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Coordination Optimization of VSL Strategy on Urban Expressway and Main Road Intersection Signal

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ABSTRACT With the rapid urbanization during the past three decades in China, the urban expressway network has arisen with large numbers in many cities. However, the traffic conditions are becoming worse and worse. One of the main reasons is that the connected sections of main road and expressway do not have a coordination by the intersection signal and variable speed limits (VSL) on expressway. In this paper, a new cooperation optimization model of VSL on urban expressway and the intersection signal timing are proposed based on the mesoscopic traffic flow model. Its objective is to minimize the total delay and the number of parking. Its essence is adjusting traffic flow on the network in space-time so that the whole network can be in a state of equilibrium. It is effective to the control of local traffic congestion and can avoid the spread of congestion, thus improving traffic safety. Additionally, the optimal VSL strategy is proposed. And then a solution algorithm based on the simultaneous perturbation stochastic approximation (SPSA) is designed for the proposed model. In the end, a practical example of Yanshan overpass in Ji'nan elevated expressway is used to validate the effectiveness of the proposed method. The simulation results are satisfactory. The conclusions are very useful for traffic management department to implement reasonable traffic control strategy.

INDEX TERMS Urban expressway, variable speed limit, traffic flow, traffic simulation, signal timing.

I. INTRODUCTION

In recent years, the traffic congestion has spread from big cities to medium-sized and small ones in China. Unfortunately,, it not only appears on the main road of the city, but also appears on the urban expressway. This leads to the inefficient operation of the whole urban transportation system. One of the main reasons is that the coordination of the urban expressway and main road fail to perform their functions. The traffic congestion may start from these key areas and further spread to other urban roads. What is worse is that the poor coordination also brings great difficulties to traffic safety and management. Fortunately, the development of technology such as intelligent transportation system (ITS), big data, cloud computing and internet plus, brings new chance for a series of traffic problems. In particular, the new technologybased on ITS provides a guarantee for solving large-scale optimization problems. The key models include the traffic simulation technology based on mathematical model and data driven technology.

In order to achieve a better optimization result, the coordination region must be extended in a large region that includes the variable speed limit (VSL) on the expressway and the signal on major urban roads. By indexing, the optimization technology is not explored in recent years. Therefore, this paper focuses on the combination of the two aspects. The main idea is used to establish a standard state for the currently traffic network. And then, a new optimization model is

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proposed to minimize the traffic congestion on the network. Of course, the mentioned work is to ensure the premise of traffic safety.

Emphasis of most references was on the VSL on expressway. Zhao analyzed the causes of highway congestion based on truck data [1]. Carlson proposed an optimal method of VSL integrated into ramp metering [2]. Hegyi studied a model based on control of VLS [3]. Zhang *et al.*. [4] studied the VSL strategy with cellular automaton model. Li [5]–[7] studied the VSL with a variety of models, drawing some interesting conclusions. At present, a lot of research results on variable speed limit control have been explored with the aim of maintaining traffic safety [8]–[10].

For signal optimization, Huang summarized the traffic signal optimization in intelligent control,which has been achieved at home and abroad [11]. Gao introduced a two-dimensional Chebyshev wavelet method (TCWM) for solving partial differential equations (PDEs) in L 2 (R) space [12]. Baldi *et al.* developed a simulation-based traffic signal control for congested urban traffic networks [13]. Hu *et al.* proposed a novel Multi-Intersection Model (MIM) based on Cellular Automata (CA) and a Multi-Intersection Signal Timing Plan Algorithm (MISTPA), which can reduce the delay time at each intersection and effectively alleviate the traffic pressure on each intersection in the urban traffic network [14]. Yu *et al.* presented a mixed integer linear programming (MILP) model to optimize vehicle trajectories and traffic signals in a unified framework at isolated signalized intersections in a Connected and Automated Vehicle (CAV) environment [15]. Li *et al.* proposed a multiobjective optimization method for signal control design at intersections in urban traffic network. They employed Cell Transmission Model (CTM) which was based on four measures in network traffic performance, i.e., maximizing system throughputs, minimizing traveling delays, enhancing traffic safety, and avoiding spillovers [15]. There are many scholars who have conducted a lot of researches on coordinated control [17]–[21]. It is unknown that which direction these vehicles will select at the diverge nodes or at the overpass without any detector. Therefore, it is difficult to access the network state. Recent years, much more practical problems have been relieved by traffic flow models [22]–[26].

In relieving traffic congestion and ensuring traffic safety, traffic flow model is the key part of simulating vehicle dynamics on the network. Generally speaking, traffic flow models can be divided into macroscopic [27], [28], mesoscopic [29], [30] and microscopic models [31]–[32]. Mesoscopic traffic flow model can achieve the balance between simulation accuracy and efficiency. Therefore, the proposed network estimation method uses the mesoscale model.

The main contributions of this paper are as follows: 1.We simulate the movement of the vehicles in the network by using the improved mesoscopic traffic flow model, and form an assessment of the traffic network state. 2.A new mathematical optimization model with the combination of signal optimization and variable speed limit is proposed. 3.Perturbation Stochastic Approximation (SPSA) algorithm is designed to solves the optimization problem. This work can reduce traffic congestion to the area connecting the urban expressway and the main road in the city. At the same time, it can also guarantee the transportation safety, transportation order and improve traffic efficiency. Although there are a lot of reports on the control method proposed in this paper, there is no case of using VSL in urban expressway and combining it with trunk road signal. Due to the influence of ground traffic, one of the defects of this paper is that the traffic condition of main road is not considered, which is one of the contents of further study.

II. THE TRAFFIC STATES ESTIMATION

Figure.1 describes the state estimation process. This process tries to capture the existing state of the network. The first step in the procedure is to dis-aggregate the Origin-Destination (OD) matrix for the time interval and perform update behavior of the vehicles in response to pre-trip information. The resulting updated packets are then aggregated to produce the updated list of packets.

The process then estimates that the state of the network is an iterative one which involves multiple demand-supply interactions. The first step in the process is to estimate an OD matrix based on the surveillance data. This procedure requires an assignment matrix that maps OD flows onto links in the network. This assignment matrix is however obtained by employing the supply simulator. Thus the problem is a fixed-point problem. In order to obtain a convergent state, an OD matrix is estimated, the supply simulator is running, and the convergence criteria which compares the simulated with versus the actual flows is performed. If convergence is obtained, the process terminates and the list of packets is updated to remove finished trips; Otherwise an assignment matrix is built and fed back into OD estimation and the process continues until convergence is obtained..

