A Bi-Level Multi-Objective Optimization Model for Micro-Circulation Road Networks in the Open Block Area Considering Traffic Pollution and Intersection Delays

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ABSTRACT It is important for urban traffic micro-circulation to improve the density of urban branch road networks by opening roads inside blocks. To reasonably optimize the micro-circulation road network in the open block area, a bi-level multi-objective programming model that considers traffic pollution and intersection delays was developed. In this paper, the goals of minimizing traffic pollution and total travel cost are added to the upper-level programming model and the user equilibrium assignment model with the consideration of intersection delay was presented as the lower-level programming model. A modified genetic algorithm (GA) embedded with the Frank-Wolfe algorithm was designed to solve the established model. The traffic conditions of arterial roads and micro-circulation branch roads before and after optimizing the micro-circulation block road network were compared and analyzed by a numerical example. The results demonstrated that the bi-level programming model can effectively determine the traffic direction of branch roads and the forbidden situation of intersections in the micro-circulation network. Compared with the closed block, the average saturation of the main trunk road decreased from 0.97 to 0.83 with a decline ratio of 14.43% after optimizing the micro-circulation network in the open block area; the average saturation of the secondary trunk road decreased from 0.86 to 0.77, with a decline ratio of 10.47%. The travel time cost decreased by approximately 6.55%, and the traffic pollution decreased by approximately 3.40%, which verified the optimization effect of the model and the algorithm.

INDEX TERMS Urban traffic micro-circulation, open block, road network optimization, bi-level multi-objective programming model, genetic algorithm.

I. INTRODUCTION

With the rapid development of China's urbanization and the substantial increase in the number of private cars, traffic congestion has become one of the bottlenecks restricting the future development of cities. The prevailing approach of ''wide road, low density'' proposed in the past has been unable to meet the traffic demand, and the road network pattern of ''focusing on trunk roads, ignoring branch roads'' has gradually suffered from disadvantages. When the trunk road is congested, the internal roads in the closed blocks are left unused, which leads to unreasonable road grading and a reduction of the entire road network capacity. It is important to alleviate traffic congestion and enhance mobility within a city by opening internal roads associated with closed blocks and integrating them into the urban branch road network system to divert part of the traffic flow of trunk roads and increase urban traffic micro-circulation.

A. LITERATURE REVIEW

Urban roads are the veins of the city, and blocks are the places where human activity occurs. Roads and blocks are two main elements that people perceive the overall image of the city [1]. In China, almost all new urban residential

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communities have been closed blocks since the housing reform during the 1980s [2]. Closed blocks generally have strict boundaries, and automobiles cannot pass through them; Currently, the construction scale on closed blocks is continuously increasing. The large number of closed blocks not only destroy the layout of the urban road network but also reduce the branch road density of the city and lead to traffic congestion [3].

Branch roads are the "capillary vessels" of the urban road network. It is important to form an urban road network system with the coordination of expressways, main and secondary trunk roads and branch roads. As early as 1998, Hai and Michael proposed that adding branch roads in the urban road network would greatly improve the efficiency of the road network and reduce travel costs [4]. Szeto *et al.* established a multi-objective programming model and obtained the optimal road network design with an artificial bee swarm algorithm, which verified that branch roads play an irreplaceable role in the urban road network [5].

However, closed blocks cut off the "capillary vessels" of urban road networks so that the traffic flow is concentrated on a few main city roads [6]. Roitman proposed that closed blocks interrupt the urban road network, reduce the density of urban branch roads and cause traffic congestion on urban trunk roads [7]. Handy *et al.* summarized the plans of 11 U.S. cities to improve the connectivity of residential streets and then found that connecting the end breaking roads caused by closed blocks can improve the accessibility of urban roads and reduce urban traffic conflicts [8].

To solve this problem, the urban planning policy in which an "open block" is used was put forward for the first time by the State Council of the People's Republic of China in 2016 [9]. The policy pointed out that the idea of "narrow streets and a dense network" should be gradually promoted. Moreover, the policy encouraged opening closed blocks to optimize the micro-circulation road network structure and to share internal roads with the public [10]. The traffic micro-circulation of road networks in open block areas is essential. The addition of block roads as part of the urban road network can obviously increase the branch road density, promote urban traffic micro-circulation and improve the operation quality of the road network [11].

In the literature, a large body of studies have been carried out focusing on urban traffic micro-circulation and open blocks [12]–[15]. Feng *et al.* proposed that the traditional closed block structure will no longer be applicable but will be replaced by an open block with more advanced concepts and more adapted to the requirements of modern urban development [16]. Grant J. proposed that the planning and construction of blocks should aim at the accessibility of roads so that people can carry out various activities within the acceptable range of walking [17]. Christopher *et al.* proposed that reasonable and effective design of traffic micro-circulation routes and intersections can alleviate urban traffic congestion to some extent [18]. Tam *et al.* and Lammer *et al.* indicated that grid-like urban traffic micro-circulation

systems can increase the number of travel paths and alleviate urban traffic congestion [19], [20]. Shi *et al.* summarized the functional characteristics of the urban traffic micro-circulation network, established an optimization model and designed an intelligent solution algorithm to solve the model [21]. Wang and Ding established a bi-level programming model for the optimization of traffic micro-circulation in historical blocks, which can relieve the traffic pressure of trunk road networks and improve the overall operation efficiency of the block network [22]. In essence, open blocks are an increase in the supply of transportation resources. Dong *et al.* proposed that after opening the closed blocks, the density of the road network will be improved and the road area can increase, a result of which the road traffic capacity is naturally improved [23]. Zeng *et al.* proposed that open blocks have a significant effect on the improvement of network performance and capacity and found that breaking "large blocks" and developing small-scale blocks can help to alleviate traffic pressure [24]. Zhang *et al.* studied the specific impact of different block sizes on urban traffic and analyzed the variation in generalized travel costs of transportation modes with block sizes [25]. Luo *et al.* established a bi-level programming model to optimize the block road network based on the detour distance and the average ultra-limited saturation of roads [26]. There are also studies exploring the degree of openness of closed blocks by using a number of measurable indicators, such as road capacity, traffic delay, queue length, road service level, and so on [27].

However, people who oppose the open concept are afraid that it may result in traffic pollution in their living environment, especially when the block area is congested or an intersection is added. On a congested road network, frequent starting and braking activities increase the amounts of emissions. Therefore, it is significant to ensure that the block area will not be congested after opening. According to a literature review, we find that some studies have incorporated environmental impact as design objectives in road network design problems. For example, Pternea *et al.* established a nonlinear programming model for the road network design problem that considered environmental impacts and designed an iterative approach combined with GA to solve the model [28]. Qiang *et al.* presented some energy-efficiency models of sustainable urban transport structure optimization and solved the models via the artificial fish swarm algorithm [29]. Some studies have confirmed that traffic pollution can be reduced with a reasonable road network design and traffic control [30].

B. FOCUS OF THIS STUDY
The above literature review reveals that there are many studies on directing urban traffic micro-circulation through open blocks. However, few articles have studied open block micro-circulation road networks from the perspective of traffic pollution and intersection delays. The impact of traffic pollution emitted by passing vehicles on block residents' normal lives and the impact of the increasing number of

intersections on road network impedance have rarely been discussed in the existing literature. In addition, it is not particularly clear whether block openness can optimize the micro-circulation network structure and improve traffic efficiency. Moreover, most of the studies set the branch roads in the open blocks as two-way traffic, resulting in a lower traffic efficiency of the road network. Therefore, to some extent, it should be further investigated.

To this end, this study aims to concentrate on the optimization of the road network in open block areas from a more comprehensive perspective. In this paper, the goals of minimizing traffic pollution and total travel cost are added to the upper-level programming model. In addition, the traffic direction decision variable of the micro-circulation branch road and the traffic prohibition decision variable of the intersection virtual turning link are introduced, and the traffic allocation model considering the intersection delay is presented as the lower-level model. After using the bi-level model, the micro-circulation road network of the open block area is optimized, and a more reasonable traffic organization plan is obtained.

In summary, the contribution of this work lies in the following aspects.

