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Contents

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Research Article

Research on the Optimization of Cross-Border Logistics Paths of the "Belt and Road" in the Inland Regions

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Taking logistics time, logistics cost, and carbon emissions as optimization objectives, air transportation is included in the cross-border logistics paths optimization of multimodal transportation. Considering the scale effect of transportation, a multiobjective optimization model of cross-border logistics paths including road, water, railway, and air is constructed. The problem of cross-border logistics paths along the "Belt and Road" regions for cities in inland is studied via the NSGA-II method. The research results show that Chengdu and Xi'an should bear a large number of cross-border air transportation and be constructed as the national airport-type logistics hub. The foreign destinations of cross-border air transportation are distributed in different regions, mainly in Eastern Europe and Eastern Central Europe. The optimization result shows that if there is a 1-fold increase in logistics cost, the logistics time can reduce by 1.37 folds after the cross-border air transportation joins in the model. Such a result has effectively guided the transition from cross-border water transportation to cross-border air transportation.

1. Introduction

The "Belt and Road" is a major national initiative for China's opening up. It aims to promote trade development through the interconnection between China and the countries along the "Belt and Road." Efficient cross-border logistics can promote international transaction processing and accelerate the development of international trade [1]. In China, the economic development of different regions is unbalanced, and the level of logistics development in the inland regions is generally slow. To a certain extent, although the "China Railway Express" has strengthened the cross-border logistics capacity of inland regions to the west, its function is still very limited. Taking the western region of China as an example, according to the "Belt and Road Trade Cooperation Big Data Report" released by the State Information Center, the cross-border transportation in the region to the "Belt and Road" countries are mainly by water transportation and road transportation, which account for about 78% of the total exports of freight, while air transportation and railway transportation account for about 15% and 4% of the total exports of freight respectively. Inland regions of China are excessively relying on water transportation of coastal ports and highly polluted road transportation. This not only hinders the development of cross-border logistics and trade but also has a negative impact on the trade of the whole "Belt and Road" initiative. Therefore, based on the existing transportation facilities, inland regions effectively organize cross-border logistics according to their transportation conditions, which is the key to improve the level of interconnection between China and the countries along the "Belt and Road."

Cross-border logistics has the characteristics of long-distance transportation, usually using multimodal transportation [2–5]. At present, the theoretical research of cross-border multimodal transportation mainly focuses on road-sea multimodal transportation, road-rail multimodal transportation, and road-rail-sea multimodal transportation. These researches are optimized by developing a mathematical model. According to different optimization objectives, they can be classified into two categories as follows:

One is to construct a single-objective optimization model to minimize logistics costs. For example, some scholars not only consider transportation cost but also consider transit costs, storage costs, and transportation scale effects when constructing an optimization model [6–8]. Among them, Zhang et al. [6] put forward a basic framework to solve the problem of multimodal transportation paths optimization, which provided a solid foundation for future research. These studies did not consider logistics efficiency and environmental factors, thus, time and carbon emission restrictions are absent in their models. However, with the trend of high-quality economic development, logistics efficiency and environmental factors have become important objectives of cross-border logistics transportation. Scholars have further studied the optimization model, including adding the time window constraint into the optimization model [9–11] or adding logistics time and carbon emissions to logistics costs for optimization [12–15]. Moreover, some scholars have studied models under uncertainty [16–18].

The other one is to construct a multiobjective cross-border logistics optimization model that includes logistics cost, logistics time, and carbon emission [19–21]. It is difficult for single-objective optimization model to balance logistics time, logistics cost, and carbon emission [19]. Due to the release of low-carbon policy, some scholars have focused on the optimization of cross-border logistics paths under low-carbon policy [22–24]. The optimization conclusion of the above literatures is that the proportion of road-sea multimodal transportation and road-rail-sea multimodal transportation is much higher than that of road-sea multimodal transportation. Such a result indicates that it is important for supporting road-rail multimodal transportation and road-rail-sea multimodal transportation to construct the dry ports. We can find that the exploration of air transportation on cross-border multimodal transportation is absent in the existing theoretical studies.

In December 2018, the logistics hub policies were published by relevant departments of the Chinese government. In September 2019 and October 2020, there are 23 cities and 22 cities respectively that became national logistics hubs. Among these cities, there are 13 dry port-type national logistics hubs, 14 seaport-type national logistics hubs, and 3 airport-type national logistics hubs. Since the inland cities in China are far away from seaports, air and railway transportation are important ways for them to carry out cross-border logistics. However, inland cities in China mainly build dry port logistics hubs, while the existing airport-type national logistics hubs are only Beijing, Zhengzhou, and Shenzhen. Therefore, the importance of air transportation in inland cities and the impact of air transportation on cross-border logistics along the "Belt and Road" need to be explored.

This study incorporates air transportation into the theoretical framework of cross-border multimodal transportation. Taking logistics cost, logistics time, and carbon emission as the optimization objectives, a cross-border logistics path optimization model including water, railway, air, and road is constructed. This study not only improves the theory of multimodal transportation but also provides decisions for cross-border logistics transportation and airport-type national logistics hubs construction in inland regions.

2. Construction of Cross-Border Logistics Paths Optimal Model

2.1. An Abstract Description of Cross-Border Transportation Problems. The cross-border transportation, consisting of different types of transportation nodes, is to transport cargoes from the domestic source of supply to the foreign destination. As shown in Figure 1, the different types of transportation nodes are represented by different graphics, including the domestic source of supply $i\,(i \in I)$, domestic dry port $d\,(d \in D)$, domestic airport $a\,(a \in A)$, domestic seaport $p\,(p \in P)$, foreign dry port $d'\,(d' \in D')$, foreign airport $a'\,(a' \in A')$, foreign seaport $p'\,(p' \in P')$, and foreign destination $j\,(j \in J)$. Among them, the channels between the nodes represent different transportation modes, including road transportation, railway transportation, air transportation, and water transportation. The railway transportation involves both domestic railway transportation and cross-border railway transportation. The channels between different transportation nodes have resulted in multiple paths of multimodal transportation.

As shown in Figure 1, four multimodal transportation modes can be selected for cross-border transportation of cargoes from the domestic source of supply i to foreign destination j.(1) The cargoes are transported first from the domestic source of supply i to domestic seaport p through road transportation, then to foreign seaport p' through water transportation, and finally to the foreign destination j through road transportation. This mode is the road-sea multimodal transportation. (2) The cargoes are transported first from the domestic source of supply i to domestic dry port d through road transportation, then to domestic seaport p through railway transportation, and then to foreign seaport p' through water transportation, and finally to the foreign destination j through road transportation. This mode is road-rail-sea multimodal transportation. (3) The cargoes are transported first from the domestic source of supply i to domestic dry port d through road transportation, then to foreign dry port through cross-border rail transportation, and finally to the foreign destination j through road transportation. This mode is the road-rail multimodal transportation. (4) The cargoes are transported first from the domestic source of supply i to domestic airport a through road transportation, then to foreign airport a' through air transportation, and finally to the foreign destination j through road transportation. This mode is the road-air multimodal transportation.

When cargoes are transported from domestic source of supply i to foreign destination j, there are not only four multimodal transportation modes to select but also many

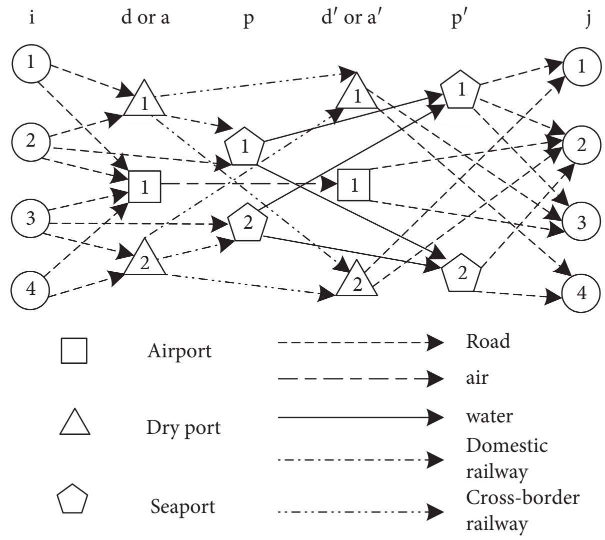

Figure 1: Abstract description of cross-border transportation problems.