In the dynamic OD estimation model, the state space model of Ashok and Ben-Akiva [33] will be adopted. The state variable is defined as a deviation: $\delta x_h = x_h - x_h^H$, where, x_h are vectors of all OD flows and the corresponding historical estimates be given by x_h^H. This deviation follows an autoregressive process:

$$\delta x_{h+1} = \sum_{p=h+1-q'}^{h} f_{h+1}^{p} \delta x_p + w_{h+1} \tag{1}$$

In this process, f_{h+1}^{p} is an autoregressive coefficient matrix reflecting the effects of δx_p on δx_{h+1}; q' is the order of the autoregressive process; w_{h+1} is the random error, $E(w_{h+1}) = 0, E(w_h w_l^T) = Q_h \delta_{hl}$, Q_h is the error covariance matrix,

$$\delta_{hl} = \begin{cases} 1\,, & h = l \\ 0, & h \neq l \end{cases}.$$

$$\delta y_h = \sum_{p=h-p'}^{h} a_h^{p} \delta x_p + v_h \tag{2}$$

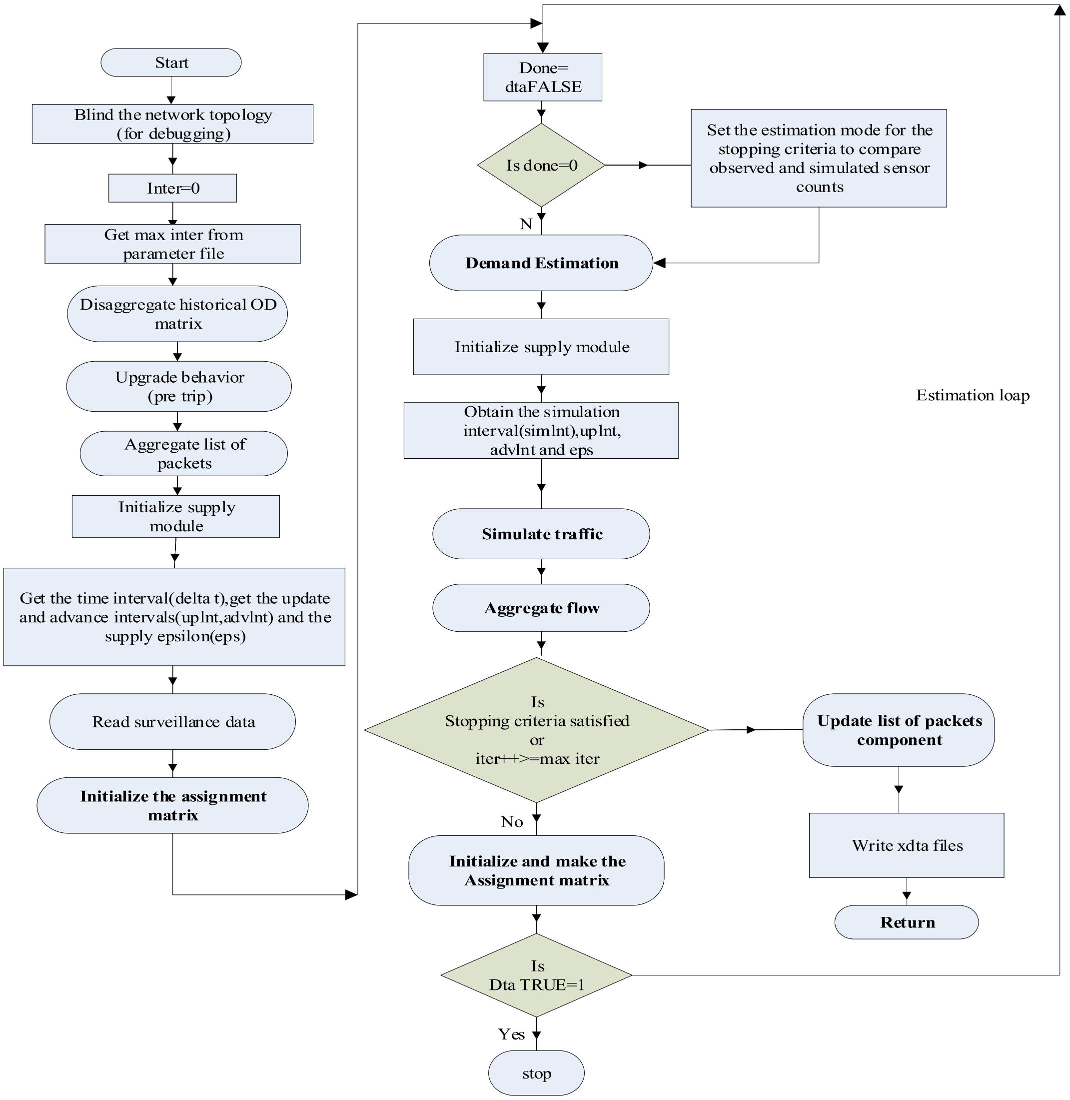

FIGURE 1. The traffic state estimation process.

In equation (2), $\delta y_h = y_h - y_h^H = y_h - \sum_{p=h-p'}^{h} a_h^p X_p^H{}_{,} y_h$ is the transportation volume measured during interval h, y_h^H is the corresponding historical value. The matrix a_h^p is an assignment matrix of contributions of δx_p to δy_h, and it is the fraction of the rth OD that departed its origin during interval p and crossed the counting point during interval h, $(p' + 1)$ is the maximum number of time intervals taken to travel and OD is the pair of the network. v_h is the measurement error, and $E(v_h) = 0$.

Equations (1) and (2) construct the state space model for dynamic OD estimation and prediction. Kalman Filter is used to estimate and predict OD information.The traffic state estimation process is illustrated in Figure.1. In Fig 1, "Inter","TRUE", "done" are all programming code. "Inter" is a set threshold, "TRUE" means the threshold is met. "done" is defined characters string.