(1) A bi-level multi-objective programming model considering traffic pollution and intersection delays was proposed to optimize the micro-circulation road network design in open block areas. The model is able to minimize traffic pollution and the total travel cost while alleviating traffic congestion.

(2) A user equilibrium assignment model under fixed traffic demand with the consideration of intersection delay was presented as the lower-level programming model.

(3) A modified genetic algorithm (GA) embedded with the Frank-Wolfe algorithm was designed to solve the established bi-level programming model.

(4) A numerical example was used to test the effectiveness of the proposed model and solution algorithm on different designs of open block networks.

The rest of the paper is organized as follows: Section 2 presents the analysis of the micro-circulation road network optimization problem in open block areas. Section 3 presents the problem formulations, and the bi-level multi-objective programming model is proposed. Section 4 develops the detailed steps of the modified genetic algorithm. Section 5 illustrates the proposed model by a case study. Section 6 presents final remarks and future work.

II. MICRO-CIRCULATION ROAD NETWORK OPTIMIZATION PROBLEM IN OPEN BLOCK AREA

In China, the open block concept is currently in the early stage of development. It should be noted that a block can be opened gradually rather than in one step. Whether the closed block should be open and how to optimize open blocks must be analyzed according to specific conditions. Once a block is opened, it is necessary to ensure that the internal branch roads can divert a certain amount of traffic flow. Since the width of the internal branch road in the block is very

limited, the determination of the traffic direction of the branch road is very important to the optimization of the micro-circulation road network in the open block area. Moreover, intersections are bottlenecks that restrict the traffic capacity of the entire road network, and the number of intersections may increase after the opening of the block. To optimize the road network more realistically, the consideration of turning delays at intersections should not be ignored and it is necessary to determine the ban on straight, right and left. Therefore, a bi-level programming model is established in this paper to optimize the micro-circulation road network in open block areas to ensure that the micro-circulation road network can better alleviate traffic congestion in urban trunk roads.

Not all of the closed blocks need to be opened when the government re-plans the network [10]. For the selection of traffic open blocks, the following principles are suggested in this paper.

(1) The block properties make it suitable for opening to the public. In reality, some blocks cannot be opened, such as government courtyards, school lands, private territories, etc.

(2) The structure and scale of the block should be suitable for opening, and there should be available road resources inside. Generally, grid-like network blocks are considered the first choice for opening.

(3) The density of branch roads in the open block area is too low. In addition, when selecting the opening target, the block surrounded by traffic congestion is given priority. If there is no traffic congestion in the road around the closed block, it is of slight significance to open it.

III. PROPOSED METHODOLOGY

The optimization of micro-circulation road networks in open block areas is a typical bi-level programming problem. The upper-level problem represents the traffic authority's decisions with multiple objectives, and the lower-level problem represents the traffic users' decisions based on the upper-level road network design. The upper level is constrained by the optimal solution set of the lower level. In this paper, a bi-level multi-objective optimization model is constructed to optimize the micro-circulation road network in the open block area.

A. ROAD NETWORK REPRESENTATION

In this paper, it is assumed that the intersections in the road network are all unsignalized, and the extended network method is adopted to add 12 virtual turning links at each intersection. Adding virtual turning links to the network just increases the size of the network and does not change the original structure [31]. To make the model further realistic, each intersection is simplified as a node, and the traffic network is simplified into a lattice road network $G = \{V, A \cup B(y) \cup C(z)\}$.

In this paper, the symbols are used to signify the general road network. The notations are listed in Table 1.

TABLE 1. Notations and their definitions.

Symbol	Description
V	the set of road network nodes
A	the set of main and secondary trunk roads in the micro-circulation road network
$B(y)$	the set of candidate micro-circulation branch roads inside the blocks
$C(z)$	the set of intersection virtual turning links in the micro-circulation road network
a, b	the roads in the network, $a, b \in A \cup B(y)$
c	the intersection virtual turning link from road a to road b, where $c \in C(z)$
l_a	the length of road a
$C(a)$	the transport capacity of road a
$S(a, y)$	the saturation of road a, which means the ratio of road traffic flow to road capacity
$\overline{S}(a)$	the upper limitation of saturation of road a
$x(a, y)$	the traffic flow on road a
$x(c, z)$	the traffic flow on virtual turning link c
$t_a(x(a, y))$	the road impedance function of road a
$d_c(x(c, z))$	the virtual turning link impedance function of link c
r	a starting node generated to travel
s	a final destination node attracted to travel
f_k^{rs}	the traffic flow on path k between OD (origin-destination) pair r and s
q_{rs}	the traffic demand between OD pair r and s
v_i	a road network node which number is i
v_j	a road network node which number is j

The decision variables in this paper are listed below.

$y(a)$, $a \in B(y)$: the traffic direction decision variable of the micro-circulation branch roads in open blocks. For road $a = (v_i, v_j)$, $i < j$, $y(a) = 0$ indicates that road a is a two-way road, $y(a) = 1$ indicates that road a is a one-way road from node v_i to v_j, and $y(a) = -1$ indicates that road a is a one-way road from node v_j to v_i. Road capacity $C(a)$ is related to the decision variable $y(a)$ and has uncertainty. In this paper, it is assumed that the traffic capacity of both two-way roads and one-way roads is known. Therefore, regardless of the value of $y(a)$, the corresponding capacity value of the road can be obtained immediately.

$z(c)$, $c \in C(z)$: the traffic prohibition decision variable of the intersection virtual turning link c in the micro-circulation road network. $z(c) = 0$ indicates that the virtual turning link c is selected, and $z(c) = 1$ indicates that the virtual turning link c is prohibited.

B. OPTIMIZATION OBJECTIVES

From the point of view of controlling traffic pollution, reducing traffic congestion and minimizing total travel cost, the optimization objectives of the optimization problem can be analyzed from the following aspects.

1) THE TRAFFIC POLLUTION OF MICRO-CIRCULATION ROAD NETWORK

In terms of traffic pollution, the most important objective to consider is to minimize the impact of harmful gases on the lives of residents in open block areas. The block road network must be improved by better balancing traffic flow and environmental risks. After opening the block, there is no doubt that the exhaust gas emitted by vehicles while travelling within the open block area will seriously pollute the block environment and endanger the physical and mental health of residents. However, even if the block is not open, the traffic pollution caused by the surrounding traffic congestion still affects the lives of the residents in the block area, which depends on the traffic operation status of the area road network. Therefore, it is inappropriate to refuse to open blocks on the grounds of pollution. The block opening from the perspective of the long-term development of urban traffic must be considered.

Traffic emissions mainly include carbon monoxide (CO), nitrogen oxides (NOx), hydrocarbons (HC) and so on [32]. Among the varieties of traffic emissions, CO is considered as an important indicator of the level of air pollution [31]. For the sake of simplification, vehicular CO emissions were used as the only evaluation factor to measure traffic pollution, and the minimum CO emissions were taken as one of the important optimization objectives to ensure that the block residents had a relatively healthy living environment.

According to Yin and Lawphongpanich [33], the CO per vehicle discharged on road a can be expressed as:

$$Pa\left(x\left(a, y\right)\right) = 0.2038 \times ta\left(x\left(a, y\right)\right) \times e^{0.7962(la/ta(x(a,y)))} \tag{1}$$

Then, the traffic pollution minimization objective of the micro-circulation road network in the open block area can be expressed as:

$$\min \sum_{a \in A \cup B(y)} 0.2038 \times ta\left(x\left(a, y\right)\right)$$
$$\times e^{0.7962(la/ta(x(a,y)))} \times x\left(a, y\right) \tag{2}$$

2) THE AVERAGE ULTRA-LIMITED SATURATION OF TRUNK ROADS

The ultra-limited saturation reflects the degree to which the road saturation exceeds the upper limitation of saturation [26]. Minimizing the average ultra-limited saturation of trunk roads is the main optimization objective to ensure the smooth operation of trunk roads, which can be expressed as:

$$\min\left\{\sum_{a \in A} la \times \max\left\{S\left(a, y\right) - \overline{S}\left(a\right), 0\right\} / \sum_{a \in A} la\right\} \tag{3}$$

Since the main goal of micro-circulation road network optimization in open block areas is to shunt traffic from trunk roads, the saturation of trunk roads must always be less than a limit value, which can be expressed as:

$$S\left(a, y\right) = \frac{x\left(a, y\right)}{C\left(a\right)} \leq \overline{S}\left(a\right), a \in A \tag{4}$$

3) THE AVERAGE SATURATION OF MICRO-CIRCULATION BRANCH ROADS

The optimization emphases of trunk roads and micro-circulation branch roads are different. While alleviating the traffic pressure on the trunk road, it is also necessary to ensure that the

the smooth operation of the micro-circulation branch road in the block area.