Table 1: Model parameters.

	c_{rd}	The road transportation unit cost		F_d	The fixed fees for services provided by the dry port d
Unit freight	c_{rl}	The railway transportation unit cost	Fixed costs	F_a	The fixed fee for the service provided by the airport a
	c_{sea}	The water transportation unit cost		F_p	The fixed fees for services provided by the seaport p
	c_{ra}	The air transportation unit cost		q_{ij}	The freight volume from the source i to the destination j
	co_{rd}	The unit carbon emission factor of road transportation	Freight volume	$B[m]$	The freight volume discount factor
	co_{rl}	The unit carbon emission factor of railway transportation			
Carbon emission	co_{sea}	The unit carbon emission factor of water transportation		t_p	The storage time in the domestic seaport p
	co_{ra}	The unit carbon emission factor of air transportation unit carbon		t_d	The storage time in the dry port d
	r_e	Carbon tax value		t_a	The storage time in the domestic airport a
	l_{id}	The road distance from domestic source i to dry port d	Storage time	$t_{d'}$	The storage time in the foreign dry port d'
	l_{ip}	The road distance from domestic source i to domestic seaport p		$t_{a'}$	The storage time in the foreign airport a′
	$l_{p'j}$	The road distance from the foreign seaport p' to the foreign destination j		t_p	The storage time in the foreign seaport p'
Transport distance	$l_{d'j}$	The road distance from the foreign dry port d' to the foreign destination j		v_{ra}	The air transportation speed
	l_{dp}	The railway distance from the dry port d to domestic the sea port p		v_{rl}	The railway transportation speed
	$l_{aa'}$	The air distance from the domestic airport a to foreign the airport a'	Transport speed	v_{sea}	The water transportation speed
	$l_{dd'}$	The railway distance from the dry port d to the foreign dry port d'		v_{rd}	The road transportation speed
	$l_{pp'}$	The water distance from the domestic seaport p to foreign the seaport p'			

different cross-border logistics paths in each mode. Every cross-border logistics path is accompanied by logistics costs, logistics time, and carbon emissions. The purpose of cross-border logistics paths optimization is to find out the best cross-border logistics paths from the numerous logistics paths corresponding to the four multimodal transportation modes, so as to implement the optimization of logistics costs, logistics time, and carbon emissions.

2.2. A Bi-Objective Mixed-Integer Programming Model for Cross-Border Logistics Path Optimization. According to the method in the literature [14], this study converts emission into carbon tax costs and incorporates them into logistics costs. A bi-objective (logistics cost and logistics time) mixed-integer programming model is constructed in this study on the basis of the four multimodal transportation in Figure 1.

2.2.1. Model Parameters and Variables. Set the decision variables as follows: $X_{\mathrm{ipp}'j}$ as the road-sea multimodal transportation mode decision variable, $X_{\mathrm{idp}'j}$ as the road-rail-sea multimodal transportation mode decision variable, $X_{\mathrm{idp}'j}$ as the road-rail multimodal transportation mode decision variable, and $X_{\mathrm{iaa}'j}$ as the road-air multimodal transportation mode decision variable. These decision variables are binary variables. If a certain multimodal transportation mode is adopted, the corresponding decision variable is 1; otherwise, the decision variable is 0. In addition, the related parameters need to be selected including unit transportation cost, carbon emissions, transportation distance, fixed cost, storage time, transportation speed, and freight volume. The specific parameter symbols and meanings are listed in Table 1.

2.2.2. Model Objective Function. As for cross-border logistics paths optimization, there are two objective functions including cross-border logistics cost and cross-border logistics time in the bi-objective mixed-integer programming model.

Cross-border logistics costs consist of transportation costs, fixed costs at each port, and carbon tax costs converted from carbon emissions during transportation. Considering the scale effect of railway transportation, the growth rate of total transportation costs will slow down as freight volumes increase. Therefore, a constant unit transportation cost can be equivalently considered as a decrease in freight volume. Based on the size of freight volume, the decreased freight volume can be divided into three intervals with different discount factors, which is expressed as the original freight volume multiplied by the discount factor of the corresponding interval [25]. Therefore, the cost objective function is constructed as follows:

$$
\begin{aligned}
\min f_1 = & \sum_{i,j,p,p'} q_{\mathrm{ij}} X_{\mathrm{ipp}'j}\Big(\big(C_{\mathrm{rd}} + \mathrm{co}_{\mathrm{rd}} \times r_e\big)\big(l_{\mathrm{ip}} + l_{p'j}\big) + \big(C_{\mathrm{sea}} + co_{\mathrm{sea}} \times r_e\big) l_{pp'}\Big) \\
& + \sum_{i,j,d,p,p'} X_{\mathrm{idpp'}j}\Big(q_{\mathrm{ij}}\big(\mathrm{z}C_{\mathrm{rd}} + \mathrm{co}_{\mathrm{rd}} \times r_e\big) l_{\mathrm{id}} + \big(C_{\mathrm{sea}} + \mathrm{co}_{\mathrm{sea}} \times r_e\big) l_{\mathrm{pp}'} \\
& + \big(C_{\mathrm{rd}} + \mathrm{co}_{\mathrm{rd}} \times r_e\big) l_{p'j}\Big) + q_{\mathrm{ij}} B[m]\big(\mathrm{co}_{\mathrm{rl}} + \mathrm{co}_{\mathrm{rl}} \times r_e\big) l_{\mathrm{dp}}\Big) \\
& + \sum_{i,j,d,d'} X_{\mathrm{idd}'j}\Big(q_{\mathrm{ij}}\big(C_{rd} + \mathrm{co}_{\mathrm{rd}} \times r_e\big)\big(l_{\mathrm{id}} + l_{d'j}\big) + q_{\mathrm{ij}} B[m]\big(\mathrm{co}_{\mathrm{rl}} + \mathrm{co}_{\mathrm{rl}} \times r_e\big) l_{\mathrm{dp}}\Big) \\
& + \sum_{i,j,a,a'} q_{ij} X_{\mathrm{iaa}'j}\Big(\big(C_{\mathrm{rd}} + \mathrm{co}_{\mathrm{rd}} \times r_e\big)\big(l_{\mathrm{ia}} + l_{a'j}\big) + \big(C_{\mathrm{ra}} + \mathrm{co}_{\mathrm{ra}} \times r_e\big) l_{\mathrm{aa}'}\Big) \\
& + \sum_{a,d,p}\big(y_d F_d + y_a F_a + y_p F_p\big).
\end{aligned} \tag{1}
$$

The first part of the objective function of the road-sea multimodal transportation is the transportation cost and carbon tax cost. The second part is the transportation cost and carbon tax cost of the road-rail-sea multimodal transportation which has the scale effect. The third part is the transportation cost and carbon tax cost of the road-rail multimodal transportation which has the scale effect. The fourth part is the transportation cost and carbon tax cost of the road-air multimodal transportation. The last part is the fixed cost at each port, and the binary variables including y_a, y_d, and y_p indicate whether the airport, dry port, and seaport provide services respectively.