III. THE MESOSCOPIC TRAFFIC SIMULATION MODEL INTEGRATED WITH VSL

In this section, the variable speed limit values are considered as optimization variables into the mesoscopic traffic simulation model. It includes a class of models such as the queue model, the moving model, the speed-density relationship model and the capacity model. It can describe the movement of vehicles on the traffic network to a medium extent and describe some traffic phenomena such as queuing, overflow, congestion propagation etc. Based on the improved the mesoscopic traffic flow model, the VSL is integrated to it, which can clearly observe the impact of speed limit on various phenomena of traffic flow, and can also find the best time-space speed limit scheme through optimization algorithm. Moreover, one can achieve the optimal value of variable speed limits and can further analyze the placement and quantity of VMS.

The queue model used in this paper is from reference [35], which comes from queuing theory. It is mainly concerned with the delay of the i-th vehicle in queue, and D can be expressed as follows:

$$D = \frac{i}{c} \tag{3}$$

In equation (3), the parameter c refers to the output capacity of the lane group. The position of the last vehicle in the queue at time t

$$q(t) = q(0) + l(ct - m) \tag{4}$$

$q(t_0)$ is the position of the last vehicle at time t=0, l is the averaged length of vehicles in the queue. m represents the number of moving vehicles, namely those vehicles between the considered one and the last one of the queue.

In the mesoscopic traffic flow model, the road is divided into two parts: the moving part and the queuing part. The line is divided into segments with same physical properties. Each section consists of lane groups. In the simulation, the lane groups define the capacity of the road. Once traffic flow exceeds service capacity, the queues are formed. This applies to the mentioned queue model. In the moving part, the traffic flow follows the density-speed relationships. Considering the variable speed limit, the position and speed of vehicles can be described as follows:

$$v(z) = \begin{cases} \min(v_u, v_{\lim}) & (0 \le z \le L - L_s) \\ \min(\lambda(z - L) + v_d, v_{\lim}) & (L - L_s < z \le L) \end{cases} \tag{5}$$

where:

$$\lambda = \frac{v_d - v_u}{L_s} \tag{6}$$

$$v = \begin{cases} \min(v_f, v_{\lim}) & \text{if } k \le k_c \\ \min(v_f, v_{\lim}) \left[1 - \left(\frac{\max(0, \mathrm{k} - k_c)}{k_{jam}} \right)^{\beta} \right]^{\alpha} & \text{if } k > k_c \end{cases} \tag{7}$$

In equation (7), v_f refers to speed of free traffic flow, k_{jam} is jam density, k represents traffic flow density while k_c is the critical density, and α and β are the potential model parameters which can be obtained by observation of different roads and actual measure of traffic conditions. v_u represents the speed of node in the upper stream of segments while v_d refers to the speed of nodes in downstream of segments and L_s shows the length of deceleration zone, which is closely related to the actual traffic. Lastly, $v_{\lim}$ demonstrates limited speed values at that time.

A modified formula is as follows:

$$z(t) = \begin{cases} e^{\lambda(t)t}\left(z_0 + \frac{\min(v_u, v_{\lim})}{\lambda(t)}\right) - \frac{\min(v_u, v_{\lim})}{\lambda(t)}, & \text{if } t < t^* \\ q_0 + l(ct - m), & \text{if } t > t^* \end{cases} \tag{8}$$

$$z(t) = e^{\lambda(t)t}\left(z_0 + \frac{\min(v_u, v_{\lim})}{\lambda(t)}\right) - \frac{\min(v_u, v_{\lim})}{\lambda(t)} \tag{9}$$

$$\lambda(t) = \frac{-\min(v_u, v_{\lim})}{q_0 + l(ct - m)} \tag{10}$$

The meanings of q_0, l, c and m remain stable as explained above.

The mentioned models describe the dynamic of vehicles on the traffic network. In the simulation, the time is divided into several update phases. Each update phase has several advanced phases. In the first phase, all the parameters can be updated according to the new position information, say the physical properties of roads. In the second phase, the vehicles can move to the new positions according to the traffic flow dynamic model. The detailed flow chart refers to the. And then, one can know the network information such as density and speed.

IV. THE SIGNAL OPTIMIZATION MODEL AND SPSA BASED ALGORITHM

A. THE SIGNAL OPTIMIZATION MODEL BASED ON VSL

In this model, the optimization target is minimizing the total delay by all the vehicles through the network and the average travel time of vehicles. It is a multi-objective optimal problem which means it is relatively hard to achieve an optimal solution. So we use a heuristic algorithm named SPSA to solve the problem. It can get the best variable speed limit strategy and the optimal signal timings. In order to illustrate the problem clearly, we use the following notations:

$d = \{d_h\}$: the total delay time of all vehicles on the network, d_h is the delay column of vehicles in the h interval.

v $= \{v_h\}$: the total speed of all vehicles on the network, v$_h$ is the speed column of vehicles in the h interval, $v_{\lim n}$ is the limit speed column of vehicles in the h interval.

$s = \{s_h\}$: the total number of stops of all intervals on the network, and s_h is the number of stops column vector of all vehicles on all sections in the h interval.

$f = \{f_h\}$: the total flow into the intersection of all intervals on the network, and f_h is the outflow column vector of all vehicles on all sections in the h interval.

M_h : the output of the mesoscopic traffic simulation model, including the column vector of the flow on road sections, the travel delay, the average queue length and the number of stops in the h interval.

d $= \{\mathrm{d}_h\}$: the total delay of all intervals on the network, and d$_h$ is the travel delay column vector of all vehicles on all sections in the h interval.

$Ql = \{\mathrm{Q}l_h\}$: the total queue length of all intervals on the network, and Ql_h is the average queue length column vector of all vehicles on all sections in the h interval.

$\xi_h = [d'_h, ql'_h, s'_h, f'_h, v'_h]'$: the column vector of network performance evaluation in the h interval and $\xi = \{\xi_{\mathrm{h}}\}$.

h$(\cdot)$ is the mapping relationship between input and output of the mesoscopic traffic simulation model.

g$(\cdot)$ is the mapping relationship between output of the mesoscopic traffic simulation model and network performance index.

L$(\cdot)$ is the objective function.

D is the OD demand.