The minimum average saturation of micro-circulation branch roads is an important indicator to ensure the smooth and efficient operation of the branch road network, which can be expressed as:

$$\min \sum_{a \in B(y)} la \times S(a, y) / \sum_{a \in B(y)} la \tag{5}$$

Once the micro-circulation branch road is congested, it will have a significant impact on the normal life of the residents. Therefore, the saturation of micro-circulation branch roads must also be lower than a limit saturation, which can be expressed as:

$$S(a, y) = \frac{x(a, y)}{C(a)} \le \overline{S}(a), a \in B(y) \tag{6}$$

Considering that the limit saturation constraint of branch roads can be achieved by restricting the flow entering the micro-circulation branch roads, which can be expressed as:

$$x(a, y) \le \overline{S}(a) C(a), a \in B(y) \tag{7}$$

4) THE TOTAL TRAVEL COST OF MICRO-CIRCULATION ROAD NETWORK

According to the economic utility maximization theory, the travel cost of traffic travelers in the micro-circulation road network of open block areas is related to the time and money. For the sake of simplicity, this article quantifies the travel cost uniformly as the time cost, that is, the total travel cost is equal to the sum of the road impedance and the intersection turning delay. Therefore, the minimum total travel cost of the micro-circulation road network can be expressed as:

$$\min \left(\sum_a x(a, y) \times ta(x(a, y)) + \sum_c x(c, z) \times dc(x(c, z)) \right) \tag{8}$$

C. MODELING

In conclusion, the optimization problem of the micro-circulation road network in the open block area can be described by constructing a bi-level multi-objective model. The two groups of variables in the upper-level model are the traffic direction decision $y(a)$ and the traffic prohibition decision $z(c)$. The weighted sum of the traffic pollution, the average ultra-limited saturation of trunk roads, the average saturation of micro-circulation branch roads and the total travel cost of the micro-circulation road network are calculated in the upper-level model to be minimal. The lower-level traffic assignment model assigns the traffic demand to the road network and obtains the road flows [34]. In this paper, the traffic allocation model under fixed demand considering the intersection delay is selected as the lower-level model [35].

Considering the complexity of the multi-objective optimization problem and the actual characteristics of the

four objective functions, the linear weighting method was adopted to introduce four nonnegative equivalence factors $\xi 1, \xi 2, \xi 3, \xi 4$ for the built multi-objective optimization model, and four optimization objectives in the upper-level model were converted into an equivalent single objective optimization function.

As a result, the multi-objective bi-level model can be formulated as follows:

The upper-level model is expressed as follows:

$$\min Z(y) = \xi 1 \left\{ \sum_{a \in A \cup B(y)} 0.2038 \times ta(x(a, y)) \right.$$

$$\left. \times e^{0.7962(la/ta(x(a,y)))} \times x(a, y) \right\}$$

$$+ \xi 2 \left\{ \sum_{a \in A} la \times \max \left\{ S(a, y) - \overline{S}(a), 0 \right\} / \sum_{a \in A} la \right\}$$

$$+ \xi 3 \left\{ \sum_{a \in B(y)} la \times S(a, y) / \sum_{a \in B(y)} la \right\}$$

$$+ \xi 4 \left\{ \sum_a x(a, y) \times ta(x(a, y)) \right.$$

$$\left. + \sum_c x(c, z) \times dc(x(c, z)) \right\} \tag{9}$$

Subject to

$$S(a, y) = \frac{x(a, y)}{C(a)} \le \overline{S}(a), a \in A \tag{10}$$

$$y(a) = -1, 0, 1, a \in B(y) \tag{11}$$

$$z(c) = 0, 1, c \in C(z) \tag{12}$$

where Equation (9) is the objective function. Equation (10) is the saturation constraint. Equation (11) and Equation (12) define the types of decision variables. In this formulation, $x(a, y), a \in A \cup B(y)$ and $x(c, z), c \in C(z)$ can be obtained by the lower-level model.

The lower-level model is expressed as follows:

$$\min f(x) = \sum_a \int_0^{x(a,y)} ta(w)dw + \sum_c \int_0^{x(c,z)} dc(w)dw \tag{13}$$

Subject to

$$\sum_{k=1}^{L(r,s)} f_k^{rs} = qrs \tag{14}$$

$$x(a, y) = \sum_{r=1}^n \sum_{s=1}^n \sum_{k=1}^{L(r,s)} f_k^{rs} \delta_{a,k}^{rs} \tag{15}$$

$$x(c, z) = \sum_{r=1}^n \sum_{s=1}^n \sum_{k=1}^{L(r,s)} f_k^{rs} \delta_{c,k}^{rs} \tag{16}$$

$$\delta_{c,k}^{rs} = \delta_{a,k}^{rs} \delta_{b,k}^{rs} \tag{17}$$

$$f_k^{rs} \ge 0, (r, s = 1, 2, \ldots, n; k = 1, 2, \ldots, L(r, s)) \tag{18}$$

where Equations (13-18) define the user equilibrium (UE) assignment problem under fixed traffic demand with the consideration of intersection delay. In the lower-level model, the objective value $f(x)$ consists of two parts. The first part is the sum of the integrals of the road impedance functions, and the second part is the sum of the integrals of the virtual turning link impedance functions. $L(r, s)$ is the number of paths between OD pair (r, s); $\delta_{a,k}^{rs}$ and $\delta_{c,k}^{rs}$ are two indicator variables, $\delta_{a,k}^{rs}$ equals 1 if link a is on path k between OD pair (r, s), otherwise 0; $\delta_{c,k}^{rs}$ equals 1 if intersection virtual turning link c connecting road a and b is on path k between OD pair (r, s), otherwise 0.

In the above bi-level programming model, the road impedance function $t_a(x(a, y))$ used in the model is the equation developed by the U.S. Bureau of Public Road (BPR). The BPR function reflects the relationship between travel time and flow. The equation is given by:

$$ta(x(a, y)) = \begin{cases} t_a^0 \left(1 + \alpha \cdot (x(a, y)/C(a))^\beta\right), a \in A \\ t_a^0 \left(1 + \alpha \cdot \left(x(a, y)/(\overline{S}(a) \cdot C(a))\right)^\beta\right), \\ \qquad\qquad\qquad\qquad a \in B(y) \end{cases}$$

(19)

where t_a^0 is the free-flow travel time on road a, min; α and β are two positive parameters, and BPR suggests that $\alpha = 0.15$, $\beta = 0.4$.

The virtual turning link impedance function $d_c(x(c, z))$ in the model is complex and affected by many factors, such as intersection geometric design, traffic flow and driving behavior. Since the right turn traffic flow generally does not conflict with the turning traffic flow from other directions, the travel time of the right turn traffic flow at an intersection is generally the free-flow time. Moreover, in this paper, it is considered that the turning delay of the left turn and straight going is only related to the turning flow and is proportional to the turning flow. It should be noted that the virtual turning link impedance in the following numerical example is also calculated by the BPR function for the sake of simplification.

In the established bi-level programming model, the limit saturation constraint of branch roads is reflected by the BPR function. If necessary, the constraint condition of the branch road flow can be added to the lower-level model to strictly limit the flow of the branch road.

As a result, Equations (9-18) show that two interrelated mathematical models are contained in the established bi-level multi-objective programming model. The first part addresses the optimization of the micro-circulation road network in the open block area, which involves the upper-level programming model, and the second part assigns traffic demand, which involves the lower-level programming model. The model structure is shown in Figure 1.

