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Temporary Reversible Lane Design Based on Bi-Level Programming Model during the Winter Olympic Games

Weiqi Hong [1], Zishu Yang [2], Xu Sun [1], Jianyu Wang [1] and Pengpeng Jiao [1,*]

[1] Beijing Laboratory of General Aviation Technology, Beijing University of Civil Engineering and Architecture, Beijing 100044, China; hongweiqi_bucea@163.com (W.H.); sunxu@bucea.edu.cn (X.S.); wangjianyu@bucea.edu.cn (J.W.)

[2] Beijing General Municipal Engineering Design & Research Institute Co., Ltd., Beijing 100082, China; zishu_yang2016@163.com

* Correspondence: jiaopengpeng@bucea.edu.cn

Abstract: When the Winter Olympic Games were held, several roads were divided into exclusive lanes for the Winter Olympics to ensure the smooth passage of Winter Olympic vehicles. This reduced the number of lanes available for private vehicles, which caused a temporary tidal traffic phenomenon that led to traffic congestion and increased exhaust emissions. Temporary reversible lanes were added to the object lane to alleviate the temporary tide traffic phenomenon. A bi-level programming model was developed based on the principle of the minimum construction cost and the minimum total travel time of the road network. Meanwhile, three heuristics algorithms were used to solve the problem. The results show that the reasonable addition of temporary reversible lanes during the Olympic Games can reduce the total system travel cost, solve the temporary tidal traffic phenomenon, and alleviate traffic congestion.

Keywords: sustainable transport planning; the Winter Olympic Games; reversible lane; bi-level programming model; algorithm; traffic congestion

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1. Introduction

To ensure the health of all Winter Olympic Games personnel and civil organizers during the Winter Olympic Games in the face of COVID-19, Beijing traffic management departments established Olympic-exclusive lanes on several road sections. Meanwhile, they implemented a whole closed cycle and point-to-point, closed-loop management process for all Winter Olympic personnel. Beijing used signs and markings to alert private vehicles that they could not drive in the Olympic exclusive lane during specified times. Some soft isolation measures were implemented for the closed-loop traffic flow to ensure the smooth running of Winter Olympic vehicles.

When certain lanes were reserved exclusively for the Olympics, the number of lanes for private cars decreased, leading to traffic jams and tensions related to road resources. Consequently, a temporary one-way congestion was caused, namely a temporary tidal traffic phenomenon in one direction. The phenomenon of tidal traffic can cause a huge waste of traffic resources. It increased the risk of congestion and caused inconveniences and problems for travelers. Having cars driving at slow speeds for a long time produces a high level of exhaust fumes, which pollutes the environment. Moreover, it is important to leave a good impression of the traffic in Beijing on international spectators.

Setting reversible lanes is an effective way of solving the tidal traffic phenomenon [1]. Through a practical investigation over five months in the United States, it was found that the installation of tidal reversible lanes at peak hours made it possible to significantly reduce traffic congestion [2]. Reversible lanes can significantly increase road capacity, while creating road safety challenges [3,4]. The installation of reversible lanes can significantly reduce travel time [5]. Therefore, setting reversible lanes was an effective way to solve the problem of unbalanced urban traffic flow on road sections during the Olympic Games, which could quickly dissipate the traffic congestion in the direction of the main traffic flow by borrowing the capacity of the reverse section to reduce traffic congestion.

To handle the temporary tidal traffic phenomenon, temporary reversible lanes were established to utilize road resources and meet traveler's demands. Most of the time, no vehicle was seen on the Olympic exclusive lanes. Reversible lanes ensured the safe journey of Olympic personnel. They also alleviated the traffic volume on the side of high pressure during peak hours. To decrease the effect of reversible lanes on other roads [6], measures were put in place to install variable lanes, looking at the entire traffic network system based on the overall traffic network conditions.

2. Literature Review

Large-scale studies of tidal lane characteristics began in the 1960s. To form the specifications of reversible lane settings in documents such as the American Highway and Roadway Design Manual (AASHTO) [7,8], Wolshon et al. [2,9] investigated the application of variable lane settings in the US and conducted an exhaustive study of variable lane settings in the National Highway Research Program (NCHRP) [10]. Waleczek et al. [11] put the reversible lane system into practice to confirm the practicality and safety of the system. Aaron [12] summarized the implementation criteria of the tidal reversible lane scheme after analyzing many theories related to its installation. Asaithambi [13] discussed various methods of traffic control for reversible lanes using signs and signals, barriers, etc. Ampountolas [14] provided a Pareto-optimal solution based on kinematic wave theory applied to the operation of a simulation of Aston expressway.

There is a relatively large body of literature that is concerned with contraflow in the case of evacuation and construction areas. Tudydes [15] developed a tabu search heuristic to solve the problem of setting reversible lanes in response to a temporary occurrence of a disaster. It can be found that the installation of reversible lanes is a feasible strategy that can reduce traffic congestion and allow for a satisfactory evacuation time. Pyakurel has conducted several studies in response to rapidly occurring natural disasters and limited road capacity. In 2015, he developed static mathematical models and solution algorithms for the lexicographically maximum dynamic contraflow and earliest arrival contraflow problems [16]. Then, mathematical models and solution algorithms were designed for dynamic reverse traffic flow [17]. Afterwards, a continuous flow algorithm was proposed, which shows that the design of the reverse lane can increase the traffic flow [18]. Time-varying parameters were introduced to the dynamic contraflow model to calculate its minimum cost and optimize its optimal algorithm [19]. The results show that the use of contraflow can minimize congestion and allows for smooth traffic flow during evacuation. The use of reversible lanes in construction zones can reduce travel time loss and simultaneously reduce the accident rate on the highway [11].

Reversible lanes have been set up as tidal lanes for a long time to alleviate the tidal traffic phenomenon in fixed areas. They can also be used in emergency accident evacuations. The reversible lanes in the Olympic period are expected to exist for 1–2 months. Therefore, the setting conditions are slightly different from those for tidal lanes and evacuations.

Most research on reversible lane settings has been carried out using bi-level programming models. Meng et al. [20] developed a bi-level programming model with the lowest total cost of travel in the upper layer and a reset of travel paths after reversible lane transformation in the lower layer, while a genetic algorithm was used for the design. Additionally, using the feasibility of the model and algorithm were verified in the Singapore traffic network. Wang et al. [21] researched the reversible lane setting in emergency evacuation situations. They proposed a bi-level programming model for reversible lane setting and verified the validity of the model with three arithmetic examples with distinctive features. Zhen et al. [22] proposed a nonlinear bi-level programming model seeking to maximize the coupling degree of the network structure and the demand junction to find the optimal lane combination strategy in the traffic network. Lu et al. [23], in order to research the dynamic reversible lane assignment method at an intersection, developed a bi-level programming model with the maximum queue length at intersections as the upper-level objective function and the lower-layer function for traffic assignment using a logit stochastic user equilibrium model.