B is the travel choice model parameters, including the driver's travel time, and route choice model. It is obtained through system calibration process;

S is the supply simulation model parameters, including the speed-density model parameters of typical sections, and saturation flow rate. It is also obtained obtained through system calibration process;

C_h is the public cycle of all signalized intersections in the h interval.

$C_{\min}, C_{max}$: the minimal and maximal cycle.

$T = \{T_h\}$: all the controller parameters on network.

$T_h = \{t_{ih}\}$: the parameter column vector of all signalized intersections in the h interval.

$t_{ih} = [t^g_{i0h}, t^g_{i1h}, t^g_{i2h} \cdots t^g_{iP^ih}, t^{off}_{ih}]^T$ or $[C_h s^g_{i0h}, C_h s^g_{i1h}, C_h s^g_{i2h} \cdots C_h s^g_{iP^ih}, t^{off}_{ih}]^T$: the green duration and the offset in the h interval at i intersection, and P^i is the number of phase, s^g_{ijh} is the split of the j phase at i intersection.

$T_{\min}, T_{max}$: the upper and lower bound vectors of signal timing parameters.

The proposed signal optimization model which is integrated with VSL is as follows:

$$\underset{T}{MINL}(\xi) = h(\xi) + g(\xi) + \sum_h (q+f) + \sum_h s \tag{11}$$

Constraint conditions:

$$T_{\min} \le T_h \le T_{\max} \tag{12}$$

$$M_h = h(D, \beta, s, T_1, T_{2,\cdots,}T_h) \tag{13}$$

$$C = \sum T_h \tag{14}$$

$$C_{\min} \le C_h \le C_{\max} \tag{15}$$

$$\xi = g(M_1, M_2, \cdots, M_h) \tag{16}$$

It's remarkable that the designed mesoscopic traffic simulator in this paper can set various parameters flexibly, such as stop times or the total delays or the total flows according to the different purposes. In this case, the schemes of intersection timing and variable speed limit on expressway can be obtained.

B. THE ALGORITHM BASED ON SPSA

In this model, we can optimize the timing parameters and variable speed limits simultaneously, or one of them. The aim is to alleviate traffic congestion and ensure traffic safety. Because it must meet the requirement of online application, the efficiency and the accuracy should be considered. Therefore, it is necessary to design an efficient solution algorithm.

The simultaneous perturbation stochastic approximation algorithm (SPSA) can meet the mentioned requirements. It requires only two calculations for the objective function with independent number of parameters. In general, SPSA can produce a series of parameter estimator that the gradient of objective function tend to converge to zero.

The updated parameters by:

$$\theta^{i+1} = \theta^i - a_i\hat{g}(\theta^i) \tag{17}$$

where, θ^i is the parameter vector at the i iteration, $\hat{g}(\theta^i)$ is the current estimator, a_i is the step length. The iteration formula is as follows:

$$\hat{g}(\theta^i) = \frac{z(\theta^i + c^i\Delta_i) - z(\theta^i - c^i\Delta_i)}{2c^i}\begin{bmatrix}\Delta_{i1}^{-1} \\ \Delta_{i2}^{-1} \\ \vdots \\ \Delta_{ik}^{-1}\end{bmatrix} \tag{18}$$

where, Δ_i is a K-dimensional stochastic perturbation vector. For all k=1,2,…,K, it has the same value, so each iteration has the static calculation (It is nothing to do with the vector dimension K), which is the most prominent advantages of the SPSA. After several iterations, a good application value can be obtained. The detailed steps are as follows:

Step 1. Initialization. Setting the values of each parameter, such as the counter index $k = 0$, $\theta^t = \theta^0$. They are the initial values of K-dimensional Optimization vector. In order to improve the speed of optimization, the initial values should be chosen as close as possible to the actual ones according to different optimization problems, and the non-negative parameter values α, A, c, a, γ are selected according to the research of Spall [35], [36] in the SPSA.

Step 2.Setting iteration number to calculate the gradient vector in each step: grad_rep. It is in each iteration step.

Step 3. Plus 1 of the iteration counter, At the same time, the step gain is obtained: $a^k = a/(A+i)^\alpha$, $c^k = c/k$.

Step 4. The Bernoulli distribution [36] is used to generate each component Δ_i.

Step 5. Making use of the mesoscopic traffic flow model accessing the values of the objective function by $\theta^{t+} = \theta^t + c^k\Delta_k$, $\theta^{t-} = \theta^t - c^k\Delta_k$, and each point is required to meet the upper and lower limit constraints in the optimization problem.

Step 6. According to equation (18), one can calculate the K-dimensional gradient vector of the stochastic approximation, in which one component of the gradient vector of the K has the same elements. This makes the SPSA algorithm different from the traditional finite difference method (FD).

Step 7. Repeating 4-6 steps grad_rep times, and each time is for independent sampling. Finally the bias can be obtained.

Step 8. Formula (17) is calculated and new values are obtained of θ^{t+1} can be obtained. Also, it is adjusted properly..

Step 9. Returning to Step 3 and iterating to convergence. The convergence criterion is to set the number of iterations to be completed or to achieve the value of the objective function in the adjacent iterations.

The mentioned algorithm must satisfy some certain conditions, such as multi-order derivability of objective function and the proper probability distribution of perturbation vectors. Spall has pointed out the that the convergence rate of the algorithm at $k^{1/3}$ [36]. The disadvantage is the randomness of the search direction which can't guarantee each iteration has a descending direction, but the expectation of the gradient is almost unbiased [35].