Cross-border logistics time consists of transportation time and storage time at each port. The transportation time is the distance between two logistics nodes divided by the speed. Therefore, the time objective function is constructed as follows:

$$\min f_2 = \left(\sum_{a,a_\prime,d,d_\prime,p,p'} X_{\mathrm{ipp}'j} \left(\frac{\left(l_{\mathrm{ip}} + l_{p'j}\right)}{v_{\mathrm{rd}}} + \frac{l_{\mathrm{pp}'}}{v_{\mathrm{sea}} + t_p + t_{p'}} \right) \right.$$

$$+ X_{\mathrm{idpp}'j} \left(\frac{\left(l_{\mathrm{id}} + l_{p'j}\right)}{v_{\mathrm{rd}}} + \frac{l_{\mathrm{dp}}}{v_{\mathrm{rl}}} + \frac{l_{\mathrm{pp}'}}{v_{\mathrm{sea}} + t_d + t_p + t_{p'}} \right)$$

$$+ X_{\mathrm{idp}'j} \left(\frac{\left(l_{\mathrm{id}} + l_{d'j}\right)}{v_{\mathrm{rd}}} + \frac{l_{\mathrm{dd}'}}{v_{\mathrm{rl}} + t_d + t_{d'}} \right)$$

$$+ X_{\mathrm{iaa}'j} \frac{\left(\left(l_{\mathrm{ia}} + l_{a'j}\right)/v_{\mathrm{ra}} + l_{\mathrm{aa}'}/v_{\mathrm{rl}} + t_a + t_{a'}\right)}{24}. \tag{2}$$

The first part of the objective function is the transportation time of the road-sea multimodal transportation and the storage time of domestic and foreign seaports. The second part is the transportation time of the road-rail-sea multimodal transportation and the storage time of domestic, foreign seaports, and domestic dry ports. The third part is the transportation time of the road-rail multimodal transportation and the storage time of domestic and foreign dry ports. The fourth part is the transportation time of the road-air multimodal transportation and the storage time of domestic and foreign airports.

2.2.3. Constraint Conditions. The constraint conditions that must be met by the variables in the model are as follows:

$$\sum_{d,a,p,d',a',p'} \left(X_{\mathrm{ipp}'j} + X_{\mathrm{idpp}'j} + X_{\mathrm{idp}'j} + X_{\mathrm{iaa}'j}\right) = 1, \forall i \in I; j \in J. \tag{3}$$

$$X_{\mathrm{idp}'j} \le y_d, \forall i \in I; j \in J; d \in D; d' \in D'. \tag{4}$$

$$X_{\mathrm{iaa}'j} \le y_a, \forall i \in I; j \in J; a \in A; a' \in A'. \tag{5}$$

$$X_{\mathrm{ipp}'j} \le y_p, \forall i \in I; j \in J; p \in P; p' \in P'. \tag{6}$$

$$X_{\mathrm{idpp}'j} \le y_p, \forall i \in I; j \in J; p \in P; p' \in P'; d \in D. \tag{7}$$

$$X_{\mathrm{idpp}'j} \le y_d, \forall i \in I; j \in J; p \in P; p' \in P'; d \in D. \tag{8}$$

$$y_a, y_d, y_p, X_{\mathrm{idp}'j}, X_{\mathrm{iaa}'j}, X_{\mathrm{ipp}'j}, X_{\mathrm{idpp}'j} \in \{0, 1\}. \tag{9}$$

Among them, constraint conditions (3) indicate that only one multimodal transportation mode can be used for cross-border transportation. Constraints conditions (4) to (8) indicate that multimodal modes passing through this port can be adopted only after the corresponding seaport, airport, or dry port has been passed through. Constraint condition (9) indicates that the variables in the constraint are binary variables.

3. The Solution to the Optimization Model of Cross-Border Logistics Path: Genetic Algorithm

In the bi-objective mixed-integer programming model for cross-border logistics path optimization, the two optimization objectives of logistics cost and logistics time cannot be optimized at the same time. Therefore, how to balance the importance of these two optimization objectives is the key to obtain the optimal cross-border logistics paths. Following the method of solving multiple objective functions in the existing literature [22, 26, 27], the genetic algorithm is used to find the Pareto optimal solution of logistics cost and logistics time in this study. In the solution process, this study adopts the NSGA-II algorithm [28] that ensures the diversity of the population and high computational efficiency. This algorithm cannot directly calculate the fitness of the chromosomes to select the optimal solution like the single-objective algorithms, while it is used to select the optimal solution by calculating the nondominated sorting level and crowding distance of each chromosome. The optimal solutions are further optimized by genetic operations and repeated until the solutions are obtained that outperform other chromosomes in both objectives within a specified maximum number of generations. The optimal solutions are called the Pareto optimal solution sets. The specific process is as follows:

3.1. Chromosome Encoding and Decoding of Cross-Border Logistics Paths. In this study, the chromosome is encoded by integer coding. Each chromosome represents a cross-border logistics path with 8-bit codes. The first part of the chromosome is the code of multimodal transportation mode, and the second part is the code of passing through ports. The specific coding structure is shown in Figure 2.

The first part of the chromosome consists of the first four codes, representing different multimodal transportation modes. They are road-sea multimodal transportation, road-rail-sea multimodal transportation, road-rail multimodal transportation, and road-air multimodal transportation, successively. The code is taken as an integer from 0 to 1. If the multimodal transportation mode is selected, the code is 1, otherwise, the code is 0. Since only one multimodal mode can be selected for each cross-border logistics path, only one of the 4-bit codes is 1.

The second part of the chromosome consists of the last four codes that represent the number of the port passed through. They are domestic dry port or airport, domestic seaport, foreign dry port or airport, and foreign seaport, successively. Since dry port and airport do not appear in the same multimodal transportation mode, they are represented by the same location code. The second part of the code is taken as the number of the different ports (m_1, m_2, m_3, and m_4) or 0. If any port is passed through, the corresponding code is the number of this port, otherwise, the code is 0. The second part of the chromosome is determined by the first part of the chromosome. For example, in the road-sea multimodal transportation mode, the code representing the

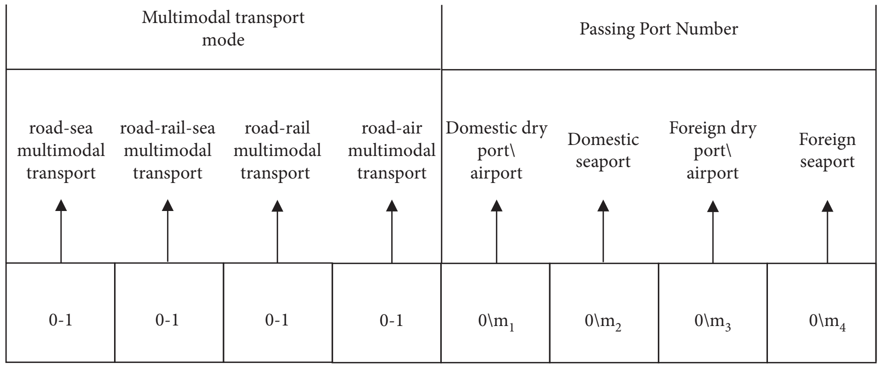

Figure 2: Chromosome coding.

seaport is the port number, while the code representing the other ports is 0. The specific decoding process is given in Figure 3.

As shown in Figure 3, based on the first part of the chromosome, it is known that the chromosome is a road-sea multimodal transportation mode. From the second part of the chromosome, the cargoes are transported through road transportation from the source of supply to the domestic seaport 3, then through cross-border water transportation to the foreign seaport 4, and finally through road transportation to destination.

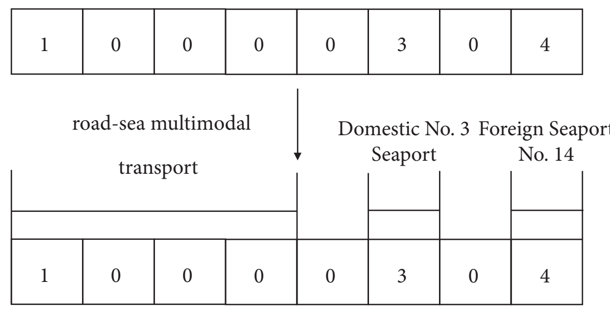

Figure 3: Chromosome decoding.