Several scholars have also studied reversible lanes using alternative mathematical models or simulation methods under different setup conditions. Punith [24] developed a microsimulation model to evaluate the operation of reversible lanes and investigate the impact of reversible lanes on road capacity. Wei et al. [25] developed a reversible lane selection model based on BPR function and environmental benefits, using the number of reversible lanes as the decision variable and considering the delay and algorithm needed to minimize energy and emission costs. Pyakurel et al. [26] proposed a new partial lane reversal strategy that can help to achieve the shortest transport time in an evacuation situation. José [27] proposed a macroscopic model and two control algorithms for the setting and control of reversible lanes for highway traffic flow operation states. Wei et al. [28] calibrated some parameters of reverse traffic flow with the help of the VISSIM platform to further evaluate the impact of reverse lanes on an evacuation situation.

Scholars have mostly used heuristic algorithms to solve the bi-level programming model, due to its complexity. Zhang et al. [29] used a multi-objective hierarchical genetic algorithm to solve a bi-level programming model to solve the job shop's scheduling and layout problems. Ma et al. [30] proposed an algorithm combining a hybrid particle swarm algorithm and a differential evolutionary algorithm to deal with bi-level programming problems. Sun et al. [31] used a genetic algorithm to find the signal control variables in a bi-level programming model. Bin et al. [32] applied a combination of a column generation algorithm, a branch constraint algorithm, and a successive averaging method to solve the problem of bus lane distribution in multimodal transport networks. Kaboli et al. [33] used simulated annealing methods to solve a multi-objective bi-level programming model. Ma et al. [34] proposed an algorithm based on a human evolutionary model to solve a bi-level programming model.

In the literature, the problem of setting reversible lanes is mostly studied using a bi-level programming model, which makes the setting of reversible lanes more reasonable by continuously changing the upper-level objective function. The focus of the temporary reversible lane setting is different from that of the previous normal tidal lane. The reversible lanes are time-sensitive and government investment only exists for a few months. Therefore, the optimal objective is to reduce the setup costs and minimize the travel time. Due to the complexity of solving the model, we used three different solution algorithms. The proposed model was implemented and the rationality of the solution using arithmetic examples was demonstrated.

3. Methods

The Olympic exclusive lane is defined by traffic marking or signage on the roadway to designate a lane for Olympic vehicles throughout the day or at certain specific times without allowing other vehicles to pass. The Olympic exclusive lane is an exclusive access space for Olympic vehicles that reduces the impact of private vehicles on Olympic vehicles. The installation of the Olympic exclusive lane changes the roadway access, travel time, and cost, affecting the traveler's choice of travel path, and thus has an impact on roadway capacity and roadway impedance functions.

The capacity of a road section is the maximum number of vehicles that can pass through a section of the road within a certain amount of time. The Olympic exclusive lane occupies an entire lane as a dedicated lane, which will change the road's access status, thus changing the overall capacity of the road. The impedance function of the road characterizes the relation between road cost and traffic. When setting Olympic lanes on the road section, we can treat the travel time of Olympic vehicles in the Olympic lanes as a constant value, while the setting of Olympic lanes will directly affect the capacity of the remaining lanes in the same direction. Therefore, to minimize the impact of Olympic exclusive lanes on the other lanes, the addition of temporary reversible lanes to the road sections, which can distribute traffic in the direction of high traffic pressure, should be considered. The installation of reversible lanes changes the previous road network structure, the capacity of the road in different directions, and the impedance function of the road, which consequently affects the travel path choice of travelers. The problem of the optimal adjustment of reversible lanes is essentially an optimization search problem.

The bi-level programming model was first proposed in 1977 and modelled according to the Stackelberg game model, which is typically characterized by a bi-level recursive structure in economic theory [35]. The reversible lane setting during the Olympic Games is a Stackelberg game model, as are other traffic network design issues. The design of tidal lanes typically aims to reduce total travel time, total cost of management and construction, and overall pollution emissions. Meanwhile, network travelers choose the travel options and the minimum travel costs based on the tidal lane settings. The choices of all travelers influence the state of the road network and then influence the decisions of management. Therefore, the goal of the optimal design of reversible lanes during the Olympic Games is to guide travelers to make travel choices that are beneficial to the overall state of the road network through the reasonable design of reversible lanes.

As the installation of reversible lanes during the Olympics is a short-term investment, minimal investment costs and administrative costs are required by the management. Finding the minimum investment cost and the lowest total cost of road network travel is the overall objective of the upper-level model. The lower model mainly considers the travel time of each traveler and introduces the first principle of Wardrop [36]: it is assumed that the traveler can clearly grasp the time spent on each route and the selection behavior; that is, the shortest route is always chosen. The traffic network distribution model is adopted to establish a bi-level programming model with the goal of ensuring the shortest travel time for travelers.

The following four aspects need to be considered when setting up tidal reversible lanes [10]: (1) The number of lanes in both directions should be no less than three. (2) The traffic flow distribution factor should be greater than 2/3. (3) The reversible lanes cannot be designed to affect the capacity of all the traffic. (4) Line-markings, signal facilities' configuration, and median strips need to be considered.

To facilitate the presentation and analysis of the bi-level programming model, all definitions and notations used throughout this work are described in Nomenclature.

Since the direction of the road tidal phenomenon has different peak hours, it is assumed that the number of tidal increase lanes in the two directions of the road is set at different peak hours. In other words, the two-way traffic flows through the Olympic vehicles during different peak hours, and the Olympic lane with less traffic does not contain the Olympic vehicles, or there is no Olympic lane.

$$u_a = -u_a \tag{1}$$

We assume that the road traffic network V is not set up with one-way streets. Additionally, vehicles are divided into two directions on the road section. Thus, the value of u_a should satisfy the relationship:

$$1 \leq n_a + u_a \leq n_a + n_{\bar{a}} - 1 \tag{2}$$

The investment management cost of the tidal lane includes investment in the construction costs of setting the tidal lane, equipment maintenance, energy loss, etc. This is generally presented as:

$$p_a(u_a) = d_a \cdot u_a \tag{3}$$

Private vehicles have fewer lanes to drive on due to the special lane. Therefore, the road capacity should be subtracted from the number of the special lanes. t_a uses the BPR function [37] as follows:

$$t_a(x_a, u_a) = t_{a0}\left(1 + \alpha\left(\frac{x_a}{c_a(n_a - 1 + u_a)}\right)^{\beta}\right) \quad (4)$$

Following the relevant studies which implement the analysis and validation with field-held data in Beijing, the model of the US Bureau of Highways was shown to be more similar to the domestic situation, and the former's recommended coefficients, α = 0.15 and β = 4 [37], can be used.