IV. DESIGN OF THE SOLUTION ALGORITHM

The solution of the established bi-level multi-objective programming model is very complex. On the one hand, the bi-level programming problem is an NP-hard
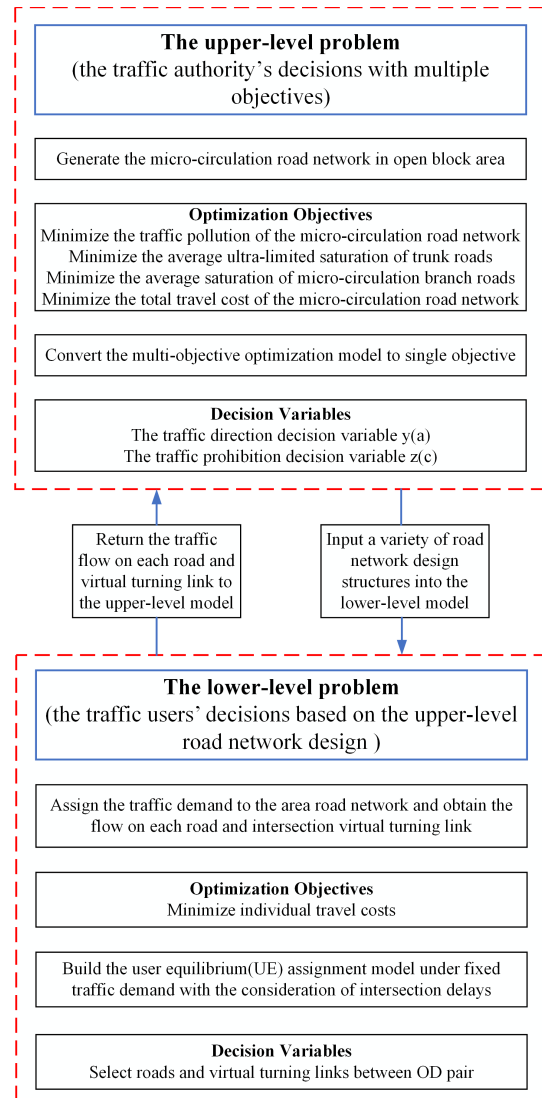

FIGURE 1. The bi-level model structure.

(Nondeterministic Polynomial) problem [36]. On the other hand, it is usually difficult to find the global optimal solution because bi-level programming problems are generally non-convex [37]. Traditional mathematical programming methods such as duality-based optimization approaches [38] and KKT-based approaches [39] may lead to locally optimal solution. Moreover, the traditional solution methods usually require the objective function to meet certain requirements, such as differentiability. Therefore, it is difficult to solve the established bi-level multi-objective programming model through traditional solution methods.

To solve bi-level programs more effectively, a variety of heuristic algorithms for the practical conditions have been designed, such as particle swarm optimization [40], ant colony optimization [41], and genetic algorithm (GA) [42] and so on. The computational complexity and accuracy of each method are different. Among these algorithms, the genetic algorithm has become one of the most

commonly used methods because of its parallelism and compatibility [43].

GA is inspired by the biological evolution process and it is widely used to generate high-quality solutions for optimization and search problems [44]. In addition, GA is characterized by global superiority and dramatic convergence [45]. Compared with other heuristic algorithms, GA has three main advantages: (1) The operation object of GA is a group of feasible solutions rather than a single solution. Hence, GA has better global search capability [43]; (2) GA dynamically changes the search process by crossover probability and mutation probability to avoid trapping in a local optimum to some extent [46]; (3) GA has fewer requirements for the objective function. For example, the objective function does not need to meet certain requirements such as differentiability. Therefore, we selected GA as a highly efficient and adaptable approach to solve the established bi-level programming model.

There are two main steps to solve the established bi-level programming model: first, the optimal value of the lower-level programming model is solved under the given feasible scheme of the upper-level programming model, and then the upper-level programming model is solved to find the overall optimal solution through the optimal solution of the lower-level programming model [47]. However, the standard GA is only suitable for solving the upper-level model, while the lower UE model needs to be solved by an efficient Frank-Wolfe algorithm. Therefore, to solve the interaction between the two levels, we must modify the basic structure of the standard GA to obtain an algorithm suitable for the established model.

Finally, we designed a genetic algorithm to solve the upper-level programming model and embedded the Frank-Wolfe algorithm to obtain the traffic demand distribution of the lower-level programming model [45]. GA is the main body of the whole algorithm, which deals with the nonlinear and non-convex properties of bi-level programming. In the designed algorithm, the binary coding was used according to the actual characteristics of the established model. Moreover, it is assumed that the total number of the candidate micro-circulation branch roads and the intersection virtual turning links is N, and the vector $(y(a)z(c))$ is encoded.

The detailed steps of the designed genetic algorithm are given as follows:

Step 1: Initialization. The population is initialized randomly. In addition, parameters such as road network traffic demand q_{rs}, road capacity $C(a)$, road length l_a, and limit saturation $\overline{S}(a)$ are input.

Step 2: Determine the fitness function. It is stipulated that the fitness function value is nonnegative. In this genetic algorithm, the fitness function is determined as $F(yi) = Z_{max} - Z(yi)$ according to the optimization objectives of the upper model. In the fitness function, $F(y_i)$ is the fitness of individual i, $Z(y_i)$ is the objective function value of individual i, and Z_{max} is the upper bound of the estimated objective function.

Step 3: Set the population number of the genetic algorithm and the genetic operators such as selection, crossover, and mutation. The maximum genetic algebra of the given population is G_m. The selection operation adopts the roulette selection method, and the probability of individual i being selected is $Pi = F(yi) / \sum_{i=1}^{M} F(yi)$. The variable M is the population number. The crossover operation uses a two-point crossover method and the crossover probability of the given population is P_c. For each individual in the population after crossover, a random number r is generated in [0,1] according to the given mutation probability P_m. If $r \leq Pm$, the gene value on the position is logically reversed, that is, 1 changes to 0, 0 changes to 1, and a new individual is obtained.

Step 4: Each individual in the population is substituted into the lower-level traffic assignment model, and the lower-level model is solved by using the Frank-Wolfe algorithm. Then, the traffic flow of each road and intersection virtual turning link is obtained.

Using the Frank-Wolfe method to solve the lower-level programming model consists of the following steps:

(1) Initialization. According to the initial feasible solutions $x^0(a, y), a \in A \cup B(y)$ and $x^0(c, z), c \in C(z)$, the all-or-nothing traffic assignment method based on $t_a^0(x(a, y)) = ta(x^0(a, y)), a \in A \cup B(y)$ and $d_c^0(x(c, z)) = d_c(x^0(c, z)), c \in C(z)$ is performed to obtain the set of road flows $\{x^1(a, y)\}$ and intersection virtual turning link flows $\{x^1(c, z)\}$. Then, let iteration time $n = 1$.

(2) Updating travel time on each road and virtual turning link.

Set

$$t_a^n(x(a, y)) = ta(x^n(a, y)), \forall a \in A \cup B(y)$$
$$d_c^n(x(c, z)) = dc(x^n(c, z)), \forall c \in C(z).$$

(3) Searching for iterative direction. The all-or-nothing traffic assignment method is conducted based on $\{t_a^n(x(a, y))\}$ and $\{d_c^n(x(c, z))\}$ so we obtain a set of additional road traffic flows $\{g^n(a, y)\}$ and additional virtual turning link flows $\{g^n(c, z)\}$.