3.2. NSGA-II Algorithm Process

3.2.1. Nondominated Sorting and Calculating Crowding Distance. The code is initialized to obtain the initial population of cross-border logistics paths. The two objective function values are calculated for each cross-border logistics path in the population. Such a result indicates that each logistics path is sorted nondominated, and the logistics paths with the least dominated rank are selected from them. Moreover, the crowding distance of logistics path in the same rank is calculated to ensure the diversity of the population. As shown in Figure 4, the crowding distance of any logistic path is the difference between two adjacent logistic paths, and the crowding distance of node n can be calculated by equations (10)–(12) [29]. Equations (11) and (12) indicate the difference between the node $n+1$ and the node $n-1$ in the objective function (1) and the objective function (2), respectively. After finishing the sorting and the calculation of crowding distance for all logistics paths, the logistics paths with the least dominant sorting and the largest crowding distance are selected as the candidate populations.

$$\text{The crowding distance of node } n = \Delta f_1 + \Delta f_2. \quad (10)$$

$$\Delta f_1 = f_1(n+1) - f_1(n-1). \quad (11)$$

$$\Delta f_2 = f_2(n+1) - f_2(n-1). \quad (12)$$

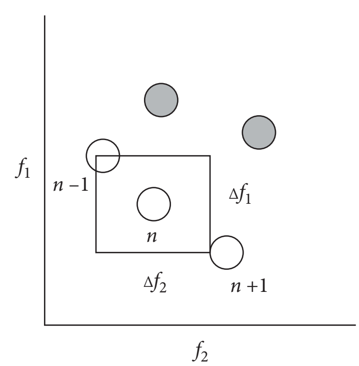

Figure 4: Crowding distance for node **n**.

3.2.2. Select. The tournament selection algorithm is used to simulate the elimination system [13] in this study. A certain number of cross-border logistics paths are randomly selected from the population for comparison every time, and the cross-border optimal logistics path is selected to join the next-generation population. This operation is repeated until the size of the next-generation population reaches the number that needs to be selected.

3.2.3. Crossing and Mutation. Based on the set crossover and mutation probabilities, some cross-border logistic paths in the new population are selected for crossover and mutation. Then crossover and mutation should follow the coding rules in 2.1, otherwise the logistics path will be discarded. The SBX [30] (simulated binary crossover) and polynomial mutation [25] are adopted to further increase the diversity of the population, enhance the local search ability, and speed up the convergence.

```
Input: Number of individuals in the population, NUM; Maximum evolutionary generation, G;
Output: The population that completes the optimization is the pareto optimal solution;
/* Initial population */
while g = 0. g ≤ G do
population: = population + offspring;/* Father and son merged */
levels: = ndSort (population, NUM);/* Non-dominant ranking */
distance: = crowdis (population, levels);/* Calculate the crowded distance */
population, FitnV: = argsort (lexsort ([dis-levels]));/*Calculate fitness */
until number of population < NUM
return population
/* Start to evolve */
offspring: = population|selecting (population, FitnV, NUM)|;/*Select individuals to participate in evolution */
offspring: = recOper (offspring);/* Simulated binary crossover */
offspring: = mutOper (offspring);/* Polynomial mutation */
population: = reinsertion (population, offspring);/*Reinsert to get a new generation of population */
g: = g + 1
end do
return population
```

Algorithm 1: NSGA-II algorithm.

3.2.4. Elitism Strategy. When generating the cross-border logistics path population of the offspring, the elitism strategy is introduced to ensure that the optimal solution is obtained [28]. This strategy combines parental population with offspring population to compete together. This results in an increased space of the selected logistics path, and hence it is helpful to improve more optimal solutions for the next generation.

3.2.5. Algorithm Pseudocode. Based on the above algorithm design, the specific steps of NSGA-II algorithm are shown in Algorithm 1.

4. The "Belt and Road" Cross-Border Logistics Path Optimization Program

4.1. Freight City and Model Parameter Selection. Considering the optimization of the "Belt and Road" cross-border logistics paths in inland regions, this study focuses on the key regions including the urban agglomeration in the middle reaches of the Yangtze River, Chengdu–Chongqing urban agglomeration, and Zhongyuan Urban agglomeration. Among these regions, 14 cities such as Yibin, Baoji, Daqing, and Luoyang are selected as domestic sources of supply. According to indicators such as economic aggregates and trade levels of foreign cities along the "Belt and Road," 11 cities, including Tashkent, Nur-Sultan, and Moscow, are selected as foreign destinations. According to the government policy issued in 2018, 10 cities such as Zhengzhou, Chengdu, and Xi'an are selected as both domestic dry ports and domestic airports, and 6 cities such as Shanghai, Dalian, and Lianyungang are selected as domestic seaports. At the same time, 10 cities such as Lodz, Almaty, and Moscow are selected as foreign dry ports or foreign airports, and 6 cities such as Haiphong are selected as foreign seaports based on the total economic volume and infrastructure of the overseas cities along the "Belt and Road." Due to good trade development and a high level of logistics development, some cities such as Moscow and Tashkent are both destinations and hub ports, as listed in Table 2.

According to the literatures [23, 31, 32] and the actual data collected, various parameters, such as the transportation costs, carbon emission factor, and speed, are set as listed in Tables 3 and 4 (1 yuan = 0.1547 $) [33]. Then the average storage time in dry ports, airports, and seaports is 12 h, 12 h, and 24 h, respectively [31]. The fixed fees for services provided by seaports, dry ports, and airports are 2,000yuan, 2,000 yuan, and 1,500 yuan, respectively [32].

4.2. Experimental Results and Analysis. Considering the parameter setting in the relevant literatures [34, 35] and the result of our tests, the algorithm parameters are set as follows: the population number is 2000, the maximum number of iterations is 500, the probability of crossover is 0.9, the probability of mutation is 0.01, and the distribution indexes of SBX and polynomial mutation are both 20. Based on the above model parameters and algorithm parameters, the model is programmed by Python to obtain the Pareto optimal solution sets for the cross-border logistics paths. Taking the cross-border logistics paths from Baoji to New Delhi as an example, its optimal Pareto solution sets are shown as star-shaped points in Figure 5.

According to the method for obtaining Pareto satisfactory solutions in the literature [22], the percentage changes of logistics cost and logistics time for the five Pareto solutions are analyzed in Figure 5. Among them, the solution indicated by the arrow is the Pareto satisfactory solution. The characteristic of this solution increasing the least logistics costs can save the most logistics time. The logistics path corresponding to this Pareto satisfactory solution is Baoji-Changsha-Guangzhou-Mumbai-New Delhi (road-rail-sea multimodal transportation). The logistics cost of this path is 232,304.24 yuan and the logistics time of this path is 18.09 days. Similarly, the optimal cross-border logistics

Table 2: Source, destination, and port hub.

Domestic sources of supply	Daqing, Tongliao, Luoyang, Xiangyang, Xinyang, Zunyi, Huaihua, Yibin, Zhaotong Yulin, Baoji, Shangrao, Changzhou, Jiaxing
Domestic dry ports/airports	Harbin, Zhengzhou, Changsha, Chengdu, Kunming, Xi'an, Nanjing, Hangzhou, Chongqing, Guiyang
Domestic seaports	Dalian, Lianyungang, Qingdao, Guangzhou, Tianjin, Shanghai
Foreign dry ports/airports	Tashkent, Almaty, Moscow, Rhodes, Tehran, Minsk, Riga, Prague, Istanbul
Foreign seaports	Haiphong, Mumbai, Abbas, Mersin, Odessa, Gdynia, Riga
Foreign destination	Tashkent, Nur, Sultan, Moscow, Warsaw, Tehran, Minsk, Riga, Prague, Ankara, New Delhi, Hanoi, Kiev

Table 3: Transportation mode parameters.

Mode of transportation	Unit transportation cost (yuan/t-km)	Unit carbon emission factor	Average speed (km/h)
Road transportation	1	0.283	90
Railway transportation	0.65	0.022	60
Water transportation	0.35	0.016	30
Air transportation	2	1.036	900

Table 4: Discount factor of freight volume.