Suppose all travel users tend to choose the path with the lowest travel cost. After the effect of price regulation, their path selection behavior will eventually satisfy Wardrop's first principle to achieve the status of user equilibrium.

A bi-level programming model is established as follows:

$$\min_u Z = \sum\nolimits_{a \in A} t_a(x_a, u_a)x_a + \gamma \sum\nolimits_{a \in D} p_a(y_a) \quad (5)$$

Equation (5) is the objective function of the road network reversible lane optimization design problem. The total system impedance of the traffic network is minimized by implementing improvements to some road sections to enhance their overall capacity.

$$\text{s.t.} \quad 1 \le n_a + u_a \le n_a + n_{\bar{a}} - 1, a \in D \quad (6)$$

$$u_a \in \{-2, -1, 0, 1, 2\}, a \in D \quad (7)$$

Equations (6) and (7) show the range of lane number adjustment. Based on the conventional road network, the number of lane adjustments is limited to no more than two. Vehicles are divided in both directions on the road section. Additionally, the total number of lanes remains constant.

$$\min_x \sum_{a \in A} \int_0^{x_a} t_a(w, u_a)dw \quad (8)$$

$$\sum\nolimits_{k \in P_{rs}} f_{rs}^k = q_{rs}, (r,s) \in RS \quad (9)$$

$$f_{rs}^k \ge 0, k \in P_{rs}, (r,s) \in RS \quad (10)$$

$$x_a = \sum\nolimits_{(r,s) \in RS} \sum\nolimits_{k \in P_{rs}} f_{rs}^k \delta_{rs}^{ak}, a \in A \quad (11)$$

Equations (8)–(11) are the user equilibrium flow distribution model and its constraints.

4. Algorithm

For the bi-level programming model of reversible lane setting during the Winter Olympics, the upper-level solution variables are mostly a set of discrete integer variables, which are recognized as one of the most difficult problems to solve, since the traffic flow and OD demand at traffic equilibrium are in most cases non-convex, non-derivable functions for increasing the number of lanes. It is more difficult to choose the traditional algorithm to solve the bi-level programming model and it is impossible to obtain the global optimal solution to the model. Consequently, we used the intelligent optimization algorithm to solve the model.

Due to the separation of employment and residence, residents need to travel from one fixed location to another. Thus, a serious imbalance of OD demand exists in one direction during peak hours. This, in turn, generates serious tidal traffic phenomena and causes one-way congestion. To put forward a more reasonable reversible lane setting scheme, we designed a solution algorithm combined with the genetic algorithm, particle swarm algorithm, quantum particle swarm algorithm, and traffic implication.

4.1. Genetic Algorithm Design

Genetic algorithms were first proposed by Professor Holland in the United States in 1975, in his monograph "Adaption in Natural and Artificial System" [38]. It is a stochastic search algorithm that draws on natural selection and natural genetic mechanisms in biology. The following algorithm was designed for the proposed model based on the genetic algorithm. The genetic algorithm was designed based on the bi-level programming model and tidal traffic characteristics.

For all road pairs $\{a, \bar{a}\}$ in a regional traffic network, the number of lanes added to the positive section $U = (\cdots, u_a, \cdots)$ in the lane adjustment scheme is coded $p = \{g_1, g_2, \cdots g_i\}$. The coding scheme adopts the decimal system. The i represents the number of lanes that are added to the positive section of the road. The fitness function is defined as the inverse of the upper model objective function value as follows:

$$F(pop_x) = \frac{1}{\sum_{a \in A} t_a(x_a, u_a)x_a + \gamma \sum_{a \in D} p_a(y_a)} \tag{12}$$

Using roulette as a selection mechanism for genetic algorithms, then, the details of the design problem are optimized with the help of reversible lanes, from which the adaptive crossover probabilities are selected. It is important that the details of the reversible lane optimization design problem in the parent generation are taken into account. The parent is repeatedly selected, and the offspring reversible lane optimization design is generated by crossover, from which a more complete offspring population is obtained. The flowchart of the genetic algorithm design is shown in Figure 1.