$$E[\hat{g}(\hat{\theta}_k)] = g(\hat{\theta}_k) + b^k \tag{19}$$

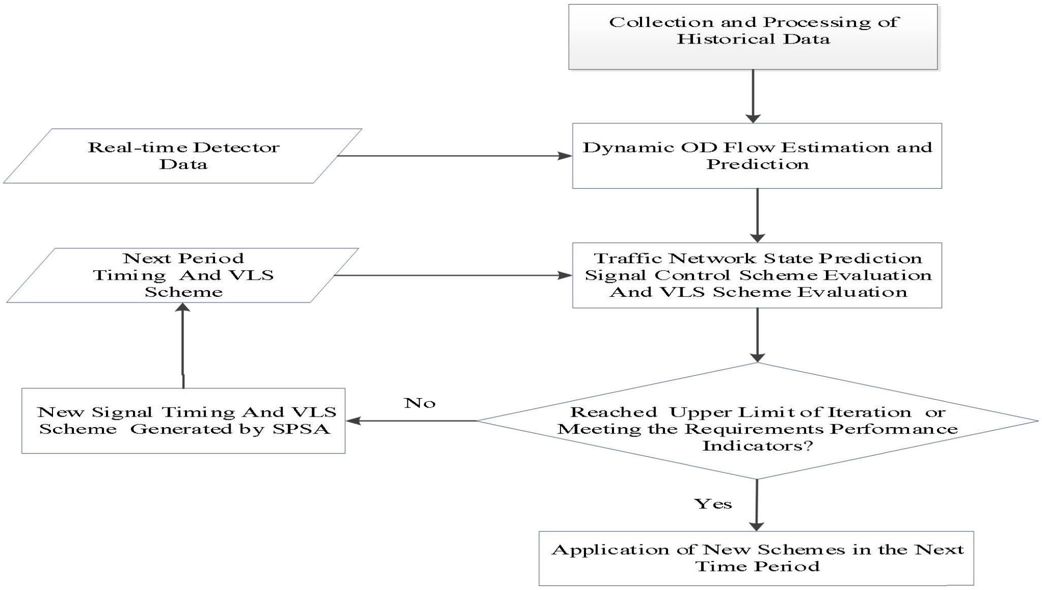

FIGURE 2. The simulation process.

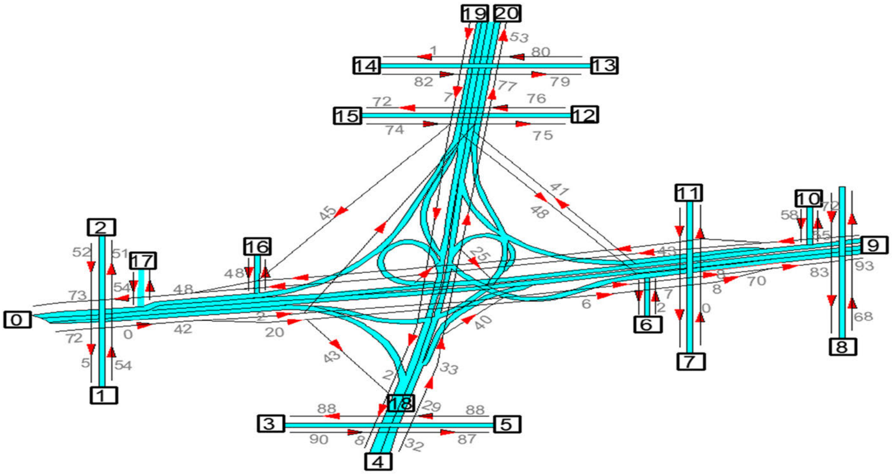

FIGURE 3. The Yanshan overpass network of Jinan.

where, $b^k = \mu c^{k^2}$, μ is going to be a constant. If c^k approaches zero with c^k (for large value of k), the deviation b^k gradually disappears. Therefore, it can be estimated that the result is close to be optimal.

V. CASE STUDY

A. THE SIMULATION ENVIRONMENT

The Yanshan overpass is located on Jingshi Road, Jinan City, Shandong Province in China. Figure.3 depicts the traffic network structure. This area has the greatest traffic pressure in Jinan, especially in the morning and evening peak hours. The congestion lasted more than 4 hours in this area. In the traffic network, the numbered nodes are defined as OD pairs. The urban road network topology mainly consists of node, connected line, line group, line, detectors, turning prohibition line, signal control equipment, traffic zones and so on. The area is 1.5 km from North to South and 2 km long from East to West. There are urban expressways on overpasses and urban main roads under overpasses. Signal control exists at the junction of the two types of road and the intersection of the main city roads.

For simplicity, each link is defined as a segment on one link in this paper. The segment is a part of the link which has the same physical property. There are two lines on every segment. According to reference [7], it is based on the length, the width, the level, the traffic capacity and the traffic flow of the section. $\alpha = 1.9420$, $\beta = 0.5040$, $k_{jam} = 0.1150$, and the capacity is 0.6667veh/s. Because the network is the urban network, the free flow speed is 90km / h. The simulation period is 15 minutes. The total simulation time is three hours from 7:00 to 12:00. There are 20 intervals. The present signal timing schemes are calculated by Synchro signal optimization software. The loaded OD is retrieved by manual traffic investigation. Usually, the variable speed limit is chosen as {80, 70, 60, 50, 40} and other values are not practical. The loaded OD matrix with the same value is in each interval. The Variable Message Signs (VMS) are placed on some segments. The VSL is displayed on VMS respectively at different periods. Because variable speed limits do not work at low and high density flows. At low traffic density, it can enhance the traffic safety, but is not conducive to traffic efficiency. Only at the medium density it can be possible to promote traffic safety as to well as ensure traffic safety. First, we set the OD requirement to 3, the network situation is slightly congested. And then, it was set by 1, The network condition is very smooth. By testing, the demand of each OD pair is 2, which can reach the medium density. For deeper research and approach the actual situation is better. 30% random perturbation is added to the OD matrix.

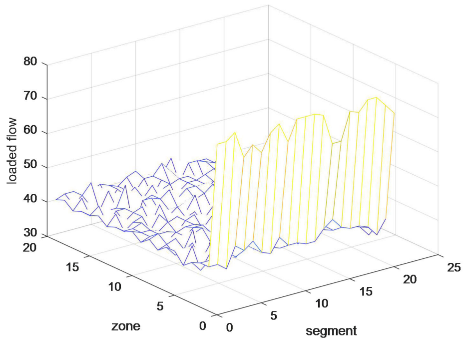

FIGURE 4. The loaded OD demand in traffic zone.

B. THE SIMULATION RESULTS

Firstly, the whole network of traffic conditions and the total traffic flow are investigated. The density distribution and the speed equilibrium are taken as the objects. Three situations are discussed: before optimization, after optimization and without any control. In each situation, the loaded OD in traffic zones is shown in Figure.4. Before the implementation of the proposed method, the total traveling time is 929.9 hours, the total traveling distance is 69359.3 kilometers, the average speed is 74.6 kilometers per hour, the total traffic flow is 132164 vehicles, the total delay is 159.2 hours, the largest delay on node is 19.6 hours, the total density is 3.0276, and the average flow is 72.8710. The average impedance is 18.26s, and the sum impedance is 2008.5s. Secondly, at the micro level, the distribution of the average density, the average speed and the average flow on each segment at every interval are shown by Figure.5∼Figure.8. Thirdly, in the medium research, the maximum density is 0.0289 at the second segment of the seventh interval. The maximum flow is 484 at the first segment of the first interval. Most segments are free-flow speed. In this situation, the outflow of the zones as shown in Figure.8.

