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A Traffic Assignment Method Based on Genetic Tabu Algorithm for the Main Skeleton Road Network in Congested Road Sections

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ABSTRACT
The existing traffic flow allocation methods lack sufficient flexibility and adaptability by analysing the impact of parameter changes on traffic flow distribution through examples, resulting in a decrease in traffic flow allocation performance on congested road sections. A traffic flow allocation method for the main skeleton road network of congested road sections is developed on the basis of the genetic tabu algorithm. First, a traffic flow allocation model is established, and data are collected using microwave vehicle detectors and high-definition checkpoint video detectors. Subsequently, the congested sections of the main skeleton road network are analysed, and the discrete-time and continuous-time forms of the section state equation are introduced. Finally, drawing on the results of the state analysis, a flow-control equilibrium joint optimisation objective function is formulated. Finally, it is proposed to use the genetic tabu algorithm to solve the model, in order to obtain the optimal traffic flow allocation scheme and improve the network traffic rate of the main skeleton. Experimental results have shown that this method can effectively determine the impedance time function of congested road sections and complete the traffic flow allocation of the main skeleton road network of congested road sections. It effectively enhances the distribution of traffic volumes across individual sections and contributes to achieving a more balanced flow throughout the entire main skeleton road network.

KEYWORDS
genetic algorithm; tabu search algorithm; congested roadway section; main skeleton road network; traffic assignment; impedance time function.

1. INTRODUCTION

The main skeleton road network is the skeleton of the urban transportation system, which bears a large amount of traffic flow [1], and its operation efficiency directly affects the operation of the entire urban transportation system. However, with the increase in urban population and economic development, the rapid growth of motorised vehicles has led to more prominent traffic congestion [2], which has become one of the key factors restricting the city's sustainable development. Congestion not only leads to prolonged travel time, increased energy consumption and increased environmental pollution, but also affects the overall operational efficiency of the city and the quality of life of residents. Therefore, how to alleviate urban traffic congestion [3] and improve the operational efficiency of the transportation system have become important issues facing current urban traffic management. In the main skeleton road network of congested road sections, traffic flow distribution is one of the important means to alleviate traffic congestion. From the theoretical level, the study of the traffic flow distribution method of the main skeleton road network in congested road sections helps to enrich and improve the theoretical system of urban transportation planning and management [4]. Through the in-depth study of traffic flow distribution, it can further reveal the distribution law and operation mechanism of traffic flow in the urban road network, and provide more scientific theoretical support for urban traffic planning and management. From the practical point of view, the study of the traffic flow distribution method of the main skeleton road network in congested road sections has important application value. On the one hand, through the reasonable traffic flow distribution, it can optimise the allocation of traffic resources [5], improve the capacity of the road network, to alleviate the problem of urban traffic congestion. On the other hand, the study of traffic flow distribution methods can also provide decision-making support for urban traffic management to help the traffic management department formulate a more scientific and reasonable traffic control strategy, and to improve the efficiency and level of urban traffic management.

In recent years, scholars at home and abroad have conducted extensive research on traffic assignment and achieved rich results. For example, Xu Yuan et al. [6] considered both the regret avoidance psychology and travel behaviour habits of travellers in traffic assignment problems. They classified travellers according to their familiarity with different paths between starting and ending points, and constructed a multi-user random user equilibrium model that considers traveller path familiarity from the perspective of regret. We provide variational inequalities equivalent to the model and prove the existence of solutions. However, the trajectory data of high-frequency commuters (high familiarity) are easy to obtain, while the data of low-frequency travellers (such as tourists) are sparse. This results in excessive subjectivity. Xiao Deyuan et al. [7] developed a multi-path non-equilibrium traffic allocation probability model based on factors such as travel preferences and income levels, employing a shortest-path game approach to determine the corresponding route allocation strategy. The model was solved using a loss matrix and an objective function, thereby deriving the traffic assignment scheme. Subsequently, a genetic algorithm was incorporated into the allocation procedure, with a selection operator applied to eliminate individuals exhibiting low-quality chromosomes. The single-point crossover algorithm was used to generate new chromosomes, and the mutation operator was combined to find the globally optimal chromosome, which is the optimal allocation result. However, the shortest path game method requires the existence of a Nash equilibrium, but the heterogeneity of traveller preferences (hobbies, income) may lead to an equilibrium that is not unique or difficult to converge. Li Chunyang et al. [8] used the "four-stage method" of transportation planning as the basis and TransCAD as the platform. Based on the known road network, the OD traffic volume obtained in the first stage was used. Using the gravity model adopted in the second stage, according to the constraints of the traffic impedance matrix, it was reasonably allocated to each road in the road network through the user equilibrium allocation method in the fourth stage, thus obtaining the traffic flow of each section in the road network. However, the traffic impedance matrix (such as time and cost) relies on historical data, but sudden congestion or policy changes (such as traffic restrictions) can lead to model failure. He Shengxue et al. [9] proposed an improved method for gradually expanding the set of effective paths by continuously searching for the shortest path during the execution of projection gradient algorithms, and theoretically proved that the new method can ultimately determine the effective paths actually used between all starting and ending point pairs, and the corresponding path flow conforms to Wardrop's first principle. In order to improve the execution efficiency of projection operators in projection algorithms, this paper proposes an algorithm that does not require an iterative solution for accurate projection based on the characteristics of projection sets. By equivalently transforming the problem form, the casting shadow problem can be transformed into a simple traffic assignment problem for a road network. However, in large-scale road networks, the algorithm complexity of sequentially searching for the shortest path is O (n^2), making it difficult to update in real-time. Long Xueqin et al. [10] proposed a traffic allocation algorithm for congested conditions constrained by road segment capacity. In their approach, regret and indifference thresholds were incorporated into travellers' decision-making processes, taking into account psychological perception differences related to travel time and queueing time. On this basis, path-selection probability models were constructed for varying levels of traveller rationality. At the level of aggregation, considering the traffic capacity limitations of the current road section and its upstream and downstream sections, as well as the spatial queuing and overflow of vehicles on the road section, a correction method for the inflow and outflow of traffic flow on the road section is proposed. By using the incremental loading allocation method, the dissipation characteristics of vehicles on road sections were studied, and the evolution process from individual path decisions to macro road network states was reproduced. Based on the Nguyen-Dupuis simulation network, the congestion levels of vehicles, as well as the inflow and outflow on different road sections, are compared under different algorithms. However, the regret threshold and undifferentiated interval depend on questionnaire surveys and have subjective biases (such as differences in risk preferences among drivers in different cities).Hu Xiaomin et al. [11] proposed using different GP control inflation methods to limit the inheritance of large-sized individuals in the population, allowing the algorithm to find smaller and better-performinghyper-heuristic strategies during training. Considering that there may be performance differences in super heuristic strategies on different structured road networks, such as network formats, circular, radial and free-form, different structured road networks are used to train super heuristic strategies for analysis and comparison. The trained hyper-heuristic strategy is effective in large city road networks of different scales and traffic volumes. However, although the GP control inflation method limits large-sized individuals in the population, it does not explicitly model the mapping relationship between road network structure and strategy performance, resulting in a lack of topological adaptability in the strategy. Yue Hao et al. [12] divided the road network into local congested areas and local unobstructed areas based on congestion space queuing, and proved that under the condition of congestion interference, the time for different queue tails to pass through the bottleneck is equal. Secondly, a minimax demand loading path selection mechanism was proposed, which selects the shortest path in the global area and the longest path in the locally congested area. Finally, based on road segment coding, the demand compression and congestion backtracking algorithms were improved, and a congestion area recognition algorithm was proposed, and an iterative weighted solution algorithm was constructed. However, simply dividing the road network into "congested areas" and "unobstructed areas" ignores the gradient changes in congestion, resulting in an overly extreme path selection mechanism (shortest or longest path).