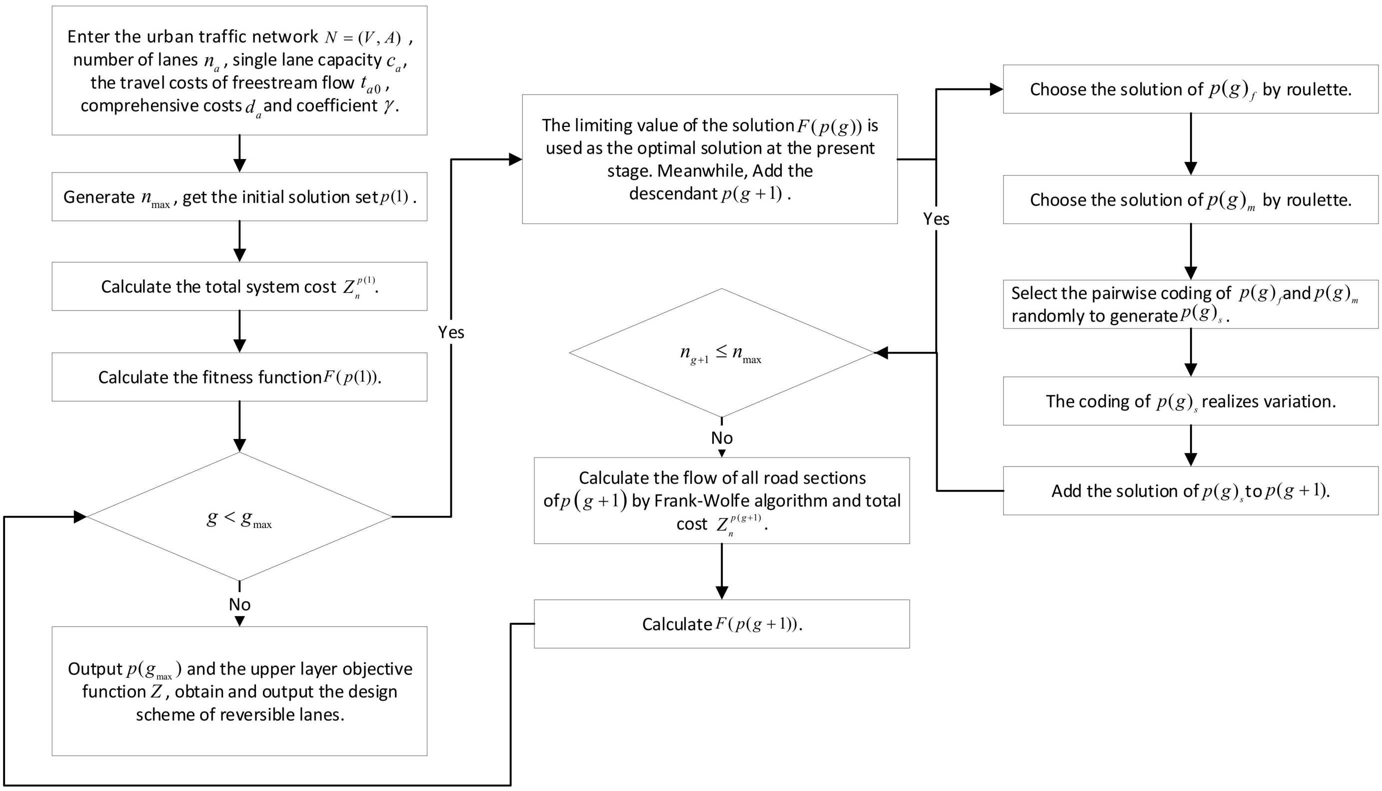

Figure 1. Genetic algorithm design process.

4.2. Particle Swarm Algorithm Design

A particle swarm algorithm [39] is also known as a particle swarm optimization (PSO) algorithm or a bird flock foraging algorithm. The particle swarm algorithm is mainly based on observations of animal group behavior. Then, the information sharing between individuals in the group is used to induce the whole group to start evolving from disorder to order in the problem–solution space. Finally, the optimal solution algorithm is obtained. Based on the bi-level programming model and tidal traffic characteristics, the particle swarm algorithm is proposed.

For all road pairs $\{a, \overline{a}\}$ in a regional traffic network, consider the number of lanes $U = (\cdots, u_a, \cdots)$ added to positive section a in the reversible lane adjustment scheme road network to be the number of particles. For any two-way road, $u_a + u_{\overline{a}} = 0$, we can make $z^i = (\cdots, z_a^i, \cdots)$ the i-th particle in a certain kind of group. $v^i = (\cdots, v_a^i, \cdots)$ represents the velocity of the i-th particle. The particle updates its velocity and position according to Equations (13) and (14) as follows (subscripts indicate the number of iterations):

$$v_{t+i}^i = \varpi v_t^i + c_1 \xi \left(p_t^i - z_t^i \right) + c_2 \eta \left(g_t - z_t^i \right) \tag{13}$$

$$z_{t+1}^i = z_t^i + v_t^i \tag{14}$$

where $i = 1, 2, \cdots, m$ and m is the particle swarm size. ω is the inertia weight factor, which is obtained by the adaptive linear decreasing method $\omega = \omega_{max} - (\omega_{max} - \omega_{min}) * t / t_{max}$. c_1, c_2 are learning factors. ξ and η are uniformly distributed random numbers between [0,1]. p_t^i refers to the best position for the individual. g_t at this point refers to the best historical position passed at time t.

The flow chart of the particle swarm algorithm design is shown in Figure 2.

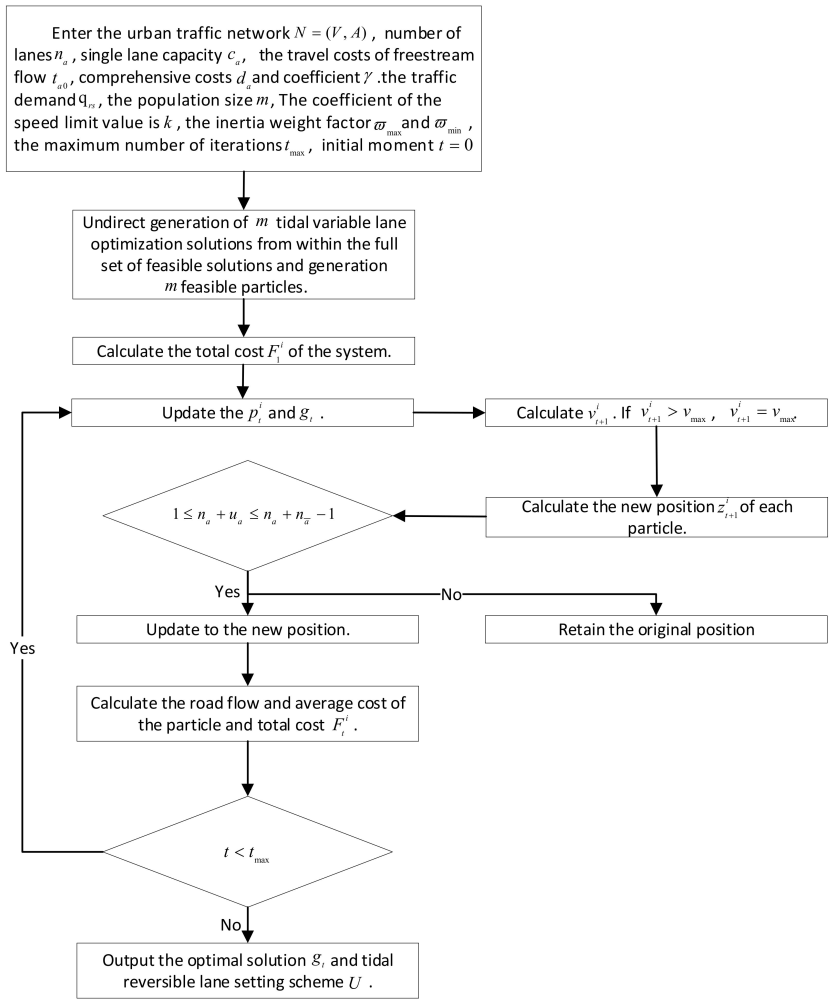

Figure 2. Particle swarm algorithm design process.

4.3. Quantum Particle Swarm Algorithm Design

The quantum particle swarm algorithm is mainly a population-based probabilistic algorithm based on the particle swarm algorithm [40]. The main idea is to use the wave function in quantum mechanics to describe the state of particle motion, replacing the position and velocity description of the particle motion state in the basic particle swarm optimization algorithm. Based on the bi-level programming model and tidal traffic characteristics, the quantum particle swarm algorithm is put forward.