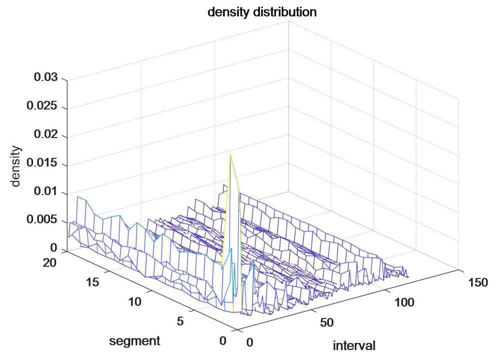

FIGURE 5. The averaged density before optimization.

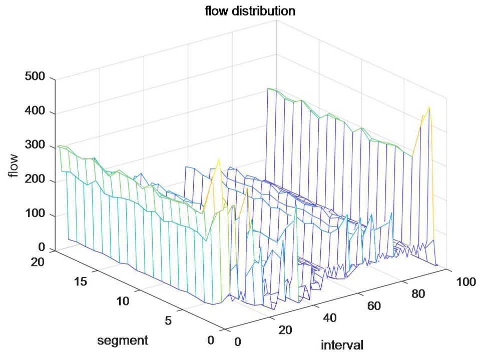

FIGURE 6. The averaged flow before optimization.

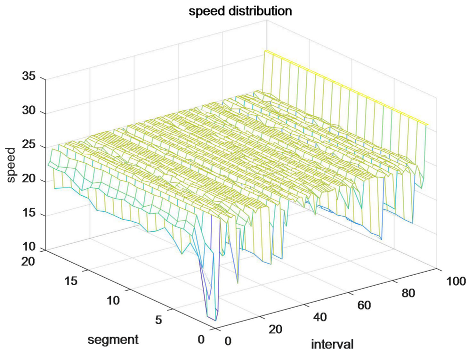

FIGURE 7. The averaged speed before optimization.

After optimization, the total traveling time is 860.2 hours, the total traveling distance is 69341.9 kilometers, the average speed is 80.6 kilometers per hour, the total traffic flow is 132187 vehicles, the total delay is 89.7 hours, the largest delay on node is 18.4 hours, the total density is 2.8591,

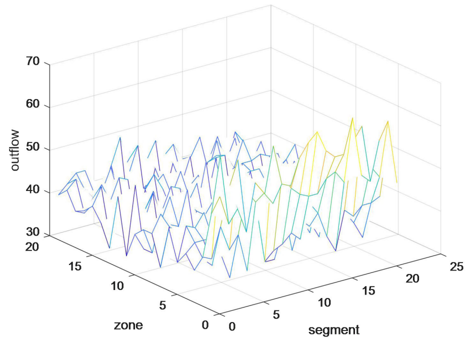

FIGURE 8. The OD zones outflow before optimization.

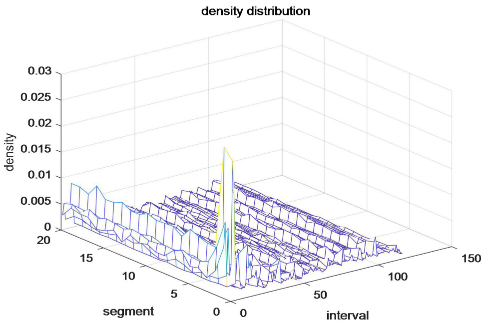

FIGURE 9. The averaged density after optimization.

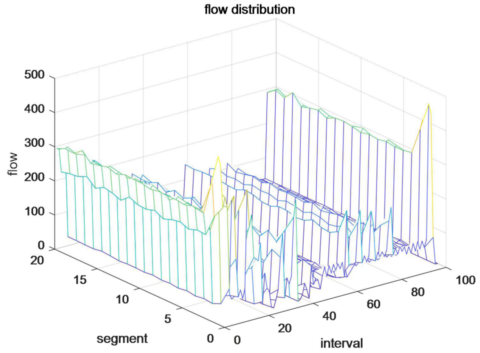

FIGURE 10. The averaged flow after optimization.

and the average flow is 72.8385. The average impedance is 12s, and the sum impedance is 816.19s. At the micro level, the distribution of the average density, the average speed and the average flow on each segment at every interval are shown by Figure.9~Figure.11. In the medium research, the maximum density is 0.0279 at the second segment of the seventh interval. The maximum flow is 488 at the first segment of the first interval. Most segments are free-flow speed. In this situation, the outflow of the zones is shown in Figure.12.

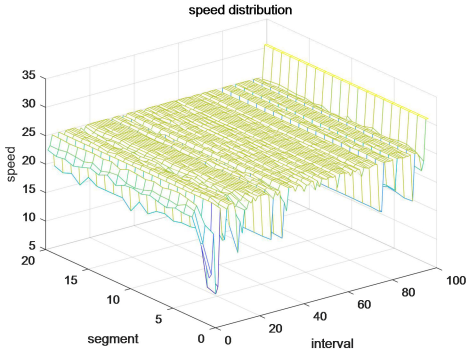

FIGURE 11. The averaged speed after optimization.

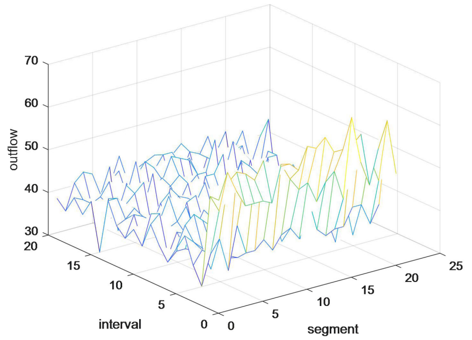

FIGURE 12. The OD zones outflow after optimization.