Based on this, a traffic assignment method for the main skeleton road network of congested road sections based on the genetic tabu algorithm is studied. This method innovates on the basis of traditional road segment state equations, introduces decision variables in discrete-time form, transforms model constraints into standard convex programming problems, and improves the road segment outflow rate function into a nonlinear convex programming problem. For the continuous time form, the W-F model divides road sections into blocked sections and free sections, and uses lag time to replace the influence of blocked sections, making the road section state equation more in line with actual traffic conditions and improving the accuracy and reliability of the model. Combining the genetic algorithm and tabu search algorithm, utilising the parallel search capability of the genetic algorithm and the local search capability of the tabu search algorithm, overcomes the limitations of a single algorithm, improves the solving efficiency and accuracy, and provides an effective method for solving the traffic assignment model of the main skeleton road network in congested sections.

2. TRAFFIC FLOW DISTRIBUTION METHOD FOR MAIN SKELETON ROAD NETWORK OF CONGESTED ROAD SECTIONS

2.1 Traffic flow distribution modelling of the main skeleton road network of congested road sections

Fundamentals of traffic flow assignment

If there are multiple paths between the origin and destination and the traffic flow between the two points is small, these traffic flows will be distributed on the shortest path. However, as the traffic flow on the shortest path increases [13], the travel time on the shortest path will become longer due to congestion, so that some road users will choose the second shortest road. Similarly, eventually, all the road sections between two points may be selected by road users. If all road users know exactly how long each road section takes and choose the shortest route, then the travel time of all used road sections between the final point of departure and the final point of destination will be the same; the travel time of the unused road sections will be longer. This state is called the equilibrium state of the network [14].

The object of traffic assignment in the main skeleton road network of the congested road section is traffic flow, to satisfy the conservation of the inflow and outflow traffic volume of the nodes of the main skeleton road network of the congested road section. In the traffic assignment model of the main skeleton road network of congested road sections, the basic principles and concepts of traffic assignment include:

1) Demand traffic, the traffic volume expected to participate in the distribution of traffic flow. It includes: OD demand traffic P^{OD} with origin O and destination D, the path demand traffic volume p^{OD} with origin O and destination D, and the required traffic volume Y_a allocated from the section a.
2) Allocated traffic volume, for the traffic assignment in the road network, is actually through the traffic volume. It includes: OD allocation traffic volumes F^{OD} with origin O and destination D, the path assigning traffic volumes f^{OD} with origin O and destination D, and the assigned traffic y_a of roadway a.

3) Roadway capacity u_a is the maximum assigned traffic that can be able to pass through the roadway a, and $y_a \le u_a$. When $Y_a > u_a$, the roadway is in traffic congestion; when $Y_a \le u_a$, the roadway is open to traffic.

Combined with the traditional smooth traffic flow distribution model, the basic assumptions of the traffic flow distribution model for the main skeleton road network of the congested road section include [15]:

1) The model is a fixed-demand traffic assignment, i.e. the OD traffic volume involved in the allocation does not vary with the traffic impedance in the road network, and the level of congestion on the roadway network does not affect the transportation needs of residents.
2) Drivers choose the route with the lowest traffic impedance according to the assigned traffic volume of the main skeleton road network.
3) The impedance function characterises the resistance of a road section and the relationship between traffic volume and travel conditions, and it is typically represented by two types of curves: a smooth-state curve and a congestion-state curve. The smooth-state curve shows a monotonically increasing trend as the allocated traffic volume rises, whereas the congestion-state curve exhibits a monotonically decreasing trend with increasing traffic volume.
4) When $Y_a > u_a$, the congestion state curve is used with the impedance function.
5) When $Y_a > u_a$, the traffic congestion occurs on the roadway, there is no congestion spreading phenomenon; congestion occurs only on the congested roadway, and the delayed traffic volume is delayed on the roadway in the form of changes in roadway density.

By describing the concepts of demand traffic and assigned traffic, it helps to understand how traffic flows are distributed on the road network.

Data collection and preprocessing

The traffic data used in this study mainly come from two types of traffic detection devices: microwave vehicle detectors and high-definition checkpoint video detectors. The three parameters of road section traffic flow detected by microwave vehicle detectors are mainly used for parameter calibration of dynamic traffic assignment models, such as providing full sample traffic flow information for dynamic OD estimation. The high-definition checkpoint device detects the recorded data of vehicles passing through the entrance lane of the intersection. Through licence plate matching processing, vehicle trajectory information can be extracted. In addition, the traffic flow information of the intersection lane can also be calculated from the vehicle passing records. Below, we will analyse the raw data collected by two types of detectors and perform corresponding data preprocessing.

1) Microwave data

By emitting microwave signals (typically at 10.525 GHz or 24.125 GHz) and receiving vehicle reflection signals, the presence, speed and flow of vehicles are detected. Each record of microwave data contains fields such as device number, lane number, date, time, flow rate, speed and occupancy rate. Among them, the device number is the unique identification of each device. The lane number is the lane number of the section where the microwave vehicle detector is located, numbered sequentially from the centre to both sides of the road. The date is the date on which the data record was generated. Time is the generation time of the data record. The number of vehicles represents the vehicles passing through the lane section during the time interval in which the flow record is located. The speed is the average speed of all vehicles passing through the time interval where the record is located. The occupancy rate is the time occupancy rate, which is the ratio of the cumulative duration of the microwave detector occupied by the vehicle within the time interval where the record is located to the length of the timing period.

Due to factors such as data transmission, device performance and environmental factors, there are often missing data records in microwave datasets. In order to improve the reliability of data, it is necessary to preprocess the collected raw data before using them. The purpose of missing data estimation is to estimate and complete missing data records based on known data, ensuring the integrity of the data. This article uses the random walk method to estimate missing data. The method takes the observed value of the same device at one time as the estimated value for the next time, and the calculation formula is:

$$\hat{X}_{t+1} = X_t \quad (1)$$

where $\hat{X}_{t+1}$ is the estimated parameter value at time t+1; X_t is the parameter observation value at time t.

2) High-definition checkpoint data

Same as microwave data. Each licence plate recognition data record contains fields such as device number, date, time, licence plate number and lane. Among them, the licence plate number is the actual licence plate of the recognised vehicle, which has undergone privacy processing in the example, but the licence plate is still used as the unique identity recognition of the vehicle during data processing. The high-definition checkpoint data have two purposes in this article. One is to determine the time sequence of the same vehicle appearing at each intersection through licence plate matching and extract the vehicle's driving trajectory. The second is to combine intersection channelisation information and high-definition checkpoint detection of passing vehicles to calculate the traffic flow of lane division at the entrance of the intersection.

The preprocessing of high-definition checkpoint data aims to extract the traffic flow and vehicle trajectory at the entrance of the intersection from the original passing record information, providing an accurate and reliable data basis for subsequent research. The preprocessing process of high-definition checkpoint data mainly includes five steps: a) deleting duplicate records; b) calculating the sampling rate of the computing device; c) calculating traffic flow statistics based on lane division; d) vehicle trajectory extraction; e) trajectory reconstruction. The specific steps are as follows:

1) Delete duplicate records

High-definition checkpoint equipment detects and tracks vehicles from video scenes based on digital image processing technology, and recognises vehicle licence plate information through character recognition algorithms. However, occasionally, there are cases where the same vehicle is recognised multiple times by the same device in a short period of time, manifested as continuous duplicate records in the data, which can lead to inaccurate traffic flow statistics and interfere with trajectory extraction. In order to remove these duplicate records, this article processes the data collected by each device as follows: first, sort the original data records using "date", "licence plate number" and "time" in sequence. Second, if the "date" and "licence plate number" of two consecutive data records are the same, calculate their time difference. Finally, if the time difference is less than a certain threshold (set to 5 seconds in this article), the two data records are considered duplicate records, and the data record with the later time is deleted. Repeat this process to delete all duplicate records.

2) Calculate device sampling rate

Due to various factors such as weather, lighting, licence plate pollution, occlusion and accuracy of character recognition, high-definition checkpoint equipment cannot fully detect all vehicles passing through the parking line and recognise their licence plates, resulting in missed detections or "unrecognised" licence plates. Therefore, high-definition checkpoint data can be considered as sampling data, and the sampling rate of the equipment is calculated by the following formula:

$$SR = \frac{n_i}{n_t} \times k_d \tag{2}$$

where n_i is the number of vehicles recognised by the device; n_t is the total number of records collected by the device; k_d is the device detection rate.