Range of freight volume	More than 30t	Between 15 t and 30 t	Less than 15 t
Discount factor of freight volume	0.93	0.96	1

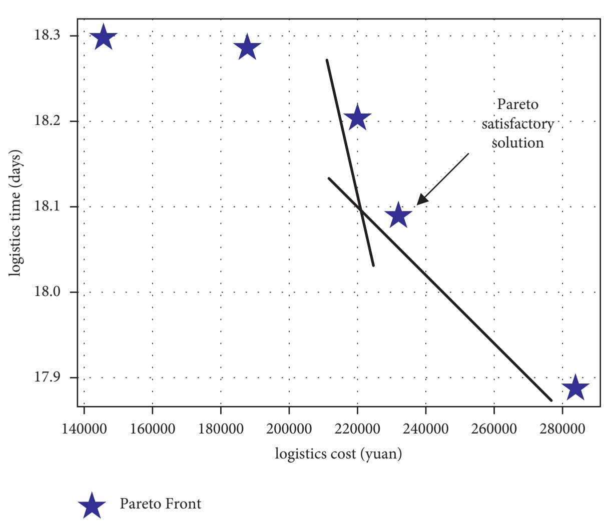

Figure 5: Baoji-New Delhi optimal path Pareto optimal solution sets.

paths corresponding to all Pareto satisfactory solutions from the source to the destination can be obtained, and there are 168 paths in total. Among them, the number of optimal cross-border logistics paths using road-air multimodal transportation, road-rail multimodal transportation, road-rail-sea multimodal transportation, and road-sea multimodal transportation are 47, 93, 26, and 2, respectively.

For simplicity of analysis, the road-sea multimodal transportation and the road-rail-sea multimodal transportation are collectively called cross-border water transportation; meanwhile the road-rail multimodal transportation and road-air multimodal transportation are called cross-border water transportation and cross-border air transportation, respectively. According to the geographical regions of the domestic sources of supply, the cross-border logistics paths are divided into five regions including the northeast region of China, the northwest region of China, the southeast region of China, the southwest region of China, and the central region of China.

4.2.1. Proportion Analysis of Optimal Cross-Border Logistics Paths. The proportion of transportation modes in the optimal cross-border logistics paths in the five regions is given in Figure 6.

As shown in Figure 6, the highest proportion of transportation modes is cross-border railway transportation. It indicates cross-border railway transportation should be more adopted by inland regions for organizing cross-border logistics. That is to say, China Railway Express is now a powerful way to enhance the capacity of cross-border logistics in the inland regions, while the lowest proportion of transportation modes is cross-border water transportation in inland regions. Though there are the greatest advantages of cross-border water transportation in southeast regions, cross-border water transportation accounts for only 9.1%. It indicates that inland regions should not use cross-border water transportation in large quantities to organize cross-border logistics. Cross-border air transportation accounts for an important proportion in all optimal cross-border logistics paths of inland regions. Among them, the region with the highest proportion of cross-border air transportation is the northwest region, reaching 45.5%. The regions with a middle proportion of cross-border air transportation are the southwest regions and central regions,

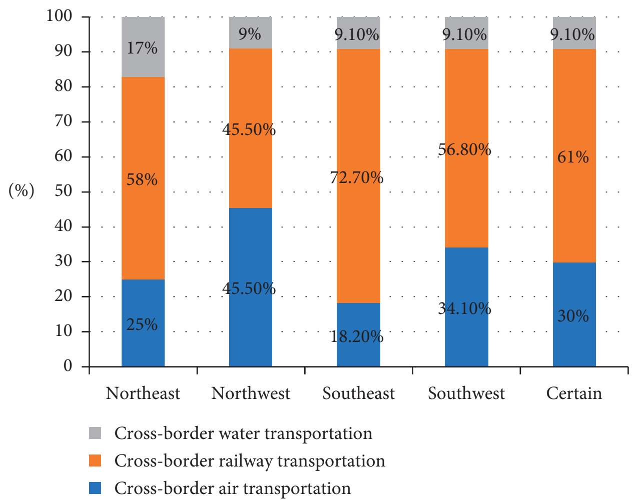

FIGURE 6: Proportion of transportation modes in optimal cross-border logistics paths.

reaching between 30% and 35%. The regions with the lowest proportion of cross-border air transportation are the northeast regions and southeast regions, reaching 25% and 18.2% respectively. Such a result indicates that there is a great potential for northwest regions, southwest regions, and central regions to organize cross-border logistics through cross-border air transportation.

However, only Beijing, Shenzhen, and Zhengzhou have been constructed as airport-type national logistics hubs among the existing national logistics hubs according to the recent government policies. Therefore, there is an urgent need for China to build national airport-based logistics hubs in the northwest and southwest regions, which can optimize and enhance the cross-border air logistics capacity of these two regions.

4.2.2. Result Analysis of Optimal Cross-Border Logistics Paths. The transportation modes of cross-border logistics from inland regions to foreign destinations are different. From the results of optimal cross-border logistics paths, the cross-border railway transportation accounts for 81% of cross-border logistics paths to Central and West Asia. That is to say, when cargoes are transported from inland regions to Central and West Asia, cross-border railway transportation should be given priority, while destinations of inland regions using cross-border water transportation to organize cross-border logistics are South Asia. It indicates cross-border water transportation should be given priority, when cargoes are transported from inland regions to South Asia. Cross-border air transportation accounts for 47% of the cross-border logistics paths to Central and Eastern Europe. Therefore, cargoes are transported from inland regions to Central and Eastern Europe, and cross-border air transportation should be given priority. Among them, there are 89% paths are passing through Lodz in Central Europe and Minsk in Eastern Europe. Therefore, Lodz and Minsk are significant foreign airports for inland regions to organize cross-border logistics.

In order to analyze the optimal cross-border logistics paths for different regions, the results of the optimal cross-border logistics paths in five regions are given in Figures 7–10.

As shown in Figures 7–10, cargoes are transported from northwest region mainly to Central and Eastern Europe, and partly to Central and Western Asia by cross-border air transport. Cargoes are transported from southwest region mainly to Eastern Europe, and partly to Central Europe and Central Asia. Cargoes are transported from central region mainly to Eastern European, and partly to Central European. Although cargoes are transported from southeast region and northeast region rarely to foreign destinations by cross-border air transportation, there are still stable cross-border logistics paths by this transportation mode. Among them, cargoes are transported from northeast region to Kiev via the path of "Chengdu–Lodz," and cargoes are transported from southeast region to Tashkent via the path of "Xi'an-Almaty." Therefore, there are differences in foreign destinations to which the cargoes are transported from each region. Therefore, the selection of cross-border air transportation should be based on the above results. Similarly, when inland regions choose other cross-border transportation modes for cross-border logistics, the optimal cross-border logistics paths should be selected based on the above results.

Since there is an urgent need for the construction of airport-type national logistics hubs in the northwest and southwest regions, the percentage of optimal cross-border logistics paths through each airport hub within these two regions is calculated. The results are listed in Table 5.

As listed in Table 5, the percentage of optimal cross-border paths through Xi'an in northwest region and inland regions are 50% and 30%, respectively. The percentage of optimal cross-border paths through Chengdu in southwest region and inland regions are 80% and 53%, respectively. For other airports hubs, Chongqing is only passed by a few optimal cross-border logistics paths. At present, according to the list of national logistics hubs, Xi'an and Chengdu are only constructed as dry port-type national logistics hubs. Therefore, China should build Xi'an and Chengdu as airport-type national logistics hubs when planning the construction of national logistics hubs in the future.

4.2.3. Necessity Analysis of Introducing Cross-Border Air Transportation. The main theoretical contribution of this study is to integrate air transportation with the theoretical research framework of cross-border logistics multimodal transportation. Therefore, this study compares the optimization results of the abovementioned cross-border logistics paths with those excluding cross-border air transportation, and focuses on analyzing the logistics cost and logistics time in the optimization objectives. The results of the comparison are given in Figures 11 and 12.