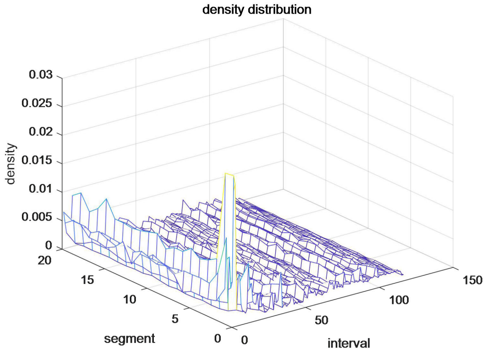

FIGURE 13. The average density without control.

In uncontrolled situation, the total traveling time is 841.0 hours, the total traveling distance is 69352.4 kilometers, the average speed is 82.5 kilometers per hour, the total traffic flow is 132202 vehicles, the total delay is 70.5 hours, the largest delay on node is 20.4 hours, the total density is 2.8030, and the average flow is 72.8400, the average impedance is 16.14s, and the sum impedance is 2582.4s. At the micro level, the distribution of the average density, the average speed and the average flow on each segment at every interval are shown by Figure.13~Figure.15. In the medium research, the maximum density is 0.0255 at

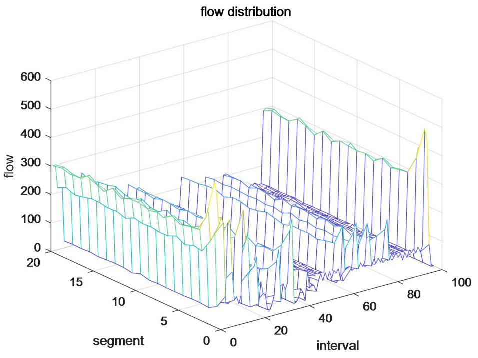

FIGURE 14. The averaged flow without control.

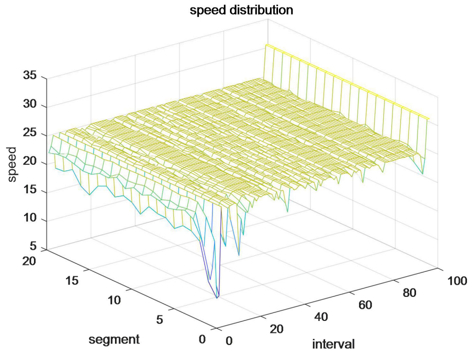

FIGURE 15. The averaged speed without control.

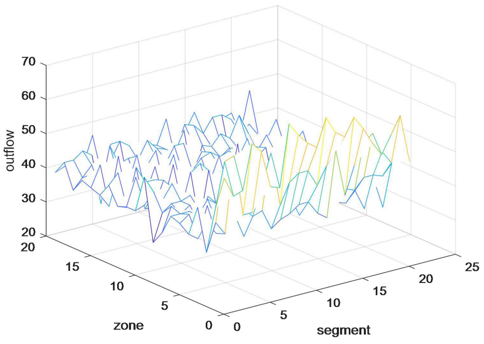

FIGURE 16. The OD zones outflow with uncontrol.

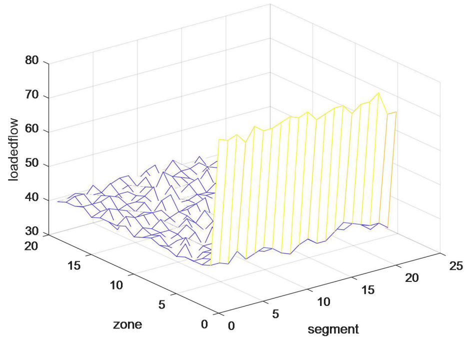

FIGURE 17. The loaded OD demand in traffic zones.

the first segment of the seventh interval. The maximum flow is 503 at the first segment of the first interval. Most segments also segments are free-flow speed. In this situation, the outflow of the zones is shown in Figure.16. Figure.17 is the loaded flows in this situation. Figure.18 is the recorded hourly flow at boundary nodes in each interval.

From the above description, it is clear that most of the optimized indicators have been significantly improved. It can not only guarantee the traffic safety, but also improve the traffic efficiency to some extent. The optimized traffic network improves the traffic flow and balances the traffic density. Among the three situations, the uncontrolled one is the highest and the safest traffic state. The only negative indicator is that the maximum node delay has increased. In the uncontrolled state, the vehicles run according to the established rules, so the vehicles arrive at the delay node quickly, which causes the total delay of the node to increase slightly.

In order to verify the effectiveness of the optimization method proposed in this paper in large-scale systems, this paper studies a new case. This case takes Jinan expressway network as the simulation object, and adopts the same parameter configuration as Yanshan overpass case. The expressway network of Jinan City is shown in Figure 19.

The density comparison before and after optimization is shown in Figures 20 and 21. It can be seen from the figure that the average network density before optimization is mostly distributed between 0.005 and 0.2, while the average network density after optimization is mostly distributed between 0.005 and 0.1. This shows that the network traffic density is more uniform and the traffic efficiency is greatly improved after the optimized control.

The simulation results show that the proposed optimization method in this paper is effective for some specific situations. For example, a free flow area can be created at upstream of the bottleneck, so that the vehicles in this area can maintain a constant speed and the traffic flow is infinitely close to the bottleneck capacity, which is conducive to preventing and alleviating the traffic congestion at the bottleneck. Similarly, the proper application of the proposed optimization method in this paper to create free flow area at upstream of signalized intersections can also ensure traffic safety and improve the traffic efficiency of the whole transportation network system. Anyway, the method can regulate the traffic order and ensure the traffic safety. In the traffic simulation without any control, the vehicles move according to the established rules like the intelligent network unit which is similar to the internet vehicles, and the traffic efficiency is the best one. But in real life, if there is not signal control and variable speed limit, the driver's disobedience to the order will cause traffic chaos, which leads to the traffic accidents