(4) Searching for the optimal iteration step length λ^n. Calculate the iteration step λ^n by solving the following function:

$$\min_{0 \leq \lambda \leq 1} f(\lambda) = \sum_a \int_o^{x^n(a,y)+\lambda(g^n(a,y)-x^n(a,y))} t_a(w) \, dw$$
$$+ \sum_c \int_o^{x^n(c,z)+\lambda(g^n(c,z)-x^n(c,z))} d_c(w) \, dw$$

(5) Updating the traffic flow on each road and virtual turning link by using the following recursion formula:

$$x^{n+1}(a, y) = x^n(a, y) + \lambda^n(g^n(a, y) - x^n(a, y)),$$
$$\forall a \in A \cup B(y)$$
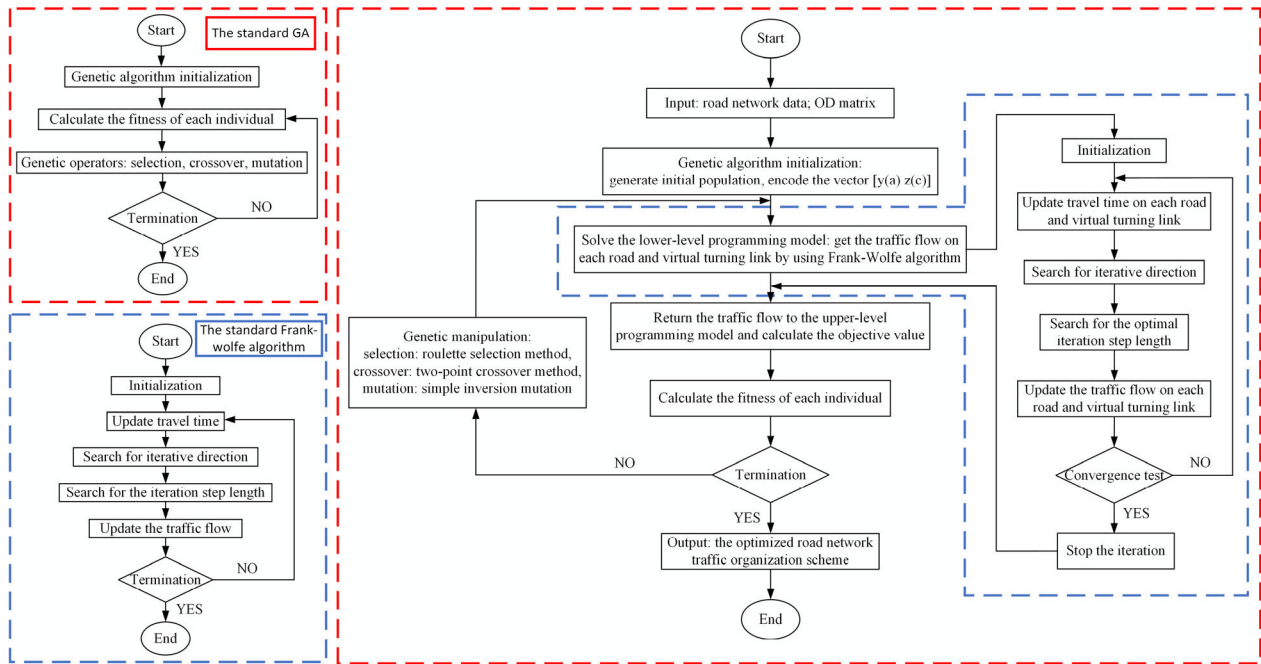$$x^{n+1}(c, z) = x^n(c, z) + \lambda^n(g^n(c, z) - x^n(c, z)),$$
$$\forall c \in C(z)$$

FIGURE 2. The algorithm procedure.

(6) Convergence test. Stop the iteration if the current solutions $\{x^{n+1}(a, y)\}$ and $\{x^{n+1}(c, z)\}$ already meet the specified convergence criterion; otherwise set $n = n + 1$ and go to Step (2).

Step 5: The traffic flow obtained in Step 4 is returned to the upper-level model to calculate the fitness of each individual and verify whether the constraint conditions are met.

Step 6: Genetic manipulation. The probability of P_i is used to select excellent individuals to produce offspring. The probability of P_c is used for population crossover. The probability of P_m is used for population mutation, and the fitness function value of newly generated individuals is calculated.

Step 7: Termination condition test. When the evolutionary algebra reaches the maximum genetic algebra, the iteration is terminated. The chromosome with the highest fitness ranking satisfying the conditions is the optimal solution of the multi-objective optimization problem. The decision variables $y(a)$ and $z(c)$ are output, and parameters such as road saturation and the optimized road network traffic organization scheme are obtained. If the maximum genetic algebra is not reached, return to step 4.

The procedure of the modified genetic algorithm embedded with the Frank-Wolfe algorithm is shown in Figure 2.

V. NUMERICAL EXAMPLE

A certain area in Xi'an intends to open the internal roads of a block, the built model is used to compare the road network operating conditions before and after optimization, and then the optimal scheme of the micro-circulation road network in the open block area is obtained.
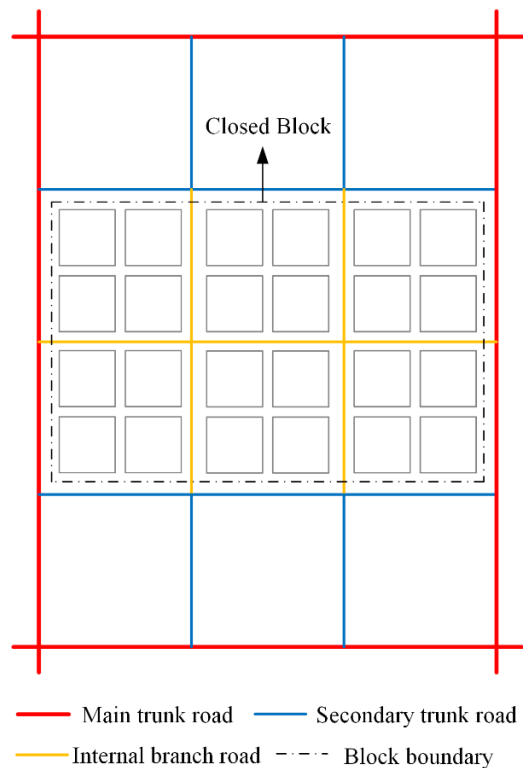

FIGURE 3. Current road network structure.

A. THE BASIC PARAMETERS SETTINGS

In this section, the basic parameter settings of the numerical example are given. After simplification, the road network structure is shown in Figure 3. It can be seen from Figure 3 that the layout of the regional micro-circulation
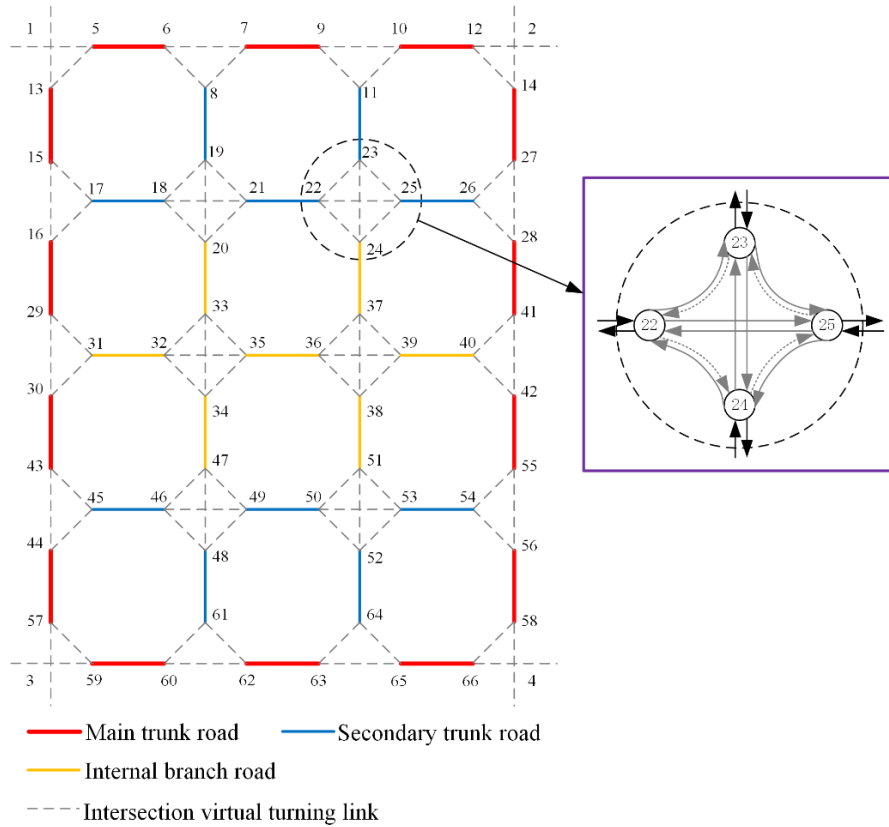
FIGURE 4. Road network structure after block opening.

road network is destroyed by the closed block and the road resources inside the blocks are left unused.

