road section, and the Dijkstra algorithm is used to solve the most reliable path through logarithmic transformation, and case verification analysis is carried out. In this research, a complete calculation model for calculating the dynamic travel time of the road segment, the reliability of the road segment travel time, and the reliability of the path travel time in the dynamic complex network is established. The traditional research on the shortest path problem has moved forward to dynamism.

This paper comprehensively considers road service level, signal control influence and other road information in the dynamic road network, and establishes a dynamic travel time reliability prediction algorithm based on the theory of distributed waves. There are over 12 types, and 27 indicators need to be measured, including various situations in which the travel time of the vehicle is affected by the downstream signal control. The travel time reliability is used to comprehensively reflect the overall characteristics of the dynamic travel time multi-classification, and the dynamic travel time reliability is used as the unit information of the complex road network vehicle path selection. The traditional shortest path problem is transformed into the most reliable path selection problem; using the characteristics of the series system between the road sections, the travel time reliability as the weight of the road section is subjected to logarithmic transformation, and the Dijstra algorithm is used to solve the dynamic road network path selection problem.

Through case investigation and construction of simulation models, the algorithm is used to solve the most reliable path. The investigation method and enumeration method are used for path selection analysis. The effectiveness of the algorithm is tested from the three perspectives. The result proves that using the reliability of travel time as the weight of the road section can get a path selection result that satisfies the driver.

The typing analysis of the dynamic path travel time in this research is more complicated and involves many variables, which limits the practical application scope of this research to a certain extent. It needs to be simplified in future research to improve the practical value of the research.

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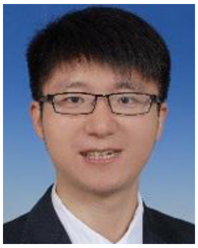

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