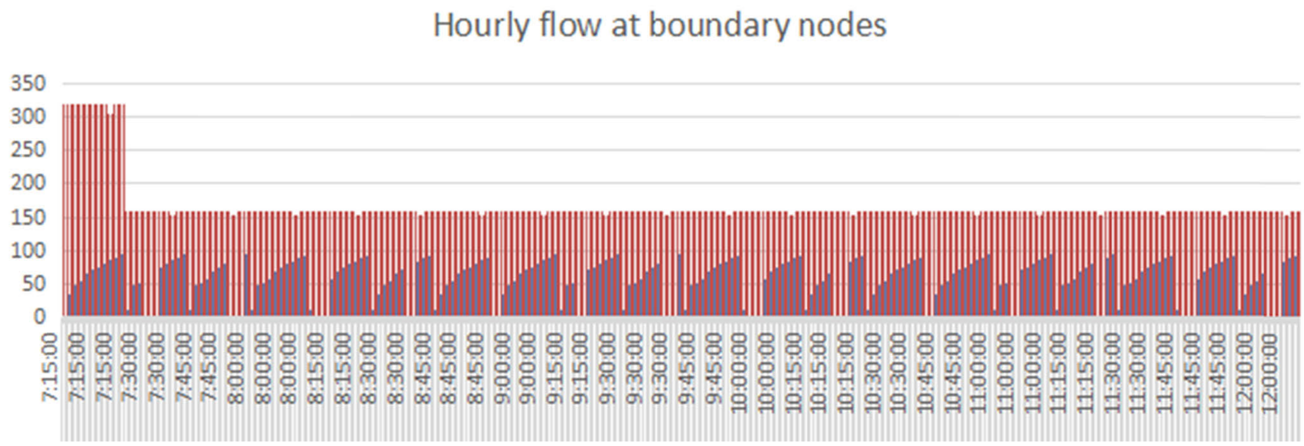

FIGURE 18. The recorded hourly flow at boundary node of intervals.

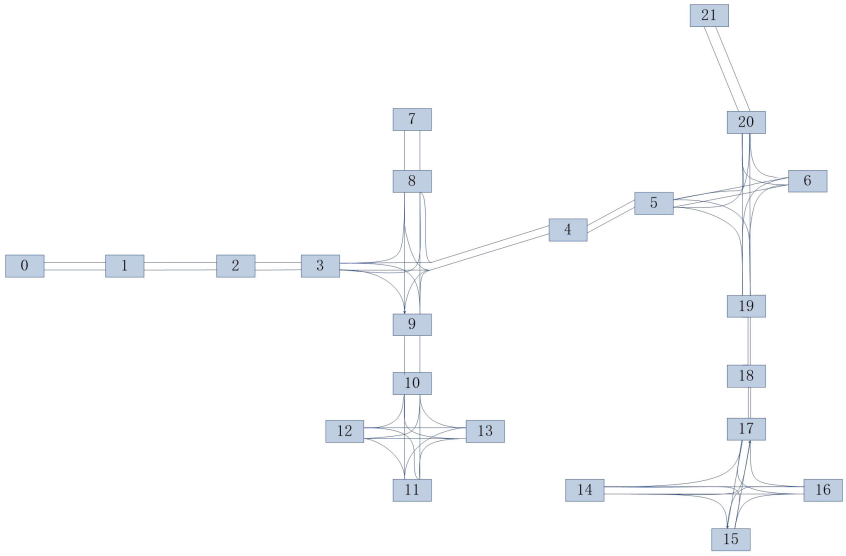

FIGURE 19. The Jinan expressway network.

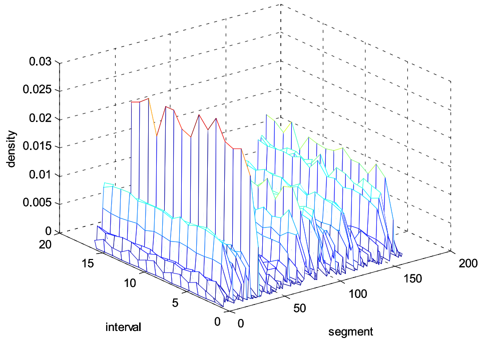

FIGURE 20. The average density on segment before controlled.

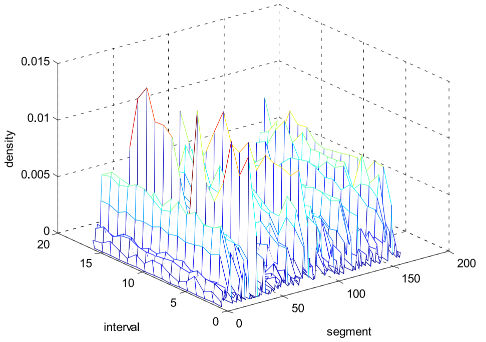

FIGURE 21. The average density on segment after controlled.

or a large-scale traffic congestion. In this sense, the signal optimization and variable speed limit can play a more active role.

VI. RESEARCH CONCLUSIONS AND PROSPECTS

The variable speed limit management system consists of the meteorological monitoring equipment, the variable speed limit signs and the forensic equipment. Among them, the variable speed limit signs analyses the collected data by meteorological monitoring equipment in real time and the speed limit values are displayed. If the speed of the vehicle exceeds the speed limit, the system will automatically collect the evidence. At present, some expressways have been implemented variable speed limit control in China. For example, the variable speed limit control system was installed at Jiguang Expressway in Shandong Province at the end of 2013, and the speed limit was adjusted according to the visibility and the snow thickness in foggy environment. The results show that the variable speed limit control not only ensures the road traffic safety but also affects normal thoroughfare for vehicles. During the Chinese Spring Festival, the traffic accidents of the pilot section decreased by 50% compared with that of the same period of the previous year in 2019.

The mesoscopic traffic flow model is improved in this paper. The mesoscopic traffic simulation process is constructed based on the dynamic OD estimation. On this basis, a coordinated control model based on variable speed limit and signal optimization is proposed, which can minimize vehicle delay and maximize traffic flow in the research area. This aims to improve the efficiency of the network operation. The proposed method can alleviate local traffic congestion and ensure traffic safety in some cases. The system simulation is carried out for three control modes. The simulation results show the best efficiency of the uncontrolled state, followed by the optimized network state. The contents for further research include three levels. Theoretically, it is necessary to study the unified coordination of green wave band and regional signal optimization and variable speed limit control. Technically, the reliable models and more stable software systems are needed in order to be suitable for online optimization and application. In application, the research on reliability and applicability of the system should be strengthened. Empirical study also helps promote the uniform distribution of the traffic flow and improve the traffic efficiency. And further application is suitable for wider network scope.

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