3) Lane-based traffic extraction

The lane flow or turning flow at the entrance of an intersection is an important data point for the parameter calibration of the dynamic traffic assignment model. Due to the fact that high-definition checkpoint data are sampled data, the lane flow obtained directly from statistics will be smaller than the actual flow. Therefore, it is necessary to expand the lane flow based on the device sampling rate. The specific formula is:

$$\hat{Y}_{ture} = \left[Y_{ture} / SR \right] \tag{3}$$

where $\hat{Y}_{ture}$ is the estimated value of lane traffic flow; Y_{ture} is the lane flow calculated from passing records; $[\cdot]$ is the symbol for rounding down operations.

4) Vehicle original trajectory extraction

The vehicle trajectory extracted based on high-definition checkpoint equipment data is defined as a sequence of intersection numbers passed by vehicles arranged in chronological order during a certain analysis period. The method for extracting vehicle trajectories is as follows: first, extract unique licence plate numbers from passing vehicle records and determine the number of vehicles in the study area during the analysis period. Second, for each vehicle, match its licence plate number in the passing record dataset, identify all device numbers that detected the vehicle, and arrange them in chronological order of detection. Finally, based on the correspondence between the device location and the intersection, the intersection number sequence passed by the vehicle is obtained, and the line connecting the location points is the vehicle's running trajectory.

5) Trajectory reconstruction

The vehicle trajectory extracted in step 4 cannot fully reflect the true driving path information of the vehicle, so it is necessary to reconstruct and complete these original trajectories. Trajectory reconstruction aims to estimate the driving path of a vehicle between two adjacent points based on the road network topology, original trajectory and travel time information, and uses the estimated path to complete the original trajectory, ultimately generating a complete driving trajectory that matches the road direction.

Analysis of congested road sections in the main skeleton road network

We conduct an analysis on the allocation of congested road segments in the main skeleton road network based on the trajectory information obtained from the vehicle dataset mentioned above. Different road segment state equations can lead to different traffic assignment results and even have unreasonable solutions, which have a significant impact on the model. Therefore, establishing the correct road segment state equation is particularly important. But in different DTA models, the equation of state for each segment is also different, mainly divided into two categories: based on discrete-time form and based on continuous time form. Whether in discrete time or continuous time form, the main variables of the road segment state equation include the number of vehicles present on the road segment, the inflow rate of the road segment, the outflow rate of the road segment, etc., and the variables have similar relationships. In the state equation of the road section, the variable relationship is shown in *Figure 1*.

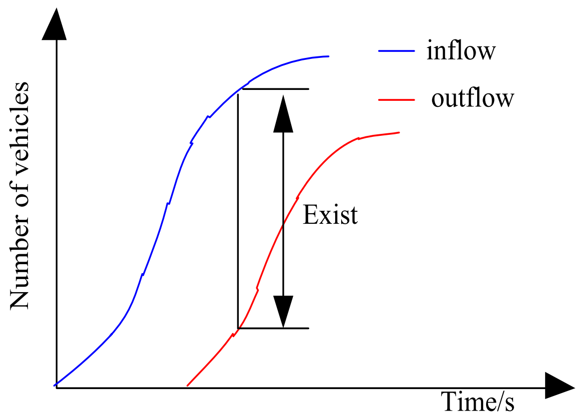


Figure 1 – Main skeleton road network model of a congested road section

1) Discrete-time form of road segment state equation

In the earliest dynamic traffic assignmentM-N model, the equation of the road segment state is:

$$x_a(t+1)=x_a(t)-g_a\left[x_a(t)\right]+u_a(t) \tag{4}$$

where $x_a(t)$ is the number of vehicles on road section a at time t, $g_a\left[x_a(t)\right]$ is a function of the outflow rate of a road section, and $u_a(t)$ is the inflow rate of vehicles on road section a at time t.

The above equation is a discrete-time form of the road segment state equation. This formula includes several main elements that determine the state equation of the road section, such as the traffic flow, inflow and outflow rates of the road section, and proposes that the outflow rate function $g_a\left[x_a(t)\right]$ of the road section that is related to the number of vehicles $x_a(t)$ present on the road section. But this equation is too simplified, ignoring the randomness and complexity of the real transportation network, which can easily lead to traffic flow "stagnation" problems. Therefore, the decision variable $b_a(t)$ vehicles heading towards the endpoint s on is introduced into the state equation of the road section to strengthen the flow control of the traffic flow flowing out of the road section. The state equation is:

$$x_a(t+1)=x_a(t)-b_a(t)+u_a(t) \tag{5}$$

The function of the decision variable $b_a(t)$ in the equation is to ensure that the model constraints satisfy the K-T condition of linear independence, which is transformed into a standard convex programming problem. At each time period, the traffic outflow of each road segment is greater than the decision variable $b_a(t)$, with the following constraints:

$$b_a(t)\leq g_a\left[x_a(t)\right] \tag{6}$$

The road segment outflow rate function $g_a\left[x_a(t)\right]$ in the above equation is different from *Equation 4*. *Equation 6* improves the road segment outflow rate function to a nonlinear convex programming, and in this model, the road segment outflow rate function $g_a\left[x_a(t)\right]$ satisfies the following conditions:

① $x_a(t)>g_a\left[x_a(t)\right]>0$;

② $x'_a(t)>g'_a\left[x_a(t)\right]>0$;

③ $g_a(0)$=0.

Condition ① indicates that the traffic volume and outflow of traffic on the road section are not negative, and the outflow of traffic on the road section at the same time is less than the traffic volume of the road section. In condition 2, the derivative $g'_a\left[x_a(t)\right]>0$ of the road outflow rate function indicates that the road outflow rate function is a single increasing function, while $g'_a\left[x_a(t)\right]$<1 is to ensure that it is a non-convex function. Condition 3 ensures that when the traffic volume of the road section is 0, the outflow rate of the road section is also 0. The outflow rate function of the road section is shown in *Figure 2*.

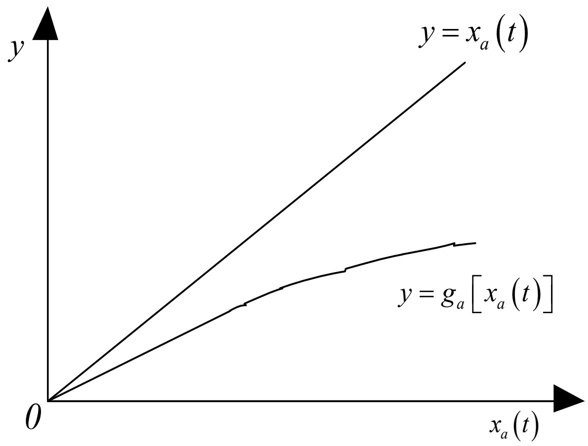


Figure 2 – Main skeleton road network model of the congested road section

In the figure, $y = x_a(t)$ represents the traffic volume of the road segment a at time t and is the independent variable. $y = g_a[x_a(t)]$ represents the actual outflow rate of the road segment a at time t, and is the dependent variable.

2) Continuous time form of road segment state equation

In the DTA model based on optimal control theory, the road segment state equation is represented in continuous time form. In the L-F model, the number of vehicles $x_a^s(t)$ heading towards the endpoint s on the road segment is used as the state variable, and the inflow rate $u_a^s(t)$ of vehicles heading towards the endpoint s on the road segment is used as the control variable. The road segment state equation is:

$$\begin{aligned} &\frac{dx_a^s(t)}{dt} = u_a^s(t) - g_a[x_a(t)] \\ &g_a[x_a(t)] = \xi_a x_a(t) \end{aligned} \tag{7}$$

In the equation, it is assumed that the outflow function of the road segment is a linear function related to $x_a(t)$, where ξ_a is the coefficient, determined based on the traffic capacity of the intersection of the road segment.