To better simulate the actual road network, the extended network method is used to add virtual turning links at the intersection nodes, and the extended road network structure after opening the block is shown in Figure 4. The numbers represent the node label, and the thick and medium thick lines represent the main and secondary trunk roads of two-way traffic, respectively. The thin lines inside the block represent the candidate micro-circulation branch roads, and the dashed lines represent the intersection virtual turning links.

Parameter settings There are fourteen main trunk roads, ten secondary trunk roads, seven branch roads and seventy-eight intersection virtual turning links in this network. Each road (virtual turning link) contains two road (link) sections in opposite directions. In Figure 4, the main and secondary trunk roads are two-way traffic. The capacity of the main trunk road in each direction is 1800 (pcu/h), and the capacity of the secondary trunk road in each direction is 700 (pcu/h). For each internal branch road, if it is two-way traffic, the capacity of each direction is 400 (pcu/h). However, if it is one-way traffic, the capacity of one-way driving is 1100 (pcu/h). For each road $a, a \in A \cup B(y)$, the length of the road is 0.3 km, and the free-flow travel time is 0.3 min. Ideally, the saturation of the trunk road does not exceed 1, and the saturation of the branch road does not exceed 0.9. For the virtual turning link of an intersection, it is assumed that the right turn travel time

TABLE 2. The OD distribution of traffic demand (pcu/h).

Node	1	2	3	4
1	0	768	913	1406
2	752	0	1346	662
3	908	1357	0	859
4	1415	654	848	0

is 2 s, the straight going travel time without interference is 4 s, and the left turn travel time without interference is 6 s.

It is assumed that the node origin-destination (OD) pairs are nodes (1, 2), (1, 3), (1, 4), (2, 3), (2, 4) and (3, 4). Traffic demand during peak hours is given in Table 2, which is assumed to be fixed traffic demand.

In this paper, the three scenarios were compared to investigate the effect of implementing city block opening. The first scenario is the basic network without block opening implementation. The second scenario is the network with block opening implementation but without traffic optimization. The third scenario is the modified network with block opening implementation and traffic optimization. Table 3 shows the settings of each scenario.

B. RESULTS AND ANALYSIS

Scenario 1 Before opening the block area, the OD traffic demand is allocated to the main and secondary trunk roads outside the block. In this scenario, the flow and saturation of

TABLE 3. The settings of each scenario.

Scenario	Block state	Trunk road	Internal branch road	Intersection virtual turning link	Upper limitation of road saturation	Simulation software
Scenario 1	close	two-way traffic	–	No prohibition	–	
Scenario 2	open	two-way traffic	two-way traffic	No prohibition	–	MATLAB R2016a
Scenario 3	open	two-way traffic	determined by traffic direction decision variable y(a)	determined by traffic prohibition decision variable z(c)	trunk road: 1.0 branch road: 0.9	

TABLE 4. Flow and saturation of the main trunk road before opening the block.

Road	Capacity (pcu/h)	Flow (pcu/h)	Saturation	Road	Capacity (pcu/h)	Flow (pcu/h)	Saturation
5→6	1800	1507	0.84	6→5	1800	1522	0.85
13→15	1800	1616	0.90	15→13	1800	1589	0.88
12→10	1800	1552	0.86	10→12	1800	1563	0.87
14→27	1800	1551	0.86	27→14	1800	1559	0.87
57→44	1800	1622	0.90	44→57	1800	1686	0.94
59→60	1800	1602	0.89	60→59	1800	1521	0.85
58→56	1800	1524	0.85	56→58	1800	1600	0.89
66→65	1800	1628	0.90	65→66	1800	1562	0.87
7→9	1800	1581	0.88	9→7	1800	1566	0.87
16→29	1800	2154	1.20	29→16	1800	2168	1.20
28→41	1800	2173	1.21	41→28	1800	2166	1.20
30→43	1800	2154	1.20	43→30	1800	2168	1.20
42→55	1800	2173	1.21	55→42	1800	2166	1.20
62→63	1800	1598	0.89	63→62	1800	1530	0.85

TABLE 5. Flow and saturation of the secondary trunk road before opening the block.

Road	Capacity (pcu/h)	Flow (pcu/h)	Saturation	Road	Capacity (pcu/h)	Flow (pcu/h)	Saturation
8→19	700	569	0.81	19→8	700	599	0.86
17→18	700	679	0.97	18→17	700	638	0.91
21→22	700	604	0.86	22→21	700	594	0.85
25→26	700	622	0.89	26→25	700	608	0.87
11→23	700	591	0.84	23→11	700	587	0.84
48→61	700	515	0.74	61→48	700	528	0.75
52→64	700	526	0.75	64→52	700	660	0.94
45→46	700	603	0.86	46→45	700	680	0.97
49→50	700	607	0.87	50→49	700	671	0.96
53→54	700	643	0.92	54→53	700	573	0.82

the main and secondary trunk roads are shown in Table 4 and Table 5, respectively.

In the first scenario, it can be observed that when the block area is not open, the saturation of each trunk road is high, and the saturation of some main trunk roads is even greater than 1. This indicates that traffic congestion is serious at this time.

Scenario 2 After block opening implementation but without traffic optimization, it is assumed that all internal branch roads are two-way traffic and that none of the intersection virtual turning links are prohibited. At this time, the OD traffic demand is allocated to the micro-circulation road network in the open block area. The flow and saturation of the main and secondary trunk roads and micro-circulation branch roads are shown in Table 6, Table 7 and Table 8, respectively.

In the second scenario, it is observed that when the internal candidate branch roads are all two-way traffic and none of the intersection virtual turning links are prohibited, the internal

branch roads divert part of the traffic flow, and the saturation of the trunk roads is reduced so that traffic congestion is alleviated. However, the saturation of some branch roads is close to 1, which indicates that there is traffic congestion. Branch road congestion will have a serious impact on resident daily life in the block. Therefore, it is not an ideal traffic organization plan to set all the candidate micro-circulation branch roads as two-way traffic.

Scenario 3 After block opening implementation and traffic optimization, the traffic conditions of the internal candidate branch roads and the intersection virtual turning links in the micro-circulation road network are determined by the established bi-level programming model. In the upper-level model, the nonnegative equivalence factors $\xi 1, \xi 2, \xi 3, \xi 4$ are finally determined to be 0.3, 0.25, 0.25, and 0.2 after many tests. In the designed solution algorithm, the number of populations is set to 200. The maximum number of iterations is set to 50. The crossover probability is set to 0.9, and

TABLE 6. Flow and saturation of the main trunk road after block opening but without optimization.

Road	Capacity (pcu/h)	Flow (pcu/h)	Saturation	Road	Capacity (pcu/h)	Flow (pcu/h)	Saturation
5→6	1800	1566	0.87	6→5	1800	1567	0.87
13→15	1800	1591	0.88	15→13	1800	1579	0.88
12→10	1800	1593	0.88	10→12	1800	1594	0.89
14→27	1800	1645	0.91	27→14	1800	1662	0.92
57→44	1800	1653	0.92	44→57	1800	1645	0.91
59→60	1800	1621	0.90	60→59	1800	1613	0.90
58→56	1800	1632	0.91	56→58	1800	1675	0.93
66→65	1800	1490	0.83	65→66	1800	1457	0.81
7→9	1800	1426	0.79	9→7	1800	1423	0.79
16→29	1800	1617	0.90	29→16	1800	1629	0.90
28→41	1800	1651	0.92	41→28	1800	1674	0.93
30→43	1800	1632	0.91	43→30	1800	1679	0.93
42→55	1800	1616	0.90	55→42	1800	1623	0.90
62→63	1800	1493	0.83	63→62	1800	1441	0.80

TABLE 7. Flow and saturation of the secondary trunk road after block opening but without optimization.