For all road pairs $\{a, \bar{a}\}$ in a regional traffic network, consider the number of lanes $U = (\cdots, u_a, \cdots)$ added to the positive section a in the reversible lane adjustment scheme road network to be the number of particles. For any two-way road, $u_a + u_{\bar{a}} = 0$, we can make $z^i = (\cdots, z_a^i, \cdots)$ the i-th particle in a certain kind of group. Update the particle positions according to Equation (15) as follows (subscripts indicate the number of iterations):

$$z_{t+1}^i = p_t^i \pm \chi \left| mbest_t - z_t^i \right| \times \ln\left[\frac{1}{u_t^i}\right] \tag{15}$$

χ is the contraction and expansion factor. $mbest_t$ refers to the average best position at this point. $u_t^i \sim u(0,1)$.

The flow chart of the quantum particle swarm algorithm is shown in Figure 3.

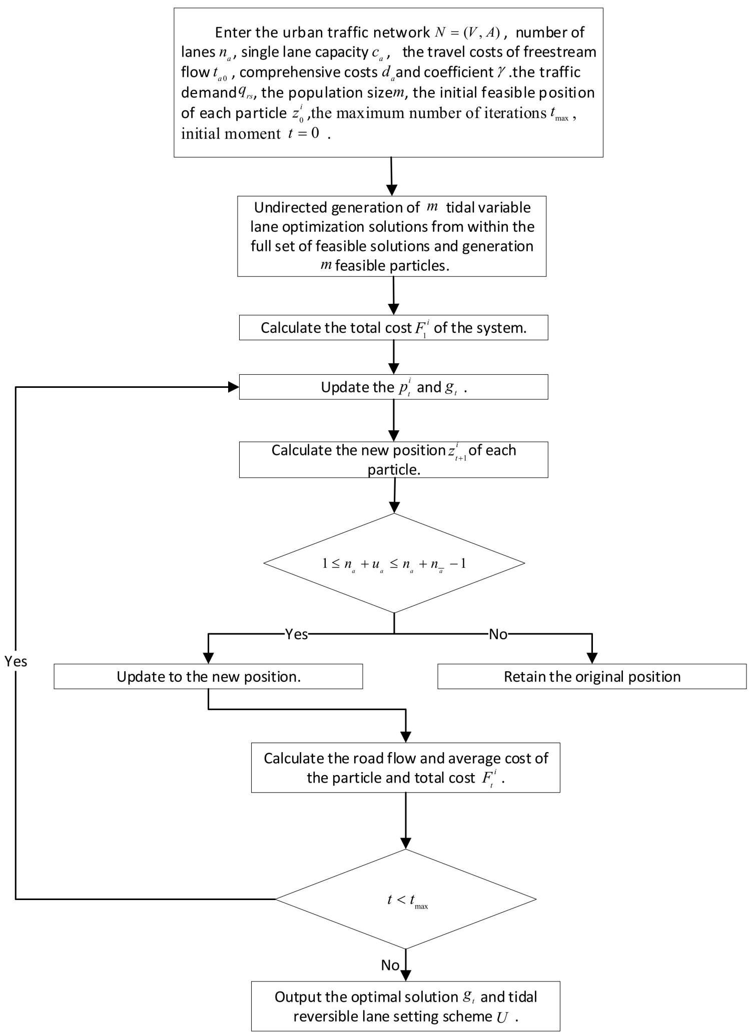

Figure 3. Quantum particle swarm algorithm design process.

According to the OD and traffic network conditions of the existing tidal traffic phenomenon, m reversible lanes' setting scheme codes are randomly selected. The bi-level programming model is calculated by the genetic algorithm, particle swarm algorithm, and quantum particle swarm algorithm. The minimum travel time relative to the initial total cost of the system is compared to that of the final minimum total cost. Traffic congestion is alleviated by the decreasing travel index. The optimal solution is used to adjust the reversible lanes according to the system's minimum total cost.

5. Examples and Results

5.1. Numerical Examples

5.1.1. Construction Examples

To verify the validity and rationality of the above model and the solution algorithm, this paper assumes a regional two-way traffic network where an Olympic lane is set up on a road with three lanes in one direction during peak hours. That is, the number of lanes available for private vehicles in one direction is two and the number of lanes available in both directions is five. During peak hours, the Olympic lanes in the direction of greater traffic are closed to private vehicles.

A regional two-way traffic network is assumed to be selected with 24 nodes and 38 two-way roads with a total of 76 road sections, as shown in Figure 4.

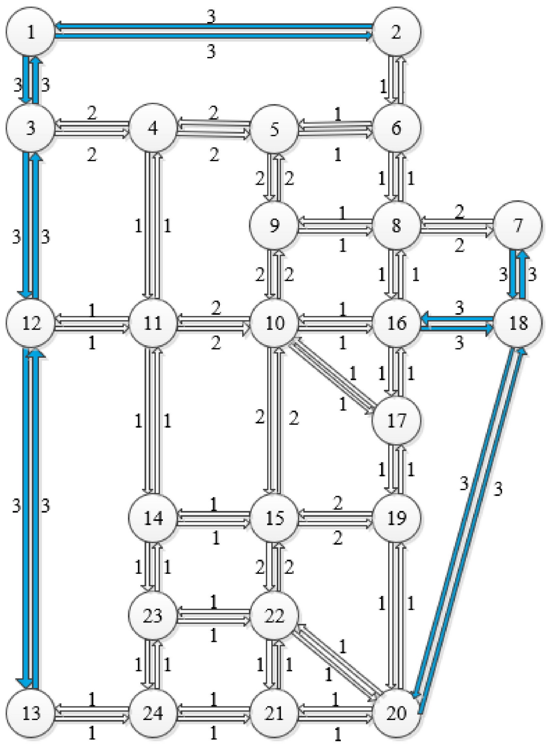

Figure 4. Transportation network structure.

The number of lanes between points is marked above the road. The relative length and width of the road gets wider as it goes out. Figure 4 is more like a mini-city, with urban areas in the middle of the road and expressways on the periphery. Depending on conditions of setting reversible lanes, only 7 roads can satisfy the limitations, which using blue color to highlight.

The situation of each road section and the peak hour OD demand are shown in Tables 1 and 2.

Table 1. Traffic network section situation.

Section Number a	**Name of Road Section**	t_{a0} **(h·10^{-2})**	n_a	c_a**(100 pcu/h)**	d_a	**The Number of Exclusive Olympic Lanes**
1 and 39	1–2 and 2–1	3.6	2	8.63	2	1
2 and 40	1–3 and 3–1	2.4	2	7.8	2	1
3 and 41	2–6 and 6–2	3	1	4.96	1	0
4 and 42	3–4 and 4–3	2.4	2	8.56	2	0
5 and 43	3–12 and 12–3	2.4	2	7.8	1	1
6 and 44	4–5 and 5–4	1.2	2	8.89	1	0
…	…	…	…	…	…	…
38 and 76	23–24 and 24–23	1.2	1	5.08	1	0

Table 2. Traffic network section OD demand matrix $\left(10^3 \text{ pcu/h}\right)$.