In order to better describe the road segment state equation in line with the actual traffic road conditions, the W-F model considers the road segment as two parts, namely the blocked road segment and the free road segment. The impact of the blocked road segment on the road segment is replaced by a lag time, and its road segment state equation is:

$$\begin{aligned} &\frac{dx_a(t)}{dt} = u_a(t - f_a) - \xi_a x_a(t) \\ &f_a = \frac{l_a}{v} \end{aligned} \tag{8}$$

where f_a is the free exercise time of the free road section; l_a is the length of section a; v is the velocity of free flow. f_a represents the lag time, which is the ratio of the length of the road section to the free flow velocity, that is, the time it takes for the vehicle to leave the road section at the fastest specified speed under clear road conditions. The introduction of lag time f_a reduces the length of the waiting queue for congested road sections to 0, which simplifies the model and quantifies the impact of previously difficult-to-calculate congested road sections on the operational status of the road section. This also avoids the influence of vehicles entering the road section that do not conform to reality on the outflow rate of the road section, and takes into account the congestion phenomenon of real traffic flow.

2.2 Objective function for traffic assignment in the main skeleton road network of congested road sections

Based on the state analysis results of congested sections in the main skeleton road network obtained in the previous section, design the objective function of the traffic assignment model for congested sections in the main skeleton road network. Introduce the congestion intensity factor $C_a(t)$, which is defined in conjunction with discrete/continuous state equations:

$$C_a(t) = \begin{cases} \int_0^t \left(x_a(t) - n_{crit}\right) + dt \\ \sum_{k=0}^{t/\Delta t} \left(x_a^s - n_{crit}\right) + \Delta t \end{cases} \tag{9}$$

where n_{crit} is the threshold for road segment capacity.

Define differentiated weights based on the traffic status indicator $\delta_a(t)$:

$$T_a(t)=\begin{cases} x_a^{free} & if\,\delta_a(t)=0 \\ x_a^{free}+\alpha\cdot\dfrac{C_a(t)}{q_{cap}} & if\,\delta_a(t)=1 \end{cases} \tag{10}$$

Incorporate the decision variable $b_a(t)$ into the objective function to form a flow control equilibrium joint optimisation:

$$J=\min\sum_a\left[\int_0^T T_a(t)\cdot u_a(t)dt+\beta\big(u_a(t)-b_a(t)\big)\right] \tag{11}$$

where $\beta\big(u_a(t)-b_a(t)\big)$ is the dynamic travel time cost; $\beta\big(u_a(t)-b_a(t)\big)$ is the cost of regulating the outflow rate, and β is the equilibrium parameter.

2.3 Constraints setting for traffic assignment on the main skeleton road network of the congested road sections

The constraints of the objective function for assigning traffic flows on the main skeleton road network of congested road sections are as follows:

$$\sum_i f_i^{OD}=p^{OD},\forall O\in R,\forall D\in\xi \tag{12}$$

where R is the set of all departure points in the road network; ξ is the set of all destination points in the road network. The constraints in Eq. represent the conservation relationship between the flow sum of the paths and volume OD, i.e. all volume OD should be fully allocated to the road network. That is, the traffic volume on all paths between the OD should be equal to the OD traffic volume.

$$f_i^{OD}\geq 0,\forall O\in R,\forall D\in\xi,\forall i\in I \tag{13}$$

where I is the set of all routes between a starting point O and destination points D. The constraints in Eq. are non-negative constraints on the flow rate of the routes, i.e. the value of the flow rate of all routes should be greater than zero.

Congestion state outflow rate coupling constraint:

$$b_a(t)\leq g_a\left[x_a(t)\right]\cdot\big(1-\delta_a(t)\big)+\kappa\cdot n_{crit}\cdot\delta_a(t) \tag{14}$$

when $\delta_a(t)$=1 (congestion), the forced outflow rate $b_a(t)$ does not exceed the maximum relief flow rate $\kappa\cdot n_{crit}$ (where κ ∈ (0,1) is the discharge coefficient). Establish a user-balancedtraffic assignment model for the main skeleton road network of congested road sections by combining the objective function and constraint conditions.

2.4 Solving the traffic assignment model of the main skeleton road network of the congested road section based on the genetic tabu algorithm

By applying the genetic tabu algorithm to solve the traffic assignment model developed for the main skeleton road network under congested conditions, it is possible to obtain both the minimum sum of travel-time function integrals across all road sections and the corresponding user-equilibrium traffic assignment scheme, thereby enhancing the overall traffic efficiency of the main skeleton road network.

Genetic algorithms, with their powerful global search capabilities, can quickly find regions close to the optimal solution from multiple points in the solution space [16-17]. The tabu search algorithm is good at conducting fine searches within local areas, avoiding repeated searches and falling into local optima through tabu tables and amnesty criteria [18]. The genetic tabu algorithm combines the advantages of both, first conducting a global search through the genetic algorithm to find the region close to the optimal solution, and then conducting a fine search within that region through the tabu search algorithm to converge to the global optimal solution faster [19-20]. This approach yields a high-quality traffic flow allocation scheme for the main skeleton road network under congested conditions.

The specific steps of the first phase are as follows:

Step 1: Encoding. It is the representation of the solution of the traffic assignment model of the main skeleton road network of the congested road section in the genetic algorithm, and the encoding of the solution is called a chromosome. According to the characteristics of the traffic assignment model of the main skeleton road network of the congested road section, the positive integer coding is constructed, and this representation consists of positive integers between directly generated n individual $1 \sim M$. Each arrangement constitutes a chromosome, i.e. a traffic flow distribution scheme for the main skeleton road network of a congested road section. n is the length of the chromosome, i.e. the number of road sections in the traffic assignment scheme of the main skeleton road network of congested road sections. The gene value of each gene is a positive integer, which represents the priority or weight of the corresponding road section in the traffic assignment, and this positive integer can be determined according to the congestion degree, capacity and expected flow of the road section. The loci (i.e. gene positions on the chromosome) are ranked by the congestion index of each road segment, with the highest-congestion segments assigned to the first loci. This design ensures that genetic operators prioritise critical segments during optimisation.

Step 2: Initial population generation. Randomly generate a population of a sequence of positive integers with a length of n, representing n critical roadway segments in the main skeleton road network. According to the characteristics of the problem, the assigned weight of each gene (i.e. each road section) is set to be a positive integer indicating its priority or ability to handle traffic flow. Based on the congestion index of road sections, this article selects priority optimized road sections by setting a reasonable threshold and uses them as the first independent optimization object. Construct an initial population using a random generation method, set the population size to N, initialize individuals to form an initial solution set, and lay the foundation for subsequent intelligent optimization algorithms. Due to the time-consuming problem of genetic algorithms, the initial population is now divided into multiple subgroups, allocated to different CPU cores for parallel evolution, and finally merged with elite solutions to shorten the single iteration time. Divide the initial population into N subgroups a (where a represents the number of CPU cores) to obtain subgroup $S_1, S_2 \cdots S_a$.

Each chromosome (i.e. traffic assignment scheme) needs to be tested for feasibility. In this problem, the feasibility test is completed based on the constraints in subsection 2.1.3. If a chromosome does not satisfy these conditions, it is deleted, and a new chromosome is randomly regenerated for testing until a population is generated that satisfies the conditions.

Step 3: The fitness function is used to evaluate the advantages and disadvantages of each chromosome (i.e. traffic assignment scheme). In the congested roadway main skeleton network traffic assignment problem, the inverse of the objective function in subsection 2.1.2 is used as the fitness value B .

Step 4: Selection operation. It is performed to select good individuals from the old population with a certain probability to form a new population (i.e. a new traffic assignment scheme) in order to reproduce the next generation of individuals. First, the probability of each individual being selected is determined based on its fitness value (the traffic assignment objective function of the main skeleton road network of the congested road section).