Road	Capacity (pcu/h)	Flow (pcu/h)	Saturation	Road	Capacity (pcu/h)	Flow (pcu/h)	Saturation
8→19	700	422	0.60	19→8	700	425	0.61
17→18	700	474	0.68	18→17	700	430	0.61
21→22	700	509	0.73	22→21	700	559	0.80
25→26	700	612	0.87	26→25	700	518	0.74
11→23	700	569	0.81	23→11	700	469	0.67
48→61	700	573	0.82	61→48	700	530	0.76
52→64	700	435	0.62	64→52	700	519	0.74
45→46	700	558	0.80	46→45	700	497	0.71
49→50	700	555	0.79	50→49	700	540	0.77
53→54	700	555	0.79	54→53	700	506	0.72

TABLE 8. Flow and saturation of the micro-circulation branch road after block opening but without optimization.

Road	Capacity (pcu/h)	Flow (pcu/h)	Saturation	Road	Capacity (pcu/h)	Flow (pcu/h)	Saturation
31→32	400	171	0.43	32→31	400	256	0.64
20→33	400	370	0.92	33→20	400	379	0.95
35→36	400	307	0.77	36→35	400	297	0.74
24→37	400	369	0.92	37→24	400	393	0.98
39→40	400	171	0.43	40→39	400	256	0.64
34→47	400	370	0.92	47→34	400	373	0.93
38→51	400	369	0.92	51→38	400	389	0.97

the mutation probability is set to 0.1. After optimization, the flow and saturation of the main and secondary trunk roads and micro-circulation branch roads are shown in Table 9, Table 10, and Table 11, respectively.

As shown in Table 9, Table 10, and Table 11, after the optimization of the micro-circulation road network in the open block area by using the established model, the saturation of the main trunk road is significantly reduced compared with the previous two scenarios, and the saturation of the micro-circulation branch road is all below 0.9, indicating that the traffic congestion is well alleviated. The road network after optimization is shown in Figure 5.

As shown in Figure 5, after the optimization of the road network with the established model, there are two situations of one-way traffic and two-way traffic in the micro-circulation branch road inside the open block. At the intersections, there are three kinds of situations: prohibiting straight going, prohibiting right turning and prohibiting left turning. The traffic conflict is reduced and the traffic efficiency is improved after the road network optimization.

According to the calculation results, the road network conditions of the three scenarios are compared as shown in Table 12.

TABLE 9. Flow and saturation of the main trunk road after block opening and optimization.

| Road	Capacity (pcu/h)	Flow (pcu/h)	Saturation	Road	Capacity (pcu/h)	Flow (pcu/h)	Saturation
5→6	1800	1472	0.82	6→5	1800	1555	0.86
13→15	1800	1618	0.90	15→13	1800	1524	0.85
12→10	1800	1648	0.92	10→12	1800	1349	0.75
14→27	1800	1113	0.62	27→14	1800	1351	0.75
57→44	1800	1338	0.74	44→57	1800	1623	0.90
59→60	1800	1541	0.86	60→59	1800	1390	0.77
58→56	1800	1582	0.88	56→58	1800	1354	0.75
66→65	1800	1435	0.80	65→66	1800	1603	0.89
7→9	1800	1449	0.80	9→7	1800	1639	0.91
16→29	1800	1593	0.88	29→16	1800	1504	0.84
28→41	1800	1397	0.78	41→28	1800	1581	0.88
30→43	1800	1613	0.90	43→30	1800	1500	0.83
42→55	1800	1475	0.82	55→42	1800	1513	0.84
62→63	1800	1573	0.87	63→62	1800	1252	0.70
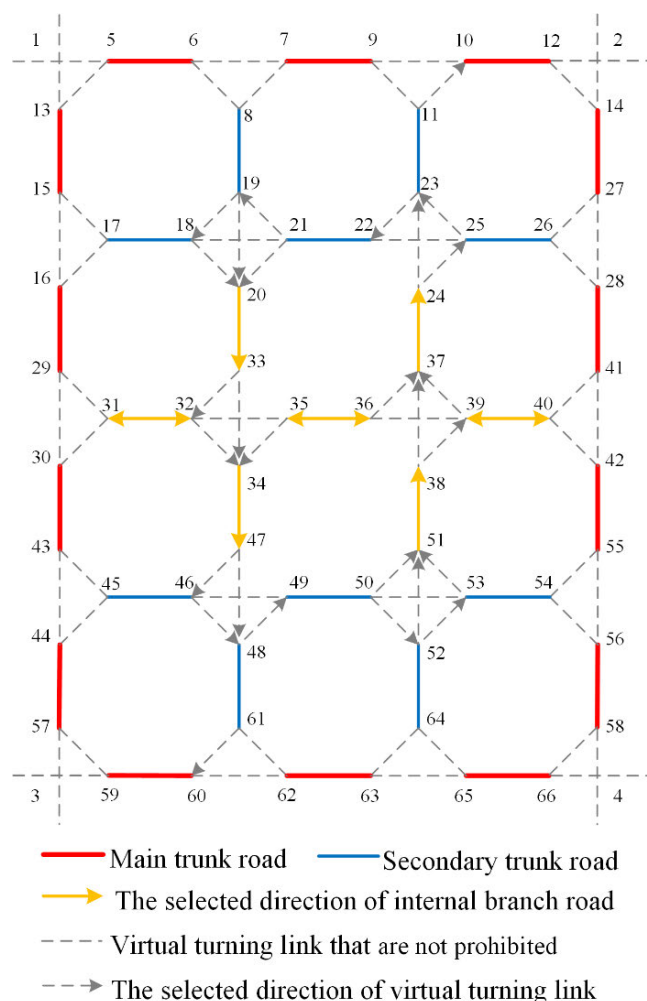
FIGURE 5. Scheme of traffic organization.

From Table 12, we know that the implementation of block opening can not only alleviate traffic congestion on trunk roads, but also reduce travel time costs and vehicle emissions. More specifically, compared to scenario 1, the average saturation of the main trunk road in scenarios 2 and 3 could be reduced by 9.28% and 14.43%, respectively, which indicates that the implementation of block opening is beneficial to alleviating traffic congestion. In addition, scenarios 2 and 3 reduce the total travel time cost by 2.52% and 6.55%, respectively, compared to scenario 1, which indicates that the implementation of block opening could improve traffic efficiency. Moreover, compared with scenario 1, the CO emissions in scenarios 2 and 3 could be reduced by 2.50% and 3.40%, respectively, which indicates that traffic pollution is reduced after traffic congestion is alleviated. In summary, scenario 3 is better than scenarios 1 and 2. To further verify the optimization effect of the established model, scenarios 2 and 3 need to be further compared in detail.

Figure 6 and Figure 7 show detailed results for the three scenarios. Figure 6 shows that in scenario 2, the average saturation of the micro-circulation branch roads (0.80) is greater than the average saturation of the secondary trunk roads (0.73), which indicates that the internal branch road is more congested than the secondary trunk road outside the block. In addition, it should be noted that in Table 8 of scenario 2, the saturation of some internal branch roads is close to 1. Congestion inside the block is not conducive to the lives of block residents, therefore, scenario 2 is apparently not ideal.

Compared with scenario 2, scenario 3 shows obvious advantages. In scenario 3, the established model is used to optimize the micro-circulation road network in the open block area. It can be seen from Figure 6 that in scenario 3, the average saturation of the micro-circulation branch roads is 5% less than that of the secondary trunk roads, and the average saturation of the secondary trunk roads is 6% less than that of the main trunk roads. This result shows that the traffic distribution of the road network in scenario 3 is the most reasonable. In addition, it should also be noted that

TABLE 10. Flow and saturation of the secondary trunk road after opening block and optimization.

Road	Capacity (pcu/h)	Flow (pcu/h)	Saturation	Road	Capacity (pcu/h)	Flow (pcu/h)	Saturation
8→19	700	581	0.83	19→8	700	567	0.81
17→18	700	576	0.82	18→17	700	615	0.88
21→22	700	593	0.85	22→21	700	545	0.78
25→26	700	534	0.76	26→25	700	542	0.77
11→23	700	444	0.63	23→11	700	521	0.74
48→61	700	447	0.64	61→48	700	638	0.91
52→64	700	467	0.67	64→52	700	406	0.58
45→46	700	571	0.82	46→45	700	583	0.83
49→50	700	569	0.81	50→49	700	592	0.85
53→54	700	433	0.62	54→53	700	608	0.87

TABLE 11. Flow and saturation of the micro-circulation branch road after opening block and optimization.