As shown in Figures 11 and 12, the logistics cost and logistics time of each logistics path are summarized in this study. The total logistics cost of all optimal cross-border logistics paths is $C_1 = 236554507$ yuan and the total logistics time is $T_1 = 636.33$ days, while the total logistics cost of all

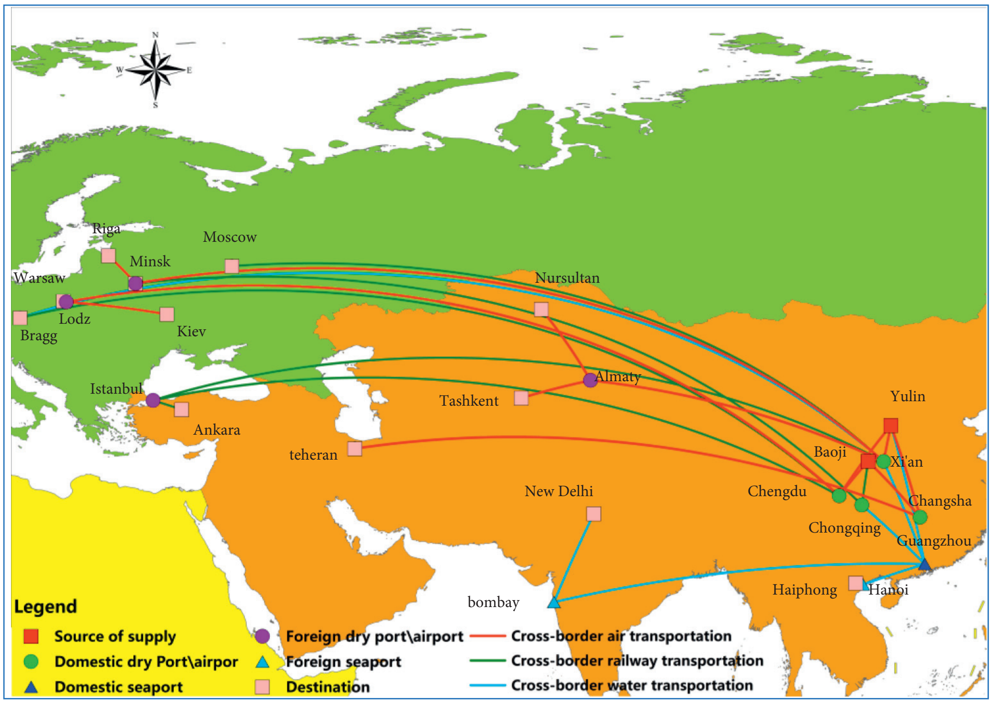

Figure 7: The optimal cross-border logistics paths in northwest region.

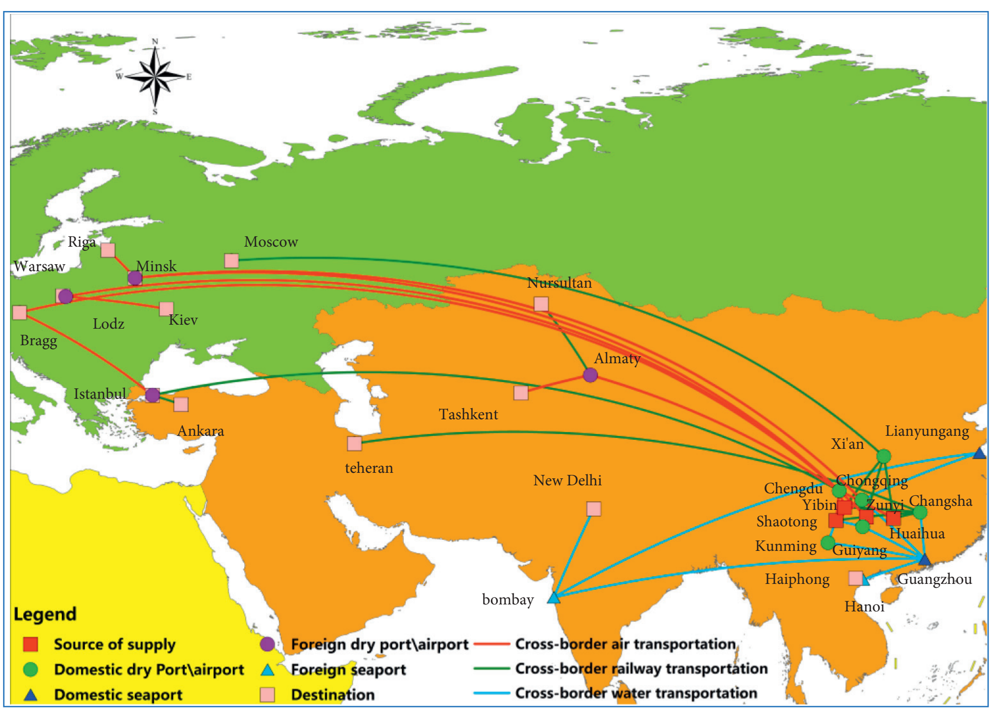

Figure 8: The optimal cross-border logistics paths in southwest region.

optimal cross-border logistics paths excluding cross-border air transportation is $C_2 = 71196217.86$ yuan and the total logistics time is $T_2 = 2654.67$ days. Therefore, if there is a 1-fold increase in logistics cost, the logistics time can reduce by 1.37 folds after joining the cross-border air transportation. The reduction of logistics time is far greater than that of the increase in logistics cost.

To explore the impact on cross-border logistics after joining cross-border air transportation, this study compares the transportation proportion of the above two optimal

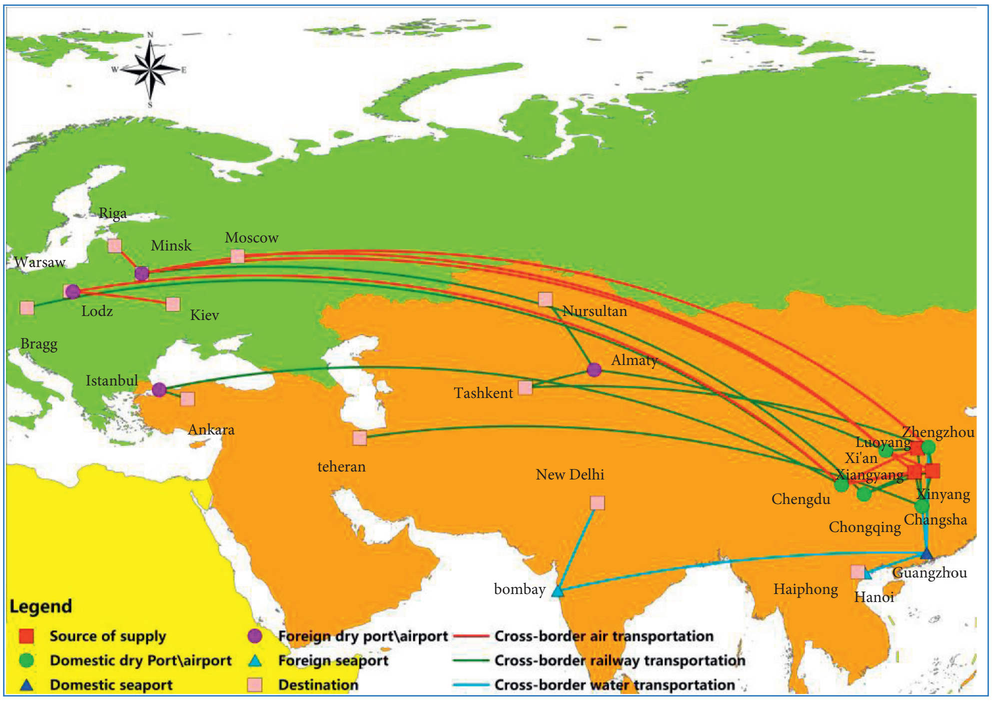

FIGURE 9: The optimal cross-border logistics paths in central region.