Calculate the relative fitness for individual z (i.e. traffic flow distribution scheme) with the following formula:

$$\hat{B}_z = \frac{B_z}{\sum_{m=1}^{M} B_m} \tag{15}$$

where B_z , B_m are the fitness value of the z , m individual.

In response to the z individuals (i.e. traffic assignment schemes), cumulative relative fitness from the first individual to the z individual is given by the following formula:

$$Q'_z = \sum_{m=1}^{z} \hat{B}_m \hat{B}_z \tag{16}$$

Within the interval of $Q'_{z-1} \leq \theta' \leq Q'_z$, selecting individuals z (i.e. traffic flow distribution scheme).

Step 5: Crossover operation. In this operation, two individuals are randomly selected from the population, and their chromosomes are exchanged and recombined. In this way, the quality characteristics of the parent strings are inherited by the offspring, resulting in the generation of new high-quality individuals. Based on the traffic flow distribution model of the congested main skeleton road network, three crossover operators are implemented: single-point crossover, two-point crossover and uniform crossover. In the crossover operation, a certain operator is randomly selected from the three kinds of crossover operators, and according to the crossover probability r to perform crossover operations. The formula for r is as follows:

$$r = \begin{cases} \theta \dfrac{B_0 - B'}{B_0 - B^*}, B' \geq B^* \\ Q'_z \theta \qquad\quad , B' < B^* \end{cases} \tag{17}$$

where B_0 is the maximum adaptation value of the population; B' is the adaptation value of the larger of the two individuals that crossed; B' is the average acclimatisation value of the population; θ is a random number.

Step 6: Mutation operation. The main objective is to maintain the diversity of the population. The mutation operation randomly selects an individual from the population, and then randomly changes some genes of the selected individual with a certain probability. Traffic assignment model for congested sections of the main skeleton road network, established in subsection 2.1, the 2-exchange mutation strategy is adopted. The mutation probability is calculated as follows:

$$\hat{r} = \begin{cases} \theta \dfrac{B_0 - B}{B_0 - B^*}, B \geq B^* \\ \theta \qquad\quad , B < B^* \end{cases} \tag{18}$$

where B is the fitness value of the mutant individual.

Step 7: Analysing whether the algorithm meets the iteration termination conditions $\left|B_{\tau,\max} - B_{\tau-1,\max}\right| \leq \varepsilon$, where, ε is a suitably small positive number. $B_{\tau,\max}$ is the maximum fitness value of the τ generation, $B_{\tau-1,\max}$ is the maximum fitness value of the $\tau - 1$ generation, the maximum fitness differences within τ generations are all less than ε, indicating that the genetic algorithm has basically come to a "standstill", the genetic iteration is terminated, and the best solution W of the traffic flow distribution model of the main skeleton road network of the congested road section is output. Each subgroup S_a independently runs the above explained genetic algorithm steps, and finally the main process collects the elite solutions W of all subgroups, merges them to generate a new generation global population W_{new}, thereby achieving efficient solving.

The specific steps of the second phase are as follows:

Step 1: Initial solution set. The best solution W_{new} of the traffic assignment model of the main skeleton road network in the first stage genetic algorithm is used as the initial solution of the tabu search algorithm.

Step 2: Tabu object. It refers to the object that is tabued in the tabu table (i.e. the traffic assignment scheme of the main skeleton road network of the congested road section), which is the reference for implementing the tabu. In the algorithm realisation, a global tabu table Z represents the set of forbidden objects. The tabu objects set by this algorithm are the gene positions exchanged in the two paths, i.e. the exchanged subtasks are stored in a tabu table, and these moves are forbidden in the current iteration.

Step 3: Unblocking and amnesty. Length of tabu $\hat{L}$ selects a constant. In the tabu search process, there may be a candidate set of all the objects (i.e. congested road section of the main skeleton road network traffic assignment scheme) that are all in tabu situation, then, there should be a selective "amnesty" on the tabu object, so that the algorithm can be carried out. The text chooses the following amnesty rule: when objects α_0 in $W(\alpha_0)$ all are tabu, select the best of the objects α from $W(\alpha_0)$ (i.e. the best traffic flow distribution scheme for the main skeleton road network of congested road sections), and release all tabu objects on $\alpha_0 \rightarrow \alpha$.

Step 4: Tabu search algorithm iterates until termination conditions. The algorithm sets the maximum number $\max \upsilon$ of tabu iterations. When the number of iterations exceeds $\max \upsilon$, the iteration terminates, and the optimal traffic assignment scheme for the main skeleton road network of the congested road section is output.

3. EXPERIMENTAL ANALYSIS

3.1 Experimental environment

A city's main skeleton road network is used as the experimental object. Given the large number of primary roads, a congested area is selected as the analytical unit. Accordingly, a model of the regional main skeleton road network for the congested sections is established, as shown in *Figure 3*.

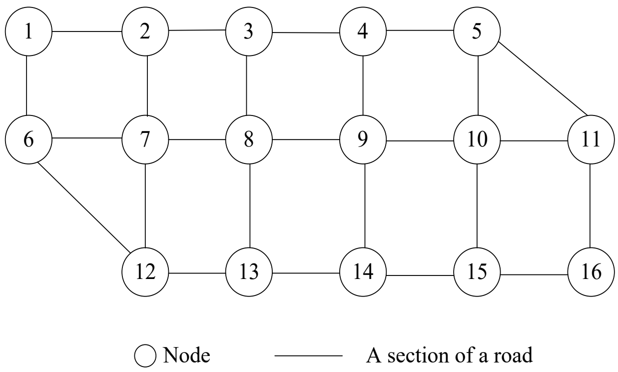


Figure 3 – Main skeleton road network model of the congested road section

There are 16 nodes and 25 road segments within the model of *Figure 1,* corresponding to starting 1, 16 nodes.

A localised image of the main skeleton road network in the area of this congested roadway is shown in *Figure 4*.

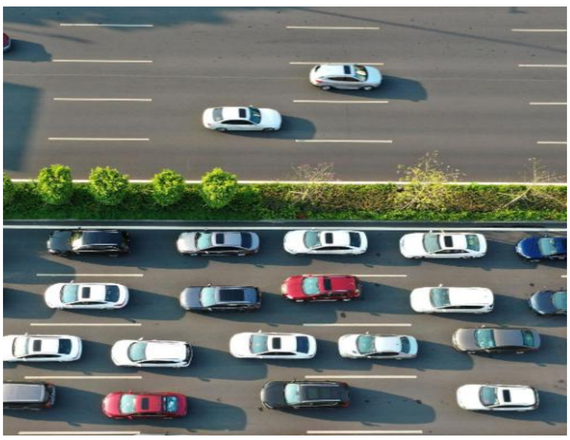


Figure 4 – Local image of the main skeleton network in the congested section area

The relevant attributes of the main skeleton road network in the area of this congested section are shown in *Table 1*.

Table 1 – Attributes of the main skeleton network in congested sections

A section of a road	Maximum traffic volume/(pcu/h)	Length /m	Maximum speed (km/h)	Free flow time /min	Congestion limit transit time /min
1-2	1400	800	60	0.8	5.41
2-3	1400	800	60	0.8	5.27
3-4	1400	800	60	0.8	3.95
4-5	1400	800	60	0.8	5.53
1-6	1400	800	60	0.8	4.55
2-7	1400	800	60	0.8	6.13
3-8	1400	800	60	0.8	5.21
4-9	1400	800	60	0.8	3.54
5-10	1400	800	60	0.8	4.79
5-11	1600	1200	60	1.2	7.81
6-7	1400	800	60	0.8	5.26
7-9	1400	800	60	0.8	5.05
8-9	1400	800	60	0.8	5.51
9-10	1400	800	60	0.8	5.27
10-11	1400	800	60	0.8	5.34
6-12	1800	1400	60	1.4	9.49
7-12	1500	1000	60	1.0	6.18
8-13	1500	1000	60	1.0	6.42
9-14	1500	1000	60	1.0	6.33
10-16	1500	1000	60	1.0	6.08
11-16	1500	1000	60	1.0	6.46
12-13	1400	800	60	0.8	5.62
13-14	1400	800	60	0.8	4.99
14-15	1400	800	60	0.8	5.38
15-16	1400	800	60	0.8	5.16

Table 1 describes the maximum capacity, length, maximum speed, free flow time and congestion limit passing time of each road section within the main skeleton road network of the congested road section area. Based on the basic environment, the specific experimental steps and related experimental data parameter settings are as follows:

1) Dynamic traffic demand generation

OD matrix construction: Based on the urban transportation planning report, generate an OD demand matrix for peak hours (7:00-9:00), which includes 120 pairs of OD pairs with 16 nodes. Partial examples: Node 1 → Node 16:1200 pcu/h; Node 6 → Node 12:800 pcu/h. The OD demand will be distributed within 15 minutes to simulate the time fluctuations of traffic flow.