	1	**2**	**3**	**4**	**5**	**6**	…	**24**
1	-	0.11	0.11	0.55	0.22	0.33	…	0.11
2	0.11	-	0.11	0.22	0.11	0.44	…	0
3	0.11	0.11	-	0.22	0.11	0.33	…	0
4	0.22	0.22	0.22	-	0.55	0.44	…	0.22
5	0.22	0.11	0.11	0.55	-	0.22	…	0
6	0.33	0.44	0.33	0.44	0.22	-	…	0.11
…	…	…	…	…	…	…	…	…
24	0.11	0	0	0.22	0	0.11	…	-

5.1.2. Solution Algorithm and Analysis

To compare and analyze the effectiveness of the model, we first calculated the system cost value of the traffic network without reversible lanes. A genetic algorithm, a particle swarm algorithm, and a quantum particle swarm algorithm were used to solve the reversible lane scheme of the road network for the arithmetic cases. Meanwhile, the system cost values were compared with the situation with no tidal reversible lanes.

This section of the tidal reversible lane setting scheme only illustrates the setting of tidal reversible lanes on forward roads. The setting of reversible lanes on reverse roads is its opposite during different peak hours.

When solving the model using a genetic algorithm, setting the population size to 10, the number of genetic iterations to 200, and the probability of variation to 0.05, the variation in the objective function value with the number of genetic iterations for the upper-level model in the bi-level programming model is shown in Figure 5.

When using the particle swarm algorithm to solve the optimal design model for reversible lanes under arithmetic traffic network conditions, the number of populations is set to 10, the number of iterations is 200, the learning factor is $c_1 = 2$, $c_2 = 2$, the maximum velocity factor is $k = 0.5$, and the inertia weight factor is $\omega_{max} = 0.9$, and $\omega_{min} = 0.4$. The variation in the objective function value with the number of iterations for the upper-level model in the bi-level programming model is shown in Figure 6.

When using the quantum particle swarm algorithm to solve the optimal design model for reversible lanes under arithmetic traffic network conditions, we set the population size to 60 and the number of iterations to 200. The variation in the objective function value with the number of iterations for the upper-level model in the bi-level programming model is shown in Figure 7.

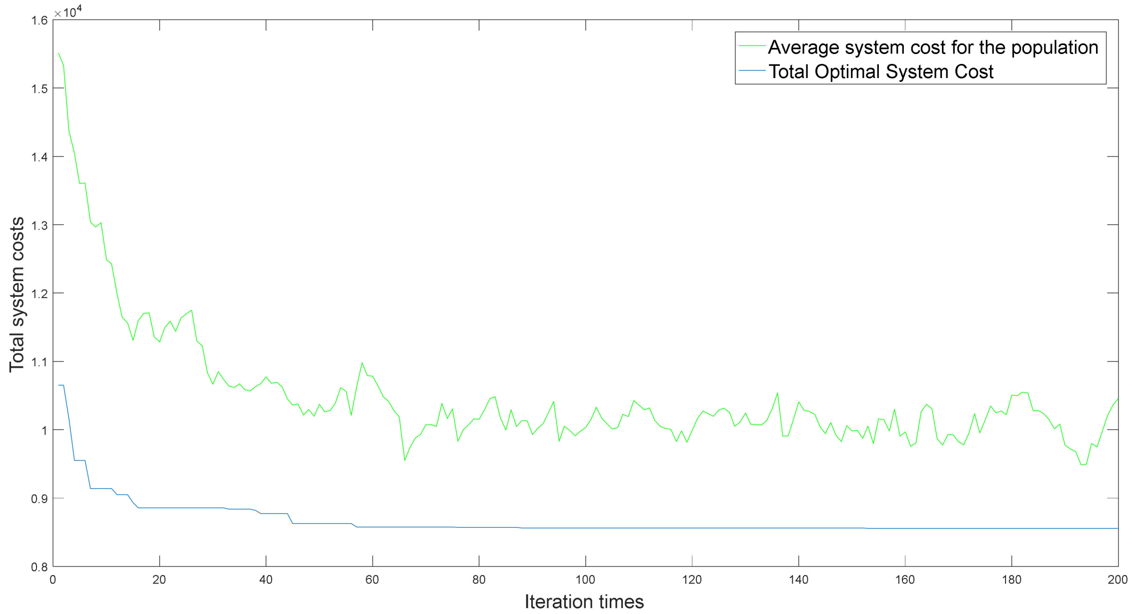

Figure 5. Solving the iterative graph with a genetic algorithm.

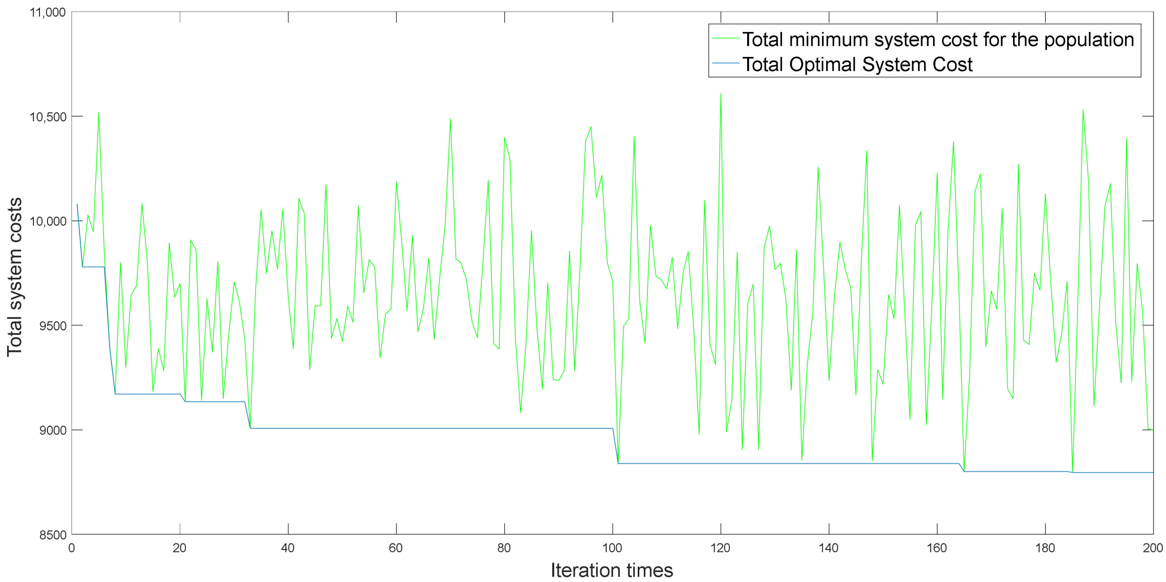

Figure 6. Solving the iterative graph using a particle swarm algorithm.