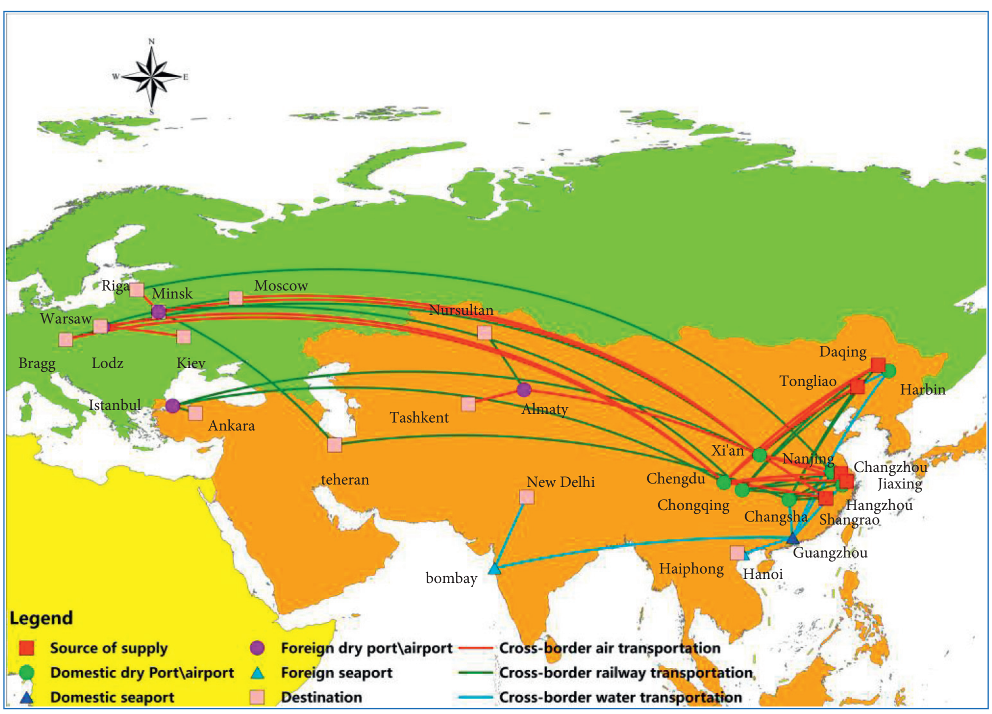

FIGURE 10: The optimal cross-border logistics paths in northeast and southeast regions.

TABLE 5: The percentage of the optimal cross-border paths through the airport.

City	Xi'an (%)	Chengdu (%)	Chongqing (%)	Kunming (%)	Guiyang (%)
Percentage of region	50	80	20	0	0
Percentage of all regions	30	53	7	0	0

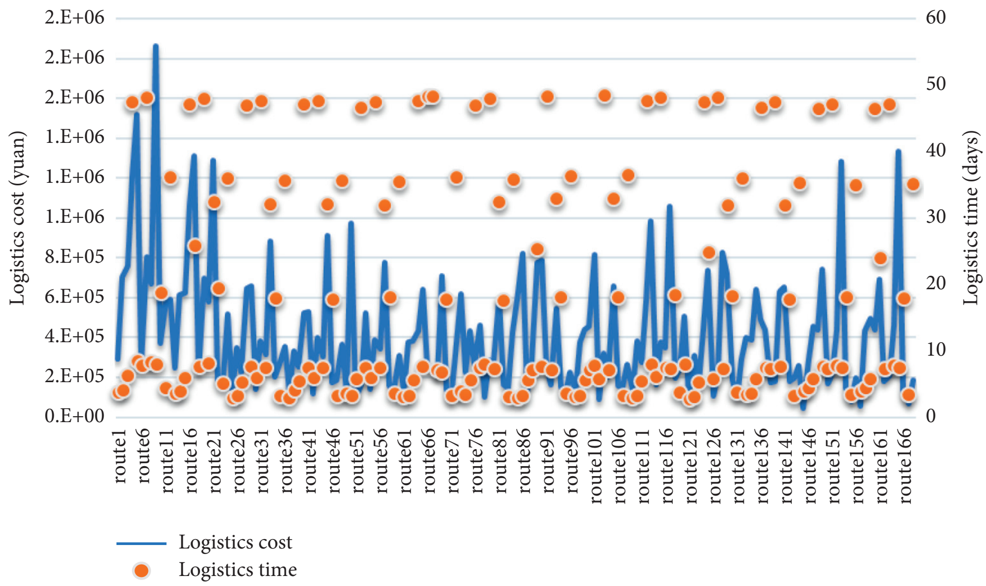

Figure 11: The result of optimal cross-border logistics paths excluding cross-border air transportation.

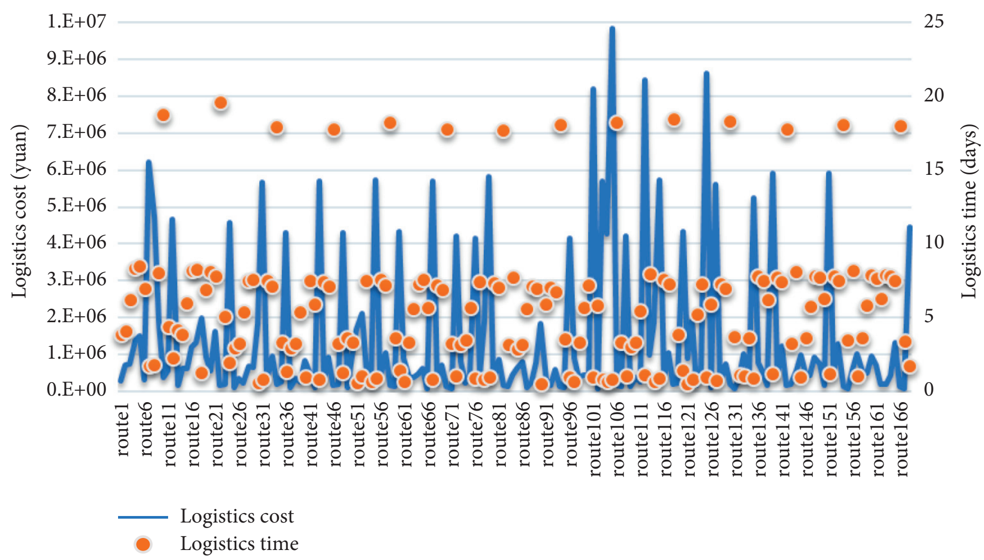

Figure 12: The result of optimal cross-border logistics paths.

Table 6: The comparison of transportation proportions for optimal cross-border logistics paths based on bi-objective optimization.

	The result of optimal cross-border logistics paths (%)	The result of optimal cross-border logistics paths excluding cross-border air transportation (%)
Cross-border air transportation	28	0
Cross-border water transportation	17	47.70
Cross-border railway transportation	55	52.30

results based on bi-objective optimization. Table 6 lists the results of the comparison.

As listed in Table 6, in the result of optimal cross-border logistics paths excluding cross-border air transportation, the transportation proportions of cross-border railway transportation and cross-border water transportation are 52.3% and 47.7%, respectively. After joining cross-border air transportation, the proportion of cross-border air transportation increases to 28%, cross-border water transportation decreases to 17%, while cross-border railway transportation slightly increases to 55%. Therefore, the joining of cross-border air transportation will not affect the development of the "China Railway Express" but will only reduce the pressure on the coastal ports of cross-border water transportation. Such a result will promote the efficiency of cross-border logistics and the development of trade along the "Belt and Road."

5. Conclusions

It is important for inland regions to choose cross-border logistics paths reasonably to participate in the "Belt and Road" initiative. In this study, the logistics cost, logistics time, and carbon emissions are taken as optimization objectives, and a mixed-integer programming model for the multiobjective optimization of the cross-border logistics paths is constructed. We integrate innovatively air transportation with the theoretical research framework, and then explore the influence of air transportation on cross-border logistics and the importance of building airport-type logistics hubs in the national logistics hub system. The NSGA-II algorithm is used to obtain the optimal cross-border logistics paths.