2) Detector data simulation

Microwave data generation: Based on the road segment attributes in *Table 1*, use SUMO simulation software to generate flow data that conform to a Poisson distribution, and add 5% Gaussian noise to simulate equipment error.

High-definition checkpoint data generation: Based on a vehicle trajectory generation algorithm, simulate the records of vehicles passing through intersections, including licence plate number, equipment number, timestamp and other information.

3) Algorithm parameter configuration

Genetic algorithm parameters: Set the population size to 100 and the chromosome encoding length to 25 (corresponding to 25 road segments). Using the roulette wheel selection method, the probability of selection is directly proportional to the fitness value. Set the crossover rate to 0.8 and the mutation rate to 0.1, using two-point crossover and 2-exchange mutation strategies. The termination condition is set to stop iteration when the fitness improvement for 50 consecutive generations is less than 1%.

Tabu search parameters: Set the length of the tabu table to 50 to avoid circular searches. When all candidate solutions are tabu, choose the solution with the highest fitness. The maximum number of iterations is set to 100.

4) Model solving process

Phase 1: Global search using genetic algorithm;

Phase 2: Tabusearch local optimisation.

Verify the traffic flow allocation scheme for the main skeleton road network based on the above process.

3.2 Analysis of experimental results

The traffic assignment methods based on regret perspective in reference [6], the shortest path game-basedtraffic assignment method in reference [7] and the TransCAD-basedtraffic assignment method in reference [8] are used as comparison methods for this paper. The four methods are used to allocate traffic flow to the main skeleton road network of the congested section, and the allocation results are shown in *Figure 5*.

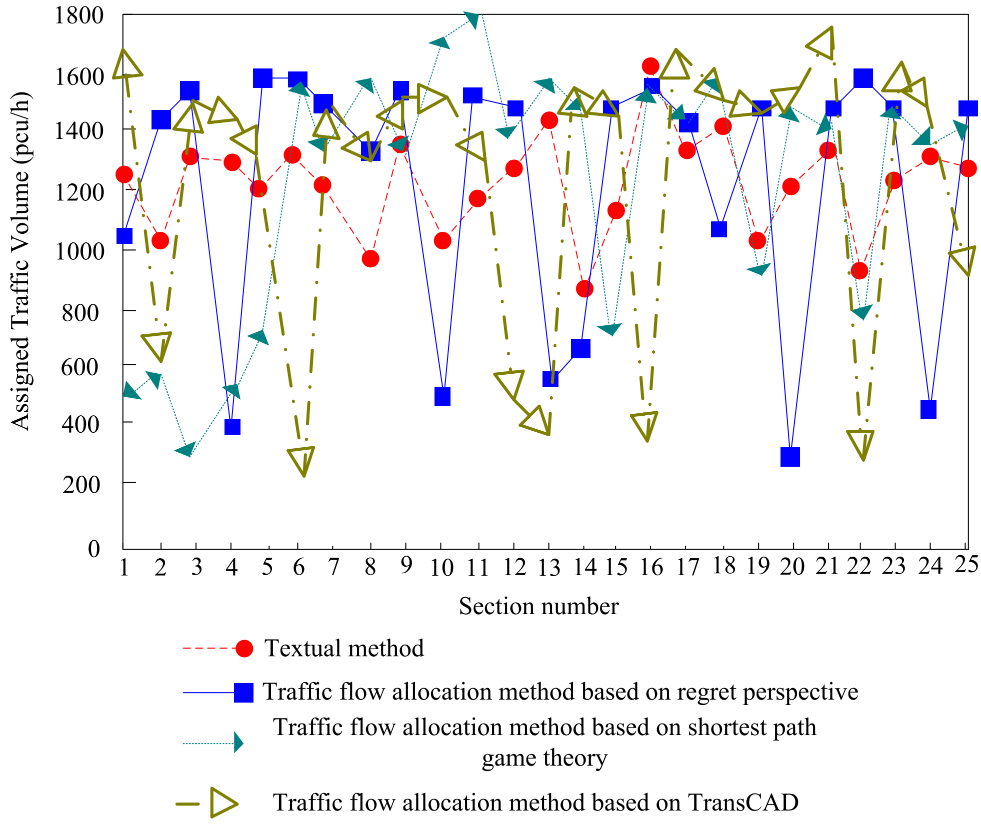
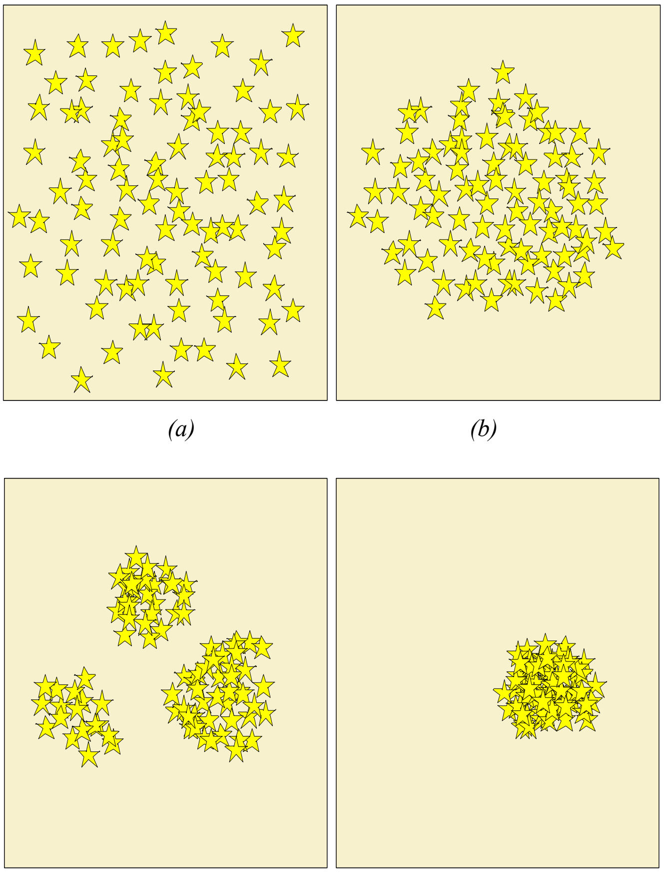


Figure 5 – Traffic flow distribution results of the main skeleton network of congested sections

From *Figure 5*, it can be seen that the method proposed in this paper can effectively allocate traffic flow in the main skeleton road network of congested road sections. Only the allocated traffic flow of road sections 8-9 exceeds the maximum traffic volume of that road section in *Table 1*; that is, only this road section is in a congested state. After being allocated by the method proposed in this paper, the rest of the road sections are not congested, indicating that the traffic assignment of the method proposed in this paper is relatively reasonable. After the traffic assignment method based on regret perspective, a total of 12 congested road sections were allocated, which exceeds the maximum communication volume of the corresponding road sections in *Table 1*, indicating that the traffic assignment of this method is unreasonable. After the shortest path game-basedtraffic assignment method, a total of 8 congested road sections were included, indicating that the traffic assignment of this method is unreasonable. After the traffic assignment method based on TransCAD, a total of 11 congested road sections were included, indicating that the traffic assignment of this method is unreasonable. Through comprehensive analysis, it can be concluded that the method proposed in this article ultimately allocates traffic flow to all road segments, and the resource allocation is reasonable. The number of congested road segments is reduced to one, indicating a high level of allocation rationality.