When there is an Olympic lane with no tidal reversible lanes in the traffic network, the total travel cost is 10,683.

The reversible lane optimization design model used during the Winter Olympics traffic network was solved using a genetic algorithm to obtain a total system cost of 8555.28. The reversible lanes were set up as shown in Table 3.

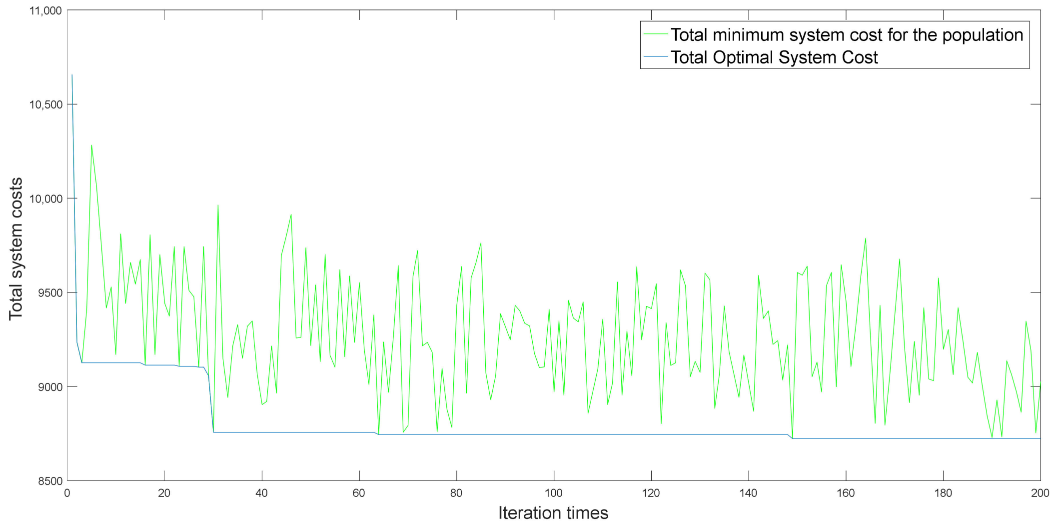

Figure 7. Solving the iterative graph using a quantum particle swarm algorithm.

Table 3. Genetic algorithm tidal reversible lane setting scheme.

Name of Road Section	1–2	1–3	3–12	7–18	12–13	16–18	18–20
Number of lane settings	5	5	5	5	5	5	5
Number of reversible lanes	0	1	0	1	0	0	1

The reversible lane optimization design model during the Winter Olympics traffic network was solved using a particle swarm algorithm to obtain a total system cost of 8796.22. The reversible lanes were set up as shown in Table 4.

Table 4. Particle swarm algorithm tidal reversible lane setting scheme.

Name of Road Section	1–2	1–3	3–12	7–18	12–13	16–18	18–20
Number of lane settings	5	5	5	5	5	5	5
Number of reversible lanes	2	1	1	1	0	−1	1

The reversible lane optimization design model for the Winter Olympics traffic network was solved using a quantum particle swarm algorithm to obtain a total system cost of 8723.47. The reversible lanes were set up as shown in Table 5.

Table 5. Quantum particle swarm algorithm tidal reversible lane setting scheme.

Name of Road Section	1–2	1–3	3–12	7–18	12–13	16–18	18–20
Number of lane settings	5	5	5	5	5	5	5
Number of reversible lanes	0	1	0	0	−1	−1	0

A comparison of the total minimum system cost (minZ) and the total system cost without reversible lanes (NoZ), as solved by each algorithm, is shown in Table 6.

Table 6. Comparison of total system costs.

Name of the Program	NoZ	GAminZ	PSOminZ	QPSOminZ
Total system cost	10,683	8555.28	8796.22	8723.47

When the bi-level planning reversible lane optimization design model based on the Olympic lane established in this paper was solved using a genetic algorithm, a particle swarm algorithm, and a quantum particle swarm algorithm, the reversible lane settings were different. Among them, the total system cost of the reversible lane setting obtained by the genetic algorithm solution was 19.92% lower than that of the no tidal variable lane setting scheme. The total system cost of the reversible lane setting obtained by the particle swarm decreased by 17.91% compared with the cost without reversible lanes. The total system cost of the reversible lane setting obtained by the quantum particle swarm decreased by 18.341% when compared with the cost without reversible lanes.

The minimum travel cost (minZ) and the minimum travel cost without reversible lanes (NoZ) solved by each algorithm are compared in Table 7.

Table 7. Comparison of travel time costs.

Name of the Program	NoZ	GAminZ	PSOminZ	QPSOminZ
Minimum cost	10,683	8526.27	8754.22	8683.46

The installation of temporary reversible lanes decreased the travel costs by 20.2%, 18.06%, and 18.72% compared with no tidal lanes.

Thus, setting a reversible lane in the opposite lane can significantly reduce the total cost of the system and the total travel time, as well as alleviating traffic congestion.

The total system cost resulting from the solution performed by the genetic algorithm is optimal. The minimum system cost was obtained after 153 iterations using the genetic algorithm. The minimum system cost was obtained after 185 iterations using the particle swarm algorithm. The minimum system cost was obtained after 149 iterations using the quantum particle swarm algorithm. By comparison, the quantum particle swarm algorithm converges slightly faster than the genetic algorithm and particle swarm algorithm.

The rationality of the reversible lane optimization design model based on bi-level programming and the effectiveness of the solution were verified through analysis of the solution algorithm.

5.2. Practical Example

Beijing Lian Shi Road, located in Beijing, was selected as an example. Lian Shi Road is 7.8 km long, as shown in Figure 8. It is an important commuter road, connecting Mentougou, Shi Jingshan, and FengTai district, passing from the W 3rd Ring Road to W 5th Ring Road. Lian Shi Road is a two-way six-lane road, where the inner lane is assumed to be the Olympic exclusive lane during peak hours. Meanwhile, the Olympic vehicles drive on the same side as private cars, in the direction of heavy traffic. The opposite Olympic exclusive lane is without vehicles during this period. Depending on the measured data as shown in Table 8, the traffic pressure is higher in the direction of the city than going out of the city. The road sections are divided between the adjacent entrances and exit.