Road	Capacity (pcu/h)	Flow (pcu/h)	Saturation	Road	Capacity (pcu/h)	Flow (pcu/h)	Saturation
31→32	400	276	0.69	32→31	400	242	0.60
35→36	400	332	0.83	36→35	400	242	0.60
39→40	400	236	0.59	40→39	400	311	0.78
20→33	1100	803	0.73	37→24	1100	821	0.75
34→47	1100	903	0.82	51→38	1100	843	0.77

TABLE 12. Comparison of road network conditions.

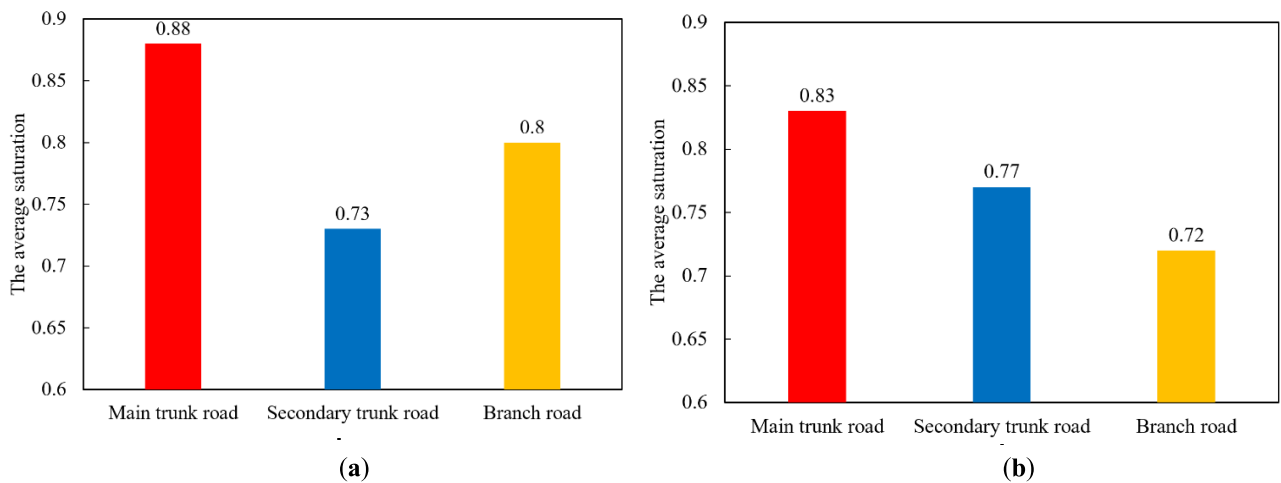| Scenario	The block state	The average saturation of main trunk road	The average saturation of secondary trunk road	The average saturation of micro-circulation branch road	Travel time cost (h)	CO emissions (g/h)
Scenario 1	Closed	0.97	0.86	–	157.44	323.84
Scenario 2	Open but not optimize	0.88	0.73	0.80	153.47	315.75
Scenario 3	Open and optimize	0.83	0.77	0.72	147.13	312.83

FIGURE 6. The average saturation of the main, secondary trunk roads and micro-circulation branch roads; (a) Scenario 2 and (b) Scenario 3.

in Table 11 of scenario 3, the saturation of each internal branch road is less than 0.9. Therefore, the road network operation effect in scenario 3 is more ideal. Moreover, it can be observed from Figure 7 that the total travel time cost in scenario 3 is reduced by 4.13% compared to

Scenario 2. Similarly, scenario 3 reduces CO emissions by 0.92% compared to scenario 2. Therefore, scenario 3 is the most suitable solution. The results support that the designed bi-level multi-objective optimization model could further reduce traffic pollution and improve traffic efficiency while
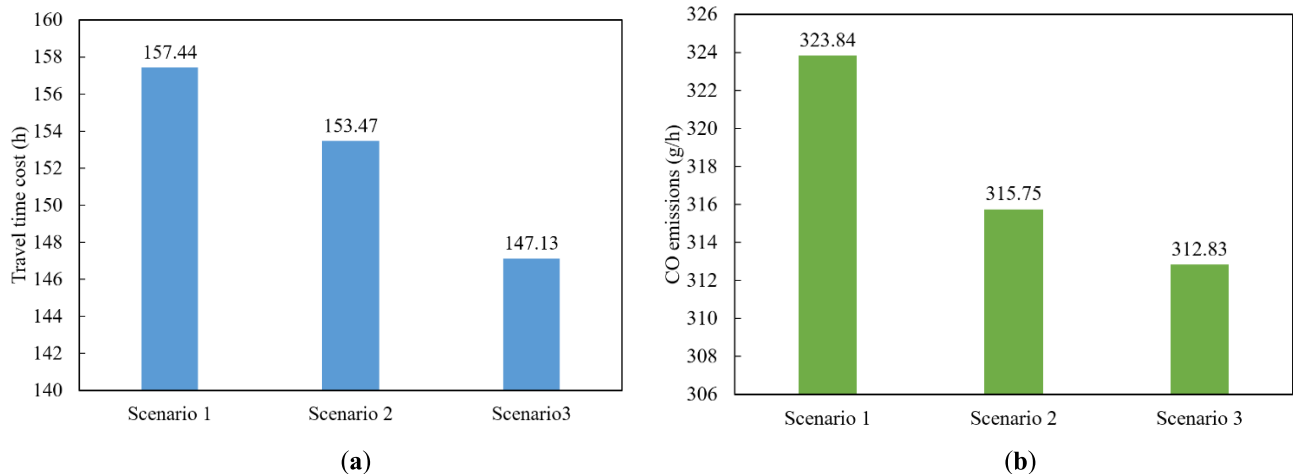
FIGURE 7. Travel time cost and CO emissions for the three scenarios (a) travel time cost; (b) CO emissions.

alleviating traffic congestion, which reflects the optimization effect of the model.

The applicability of both the bi-level programming model and the designed algorithm was tested by the numerical example. Finally, it should be pointed out that the model and the algorithm were implemented using MATLAB R2016a software on a 2.10 GHz computer with 16GB of RAM.

VI. CONCLUSION

In this paper, a bi-level multi-objective programming model considering traffic pollution and intersection delay is constructed to optimize the micro-circulation road network in an open block area, and a modified genetic algorithm embedded with the Frank–Wolfe algorithm is designed to solve the model. The main conclusions obtained are as follows:

(1) The numerical results showed that when the internal branch roads are all two-way traffic and none of the intersection virtual turning links are prohibited after block opening, the traffic congestion of the trunk roads is alleviated to some extent. The average saturation of the main trunk roads is reduced from 0.97 to 0.88, and the average saturation of the secondary trunk roads is reduced from 0.86 to 0.73. However, the micro-circulation branch roads bear a large traffic pressure with an average saturation of 0.80, and the saturation of some branch roads is even close to 1. If the road network structure is complex and the traffic demand is large, the saturation of the two-way traffic branch road may be greater than 1, which is not conducive to the stable operation of the micro-circulation road network.

(2) After the micro-circulation road network in the open block area is optimized by using the established bi-level programming model, the average saturation of the main trunk road decreases from 0.97 to 0.83 with a decline ratio of 14.43%, and the average saturation of the secondary trunk road decreases from 0.86 to 0.77 with a decrease of approximately 10.47%. In addition, the travel time cost decreases from 157.44 h to 147.13 h with a decrease of approximately

6.55%, and the traffic pollution decreases from 323.84 g/h to 312.83 g/h with a decrease of approximately 3.40%, which verifies the optimization effect of the built model.

(3) The built bi-level multi-objective programming model can effectively determine the traffic direction of the micro-circulation branch roads and the forbidden situation of the intersections in the micro-circulation road network, which provides a theoretical optimization method for road network organization in open block areas. The established model could further reduce traffic pollution and improve traffic efficiency while alleviating traffic congestion, which promotes the sustainable development of urban traffic.

AUTHOR CONTRIBUTIONS

Qiuping Wang designed research methods and edited the manuscript. Jiaxing Wang wrote the original draft and analyzed the data. All the authors contributed to the writing and revising of the manuscript.

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