To evaluate the performance of the proposed method in solving the traffic flow distribution model for the main skeleton road network under congested conditions, the population size was set to 100 and the number of search iterations to 50. Upon completion of the iterations, all individuals converged to a single position, indicating a satisfactory solution quality and the absence of local optima. The effectiveness of the proposed solution method for the congested road-section traffic flow distribution model is illustrated in *Figure 6.*



(a) *(b)*

(c) *(d)*

Figure 6 – Results of solving the traffic flow distribution model of the main skeleton network of congested sections: a) Initialise; b) 10 searches; c) 30 searches; d) 50 searches

From the analysis of *Figure 6 (a)* to *Figure 6 (d)*, it can be seen that during initialisation, all individuals are evenly distributed in the entire feasible solution space. After searching, individuals continue to gather together. When the number of searches reaches 50, all individuals gather at a location, indicating that the convergence has been completed at this time, and they have not fallen into the local extreme value. The experiment shows that the method in this paper has a better effect on solving the traffic flow assignment model of the main skeleton road network in congested sections.

The changes in the allocation-demand traffic volume of the congested road section within the main skeleton road network before and after applying the method proposed in this paper are analysed. Taking road section 1–2 as an example, the analysis results are presented in *Figure 7*.

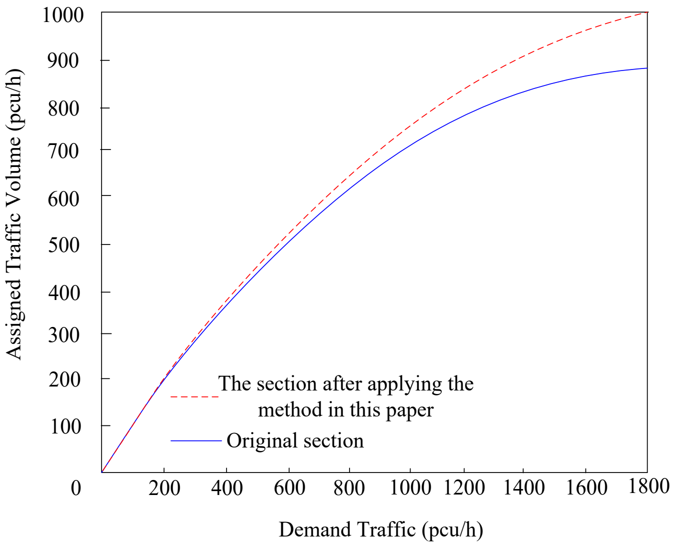


Figure 7 – Changes of the main skeleton network distribution-demand traffic volume in congested sections before and after the application of the proposed method

It can be seen from *Figure 7* that before and after the application of the method in this paper, the allocated traffic volume of sections 1–2 increases with the growth of the traffic demand. When the demand traffic volume exceeds 800 pcu/h, the allocated traffic volume after the application of the method in this paper is significantly higher than the original road network, and does not exceed the maximum traffic volume of this section, which indicates that the application of the method in this paper is helpful to guide the traffic flow that might have been congested in other sections (especially the alternative path parallel to or adjacent to section 1–2) to this section, this allocation not only alleviates the traffic pressure of other sections, but also promotes the flow equalisation of the whole main skeleton road network.

To further validate the practicality of the design method, the road network traffic rate test analysis was conducted, and the results are shown in the following figure:

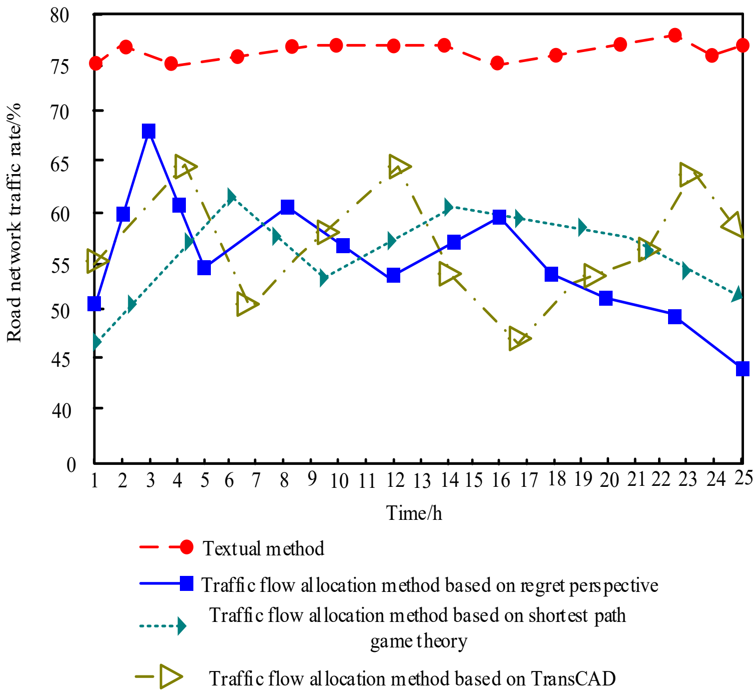


Figure 8 – Road network traffic rate test results

According to *Figure 8*, it can be seen that the method proposed in this paper can effectively allocate the traffic flow of the main skeleton road network in congested sections. Under 25 hours, the highest traffic rate reached 78% and remained between 70% and 80%. After the traffic assignment method based on regret perspective, the traffic rate ranges from 50% to 70% and fluctuates greatly. Based on the shortest path game traffic assignment method, the traffic rate ranges from 45% to 65%. After the traffic assignment method based on TransCAD, the traffic rate ranges from 45% to 65%. Through comprehensive analysis, it can be concluded that the genetic tabu algorithm proposed in this paper has demonstrated significant advantages in the traffic assignment problem of the main skeleton road network in congested road sections, with high traffic rates and stability.

To further validate the timeliness of the design method, simulate the duration of scheme generation in different congested road areas. Specifically set 5 case road sections: (1) 16 nodes, 25 road sections; (2) 32 nodes, 50 road sections; (3) 64 nodes, 100 road sections; (4) 128 nodes, 170 road sections; (5) 256 nodes and 250 road sections. The test results obtained are as follows.

Table 2 – Program generation time

Case	Textual method/s	Traffic flow allocation method based on regret perspective/s	Traffic flow allocation method based on shortest path game theory/s	Traffic flow allocation method based on TransCAD/s
1	8	20	18	30
2	25	69	57	89
3	80	179	164	201
4	160	355	302	432

Through gradient design of 4 cases (16 nodes to 256 nodes), the algorithm effectively covers scenarios ranging from small to large complex road networks, and can comprehensively verify its timeliness at different scales. In small-scale road networks (16 nodes, 25 sections), the text method takes only 8 seconds, which is the shortest time, while the traffic flow allocation method based on TransCAD takes 30 seconds, significantly higher than the method proposed in this paper. The text method takes 160 seconds on a large-scale road network (256 nodes, 250 sections), while the traffic flow allocation method based on TransCAD takes 432 seconds. This result indicates that the method proposed in this paper has higher generation efficiency and is based on practicality.

4. CONCLUSION

This article proposes a traffic flow allocation method for the main skeleton road network of congested road sections based on the genetic tabu algorithm. By formulating a flow-control equilibrium joint optimisation objective function and effectively addressing its solution through the integration of the genetic algorithm's global search capability and the tabu search algorithm's local optimisation capability, this approach provides an effective solution to urban traffic network congestion. The experimental results show that this method exhibits significant advantages in road networks of different scales. The method can quickly converge to the optimal solution without falling into local optima, and can maintain the smoothness of the road network under different demand traffic volumes, significantly improving the traffic rate. In addition, through road network decomposition and parallel computing technology, this method can efficiently handle large-scale road networks. Combined with GPU acceleration technology, it further improves computational efficiency and provides strong support for real-time traffic management. However, this method still has limitations such as high parameter sensitivity and computational cost increasing exponentially with scale. In the future, continuous improvement can be achieved through strategies such as parameter adaptive adjustment and behaviour authenticity modelling. Overall, this study provides an efficient and intelligent solution for urban traffic congestion control, with broad application prospects and important practical value.