Table 8. Lian Shi Road statistics table.

West to East		East to West	
Section Number	**Volume (pcu/h)**	**Section Number**	**Volume (pcu/h)**
0–1	3013	1–0	2271
1–2	2397	2–1	3185
2–3	3900	3–2	2317
3–4	3561	4–3	2899
4–5	4855	5–4	2349
5–6	4712	6–5	2872
6–7	3757	7–6	3165
7–8	6488	8–7	2988
8–9	5794	9–8	2922
9–10	6692	10–9	2856
10–11	6474	11–10	3184
11–12	6778	12–11	2860

Figure 8. Overview of Lian Shi Road.

The traffic pressure increased from west to east direction with more commuting vehicles entering the city for work. Setting up the Olympic exclusive lane significantly reduced the capacity of private cars, leading to an increase vehicle congestion. The traffic flow in the east to west direction was stable with an overall freestream condition. Therefore, reversible lane measures can be implemented to borrow the inner lane for use by west-to-east private vehicles. The bi-level programming model and genetic algorithm can be adopted to solve this. Variation of the objective function value with the number of genetic iterations for the upper-level model in the bi-level programming model is shown in Figure 9.

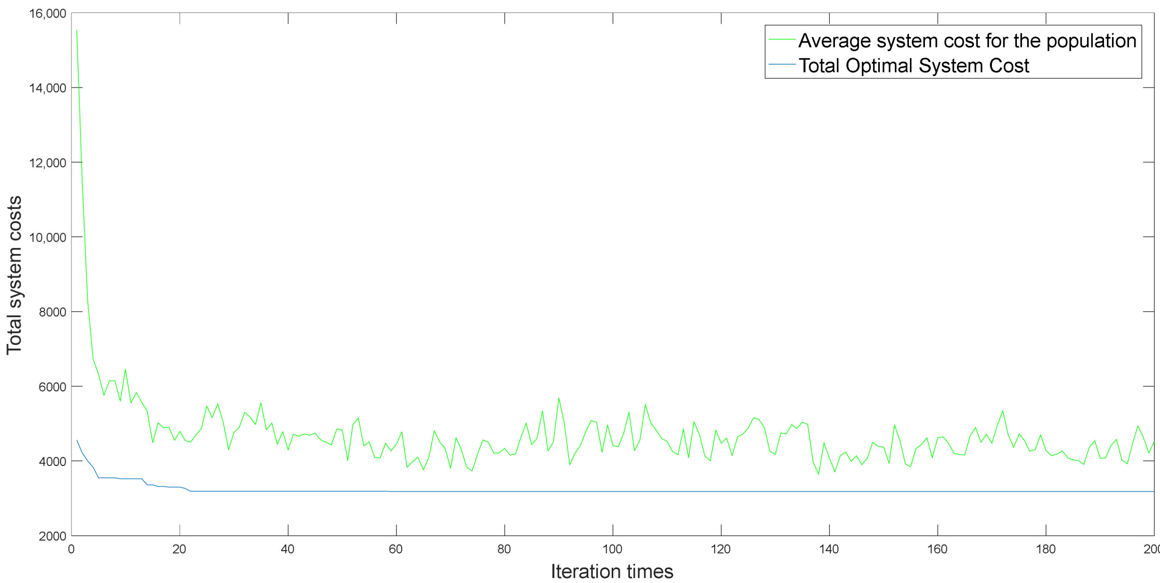

Figure 9. Genetic algorithm iteration diagram.

The reversible lane setting can be obtained by solving the genetic algorithm as shown in Table 9.

Table 9. Genetic algorithm tidal reversible lane setting scheme.

Name of Road Section	4–5	5–6	6–7	7–8	8–9	9–10	10–11	11–12
Number of lane settings	5	5	5	5	5	5	5	5
Number of reversible lanes	1	1	0	1	1	0	1	1

Sections 4–6, 7–9, and 10–12 should be installed for temporary reversible lanes. As 6–7 and 9–10 are relatively short distances, a temporary reversible lane should be set for Sections 4–12, with a total length of 4.6 km, considering its implementation and the driving habits of drivers. In the absence of reversible lanes, the travel time cost for travelers is 4539.5. With the installation of reversible lanes, the travel time cost for travelers was reduced to 3150.3, a 30.6% reduction. Thus, the installation of reversible lanes can significantly reduce travel time and traffic congestion.

6. Conclusions

Installing temporary reversible lanes during peak hours of the Winter Olympics can significantly reduce the commuting time for travelers. It can also alleviate the temporary tidal traffic phenomenon caused by the Olympic exclusive lanes. This paper proposes a method for setting up temporary reversible lanes in the short and medium term. The optimal regulation scheme is studied on the basis of overall government investment and congestion reduction. The research rationalizes the phenomenon of tidal traffic under temporary special circumstances, provides a theoretical foundation for future studies related to the temporary setting of reversible lanes. Moreover, it puts forth a method of investigation for reversible lane adjustments in the medium term. During the Olympic Games, policies regarding the use of Olympic exclusive lanes can be adjusted appropriately to ensure the safety and smoothness of travel for Olympic personnel and simultaneously satisfy the travel demands of private cars. The opposite lane relieves the traffic flow of the side with high traffic pressure and ensures the functioning of the Olympic exclusive lane. Meanwhile, personnel are needed to maintain the normal running of the vehicles.

The complex small network model depicted above was selected based on the harshness of the setting conditions for Olympic exclusive lanes. Subsequently, setting up temporary reversible lanes in different situations should consider large complex networks. However, whether our findings could be applied to emergency situations requires further clarification. Future work should consider the temporal index to explore options for reversible lane adjustment in an emergency. It is also possible to explore temporary reversible lanes establishing short- and medium-term options by selecting the appropriate indicators from the perspective of emissions and environmental indicators.

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Nomenclature

Symbol	**Definition**
V	urban transportation network
W	all nodes of the road network
A	sections of a road network
$\overline{a}$	reverse section of road section
n_a	number of the lane

c_a	single-lane capacity
x_a	section traffic flow
u_a	number of additional lanes
a	alternative tidal reversible lanes
$p_a(u_a)$	investment management cost
γ	conversion parameter of investment management cost and travel time
t_a	average travel cost
t_{a0}	section free travel time
α	regression coefficients
β	regression coefficients
RS	set of origin-destination pairs of OD demands
P_{rs}	path set
q_{rs}	traffic demand
f_{rs}^k	path flow of k

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