5. DISCUSSION

Although the genetic tabu algorithm proposed in this article has demonstrated significant efficiency and stability in traffic flow allocation in congested road networks, its performance is still limited by parameter sensitivity, computational cost and model simplification assumptions. To further enhance the real-time optimisation capability of algorithms for large-scale road networks, future research needs to explore more advanced optimisation frameworks and draw on successful experiences in cross-domain problems. The following discussion will be conducted from two dimensions: algorithm innovation and cross-disciplinary applications.

1) The dynamic decision fusion of deep reinforcement learning, the D3QN algorithm proposed in reference [21], achieves real-time decision-making in dynamic flexible job shop scheduling through an ε-growth strategy and composite scheduling rules. This type of method can be applied to traffic scenarios: encoding road congestion status and OD demand fluctuations into a state space, designing multi-objective reward functions (such as delay time and fuel consumption), and dynamically adjusting allocation weights using D3QN. Compared to traditional static models, this framework can achieve closed-loop control of congestion prediction and path adjustment.
2) The traffic balancing of the adaptive differential evolution algorithm is achieved in traffic scheduling by introducing link balancing constraints and adaptive parameter adjustment in reference [22]. This type of mechanism can be applied to transportation networks: treating road traffic as “data packets”, designing congestion monitoring functions to dynamically adjust path selection probabilities, and optimising global traffic distribution through differential evolution operators.
3) Multi-objective optimisation of hyper-heuristic algorithms. The hyper-heuristic framework proposed in reference [23] achieves a balance between workstation reconstruction and multi-skilled worker allocation in assembly workshop scheduling by iteratively optimising heuristic rules through evolutionary operators. This type of algorithm can solve multi-objective conflicts in traffic signal control: encode green light duration, queue length and parking times as heuristic rules, and use a super heuristic to automatically select and combine constructive/perturbation operators. The sensitivity problem of parameters in traffic flow allocation is expected to be alleviated through operator self-adjustment.

By integrating cross-domain technologies such as deep reinforcement learning, adaptive differencing and hyper-heuristic algorithms, traffic flow assignment methods are expected to overcome current limitations. This process not only requires algorithm innovation, but also deep integration of multiple disciplines such as transportation, computer science and operations research to address the complex challenges of future smart cities.

REFERENCES

[1] Hamdan S, et al. Central authority-controlled air traffic flow management: an optimization approach. *Transportation Science*. 2022;56(2):299-321. DOI: 10.1287/trsc.2021.1087.

[2] Jain R, et al. An improved traffic flow forecasting based control logic using parametrical doped learning and truncated dual flow optimization model. *Wireless Networks*. 2022;28(7):3101-3110. DOI: 10.1007/s11276-022-03020-x.

[3] Cui H, et al. Traffic flow allocation and optimization decision based on unblocked reliability of open community. *Operations Research and Management Science*. 2022;31(2):8-14. DOI: 10.12005/orms.2022.0036.

[4] Idrissi O, et al. Improving the management of air traffic congestion during the approach phase. *The Aeronautical Journal*. 2023;127(1316):1752-1773. DOI: 10.1017/aer.2023.20.

[5] Khan H, et al. Machine learning driven intelligent and self adaptive system for traffic management in smart cities. *Computing*. 2022;104(5):1203-1217. DOI: 10.1007/s00607-021-01038-1.

[6] Xu Y, Liu K, Lu K. A traffic assignment model based on regret perspective considering travelers’ route familiarities. *Journal of Systems & Management*. 2024;33(6):1471-1482. DOI: 10.3969/j.issn2097-4558.2024.06.007.

[7] Xiao D, Liang T. Multipath unbalanced traffic flow assignment based on shortest path game. *Journal of Wuhan University of Technology (Transportation Science & Engineering)*. 2024;48(6):1075-1080. DOI: 10.3963/j.issn.2095-3844.2024.06.009.

[8] Li C, Wu Z. Traffic flow distribution of Wuhan metropolitan area highway network based on TransCAD. *China ITS Journal*. 2024;(2):166-172. DOI: 10.13439/j.cnki.itsc.2024.02.044.

[9] He S. Network traffic assignment method based on gradually extending the set of effective paths. *Journal of Wuhan University of Technology (Transportation Science & Engineering)*. 2021;45(5):817-821. DOI: 10.3963/j.issn.2095-3844.2021.05.002.

[10] Long X, Wang R, Wang H. Traffic flow assignment method considering travelers' different rational degree under congestions. *Journal of Transportation Systems Engineering and Information Technology*. 2023;23(1):216-223. DOI: 10.16097/j.cnki.1009-6744.2023.01.023.

[11] Hu X, et al. Traffic flow optimization bloat control genetic programming algorithm. *Application Research of Computers*. 2025;42(1):171-176. DOI: 10.19734/j.issn.1001-3695.2024.05.0177.

[12] Yue H, et al. Iterative weighted algorithms of static congestion traffic assignment considering spatial queuing. *Journal of Jilin University: Engineering and Technology Edition*. 2024;54(1):136-145. DOI: 10.13229/j.cnki.jdxbgxb.20220214.

[13] Zhu X, et al. Discrimination of urban traffic congestion segment based on bus floating vehicle data. *Journal of Wuhan University of Technology (Transportation Science & Engineering)*. 2021;45(4):666-671. DOI: 10.3963/j.issn.2095-3844.2021.04.010.

[14] Cui S, Bu C. Simulation of automatic identification of traffic congested road section information under deep learning. *Computer Simulation*. 2023;40(7):100-104. DOI: 10.3969/j.issn.1006-9348.2023.07.018.

[15] Xu P. Multi-modal traffic assignment model and algorithm for an urban agglomeration considering entire travel process. *Shandong Science*. 2022;35(1):11. DOI: 10.3976/j.issn.1002-4026.2022.01.012.

[16] Palacios-Morocho E, Inca S, Monserrat JF. Multipath planning acceleration method with double deep R-learning based on a genetic algorithm. *IEEE Transactions on Vehicular Technology*. 2023;72(10):12681-12696. DOI: 10.1109/TVT.2023.3277981.

[17] Zhang L. Design of intelligent control system for traffic congestion on narrow roads based on Beidou Satellite. *Computer Measurement &Control*. 2020;28(4):121-125. DOI: 10.16526/j.cnki.11-4762/tp.2020.04.025.

[18] Hanafi S, et al. Tabu search exploiting local optimality in binary optimization. *European Journal of Operational Research*. 2023;308(3):1037-1055. DOI: 10.1016/j.ejor.2023.01.001.

[19] Casado A, et al. A GRASP algorithm with tabu search improvement for solving the maximum intersection of *k*-subsets problem. *Journal of Heuristics*. 2022;28(1):121-146. DOI: 10.1007/s10732-022-09490-8.

[20] LiuH, Claudel C, Machemehl R. Robust traffic control using a first order macroscopic traffic flow model. *IEEE Transactions on Intelligent Transportation Systems*. 2021;23(7):8048-8062. DOI: 10.1109/TITS.2021.3075225.

[21] Yang D, et al. A dynamic flexible job shop scheduling method based on deep reinforcement learning. *Modern Manufacturing Engineering*. 2025;2(7):10-16. DOI: 10.16731/j.cnki.1671-3133.2025.02.002.

[22] Zong C, et al. Time-sensitive network traffic scheduling based on adaptive differential evolution algorithm. *Application Research of Computers*. 2025;42(6):1838-1843. DOI: 10.19734/j.issn.1001-3695.2024.12.046.

[23] Zhang J, et al. Reconfigurable assembly shop scheduling based on hyper heuristics algorithms. *Computer Integrated Manufacturing Systems*. 2025;31(2):399-410. DOI: 10.13196/j.cims.2024.0052.