Based on the proportion of transportation modes in optimal cross-border logistics paths, cross-border railway transportation should be more adopted by inland regions, but the importance of cross-border air transportation cannot be ignored. Although Northwest China and Southwest China are the regions with the highest proportion of cross-border air transportation, there are no airport-type national logistics hubs in these two regions to organize cross-border logistics. Therefore, according to the percentage of the optimal cross-border paths through the airport, Chengdu and Xi'an should be constructed as airport-type national logistics hubs. Moreover, the foreign destinations of cross-border air transportation are distributed in different regions, mainly in Eastern Europe and Eastern Central Europe. To explore the impact of joining cross-border air transportation on cross-border logistics, we compared the cross-border logistics path optimization with that excluding air transportation. The results show that if there is a 1-fold increase in logistics cost, the logistics time can reduce by 1.37 folds, and the reduction of logistics time is far greater than the increase of logistics cost. Such a result has effectively guided the transition from cross-border water transportation to cross-border air transportation. Therefore, cross-border air transportation can play a more important role in the cross-border logistics of the "Belt and Road." China should speed up the construction of national airport-type logistics hubs in the Northwest and Southwest. The results of the optimal cross-border transportation paths will provide a direct basis for inland regions to organize cross-border logistics by considering cost, time, and carbon emissions. Our study provides important insight for inland regions to better participate in the "Belt and Road" initiative and enhance the level of opening up to the outside world. [36].

Data Availability

Previously reported data were used to support this study and these prior studies (and datasets) are cited at relevant places within the text as references.

Additional Points

Significance. The theoretical significance of current work lies in incorporating air transportation into the multimodal transportation theory research framework of cross-border logistics transportation. In this article, the inland regions are optimized to participate in the "One Belt and One Road" cross-border logistics route, and it is found that Chengdu and Xi'an should carry a large amount of cross-border air transportation and be constructed as a national-level airport-type logistics hub city. In addition, compared with the optimization results without air transportation, the optimization results after adding cross-border air transportation can reduce logistics time by 1.37 times for every doubling of the logistics cost. This shows that in the "Belt and Road" cross-border logistics transportation, cross-border air transportation can play a more important role.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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Research Article

Fuel Consumption and Traffic Emissions Evaluation of Mixed Traffic Flow with Connected Automated Vehicles at Multiple Traffic Scenarios

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To analyze the impact of different proportions of connected automated vehicles (CAVs) on fuel consumption and traffic emissions, this paper studies fuel consumption and traffic emissions of mixed traffic flow with CAVs at different traffic scenarios. Firstly, the car-following modes and proportional relationship of vehicles in the mixed traffic flow are analyzed. On this basis, different car-following models are applied to capture the corresponding car-following modes. Then, Virginia Tech microscopic (VT-micro) model is adopted to calculate the instantaneous fuel consumption and traffic emissions. Finally, based on three typical traffic scenarios, a basic segment with bottleneck zone, ramp of the freeway, and signalized intersection, a simulation platform is built based on Python and SUMO to obtain vehicle trajectory data, and the fuel consumption and traffic emissions in different scenarios are obtained. The results show that (1) In different traffic scenarios, the application of CAVs can reduce fuel consumption and traffic emissions. The higher the penetration rate, the more significant the reduction in fuel consumption and traffic emissions. (2) In the three typical traffic scenarios, the advantages of CAVs are more evident in the signalized intersection. When the penetration rate of CAVs is 100%, the fuel consumption and traffic emissions reduction ratio is as high as 32%. It is noteworthy that the application of CAVs in urban transportation will significantly reduce fuel consumption and traffic emissions.

1. Introduction

With the development of the urban economy, the number of vehicles has increased rapidly. Traffic congestion has become more and more serious [1, 2], and also caused massive fuel consumption and traffic emissions [3]. In 2018, the United States consumed approximately 143 billion gallons of motor gasoline, with a daily average of 391 million gallons [4]. Thence, it is a top priority to reduce fuel consumption and emissions of traffic systems.

Autonomous driving technology is a comprehensive application of traffic monitoring, route navigation, and artificial intelligence technology. The development of connected automated transportation systems has shown a trend of integrating with autonomous driving technology. Therefore, CAVs [5, 6] will cause the transformation of intelligent transportation systems [7]. In the connected automated transportation system, the preceding vehicle can transmit position, speed, acceleration, and other information to the following vehicle in real-time through Vehicle-to-Vehicle (V2V) communication technology. At this time, CAVs can drive in cooperative adaptive cruise control (CACC) mode through V2V communication technology [8]. In addition, if V2V communication conditions are not met, CAVs will drive in adaptive cruise control (ACC) mode [9]. To sum up, the widespread application of CAVs will effectively reduce the response delay of vehicles to changes in surrounding traffic conditions and shorten the car-following time between vehicles. Therefore, CAVs can improve the inherent characteristics of traffic flow, and achieve a comprehensive breakthrough in alleviating traffic system congestion, energy-saving, and traffic emission reduction. Many scholars generally believe that the CAVs are expected to improve the quality of traffic flow from the microscopic traffic flow level [10, 11], and provide an effective way to bring down fuel consumption and traffic emissions.

In recent years, lots of studies have been focused on fuel consumption and emissions of the traffic system [12]. How to calculate the fuel consumption and emission of vehicles have always been a significant research topic. Therefore, some research focused on fuel consumption and emission models.

As the earliest generation of fuel consumption and emission factor model of motor vehicles, the Emission Factors (EMFAC) model [13] is developed by the California Air Resources Bureau. In addition, the European Environment Agency also funded the development of the computer program to calculate emissions from the road transport (COPERT) model [14]. Compared with EMFAC, the COPERT model has lower requirements on parameters, including 15 parameters such as fleet composition, average driving speed, average journey length, and fuel parameters, but its coverage is not as wide as EMFAC. Due to the design requirements for emissions, micro fuel consumption and emission models appeared. The Parametric Analytical Model of Vehicle Energy Consumption (PAMVEC) [15] calculates vehicle energy consumption based on total vehicle mass, parameter driving cycle description, and other attributes of the vehicle platform. The most intuitive description of the driving state of a motor vehicle is to establish a speed-acceleration matrix. The value of the matrix is the average fuel consumption level corresponding to the speed and acceleration. On this basis, Cernuschi et al. [16] divided the data into five types: high deceleration, low deceleration, uniform speed, high acceleration, and low acceleration. Meanwhile, the regression analysis method is used to fit best the emission speed curve of each type of acceleration mode, and the idle fuel consumption and emission are analyzed. Subsequently, under the premise of combining speed and acceleration with different power products, Ahn [17] proposed the VT-micro model, which determines the value of fuel consumption and different emission indicators based on the combination of different power products of speed and acceleration. With the development of CAVs, many researchers have begun to study the impact of CAVs on fuel consumption and traffic emissions. On this basis, Zegeye et al. provided a general framework to integrate macroscopic traffic flow models with microscopic fuel consumption and emission models, and extended the VT-micro model to the macroscopic traffic flow model to further shorten the simulation time and carry out fairly accurate estimates of the emissions and fuel consumption. Chandra and Camal [18] used simulation methods to calculate the fuel consumption and emissions of connected vehicle technology (CVT). The results indicated that the CVT reduces fuel consumption and emissions in different traffic conditions. Aiming at signalized intersections, Han et al. [19] used the trajectory optimization method, PTO-GFC, to study the fuel consumption and emissions of CAVs passing intersections under smooth trajectories. Research results showed that fuel consumption and emissions will be reduced to varying degrees under the proposed method. Yao et al. [6] studied the impact of mixed traffic flow at a single intersection on fuel consumption and emissions, and proposed a joint optimization framework for traffic signals and vehicle trajectories at a single intersection, including HDVs and CAVs. The results showed that this method could reduce fuel consumption and emissions. Yao and Li [20] applied a more detailed micro-fuel model (e.g., VT-micro model) in the study of CAVs trajectory optimization at an isolated signalized intersection with a single-lane road. Then, a joint objective of travel time, fuel consumption, and safety is implemented to improve traffic mobility, energy efficiency, and safety simultaneously. Aiming at the expressway ramp, Qin et al. [21] proposed a stability analysis method applied to mixed traffic flow, which simulates the mixed traffic flow of the expressway ramp segment to evaluate the impact of stability on fuel consumption and traffic emissions. Subsequently, the correlation between CACC vehicles improving traffic flow stability and reducing traffic emissions and fuel consumption was further studied. A simulation was applied to evaluate the changes in fuel consumption and emissions under traffic oscillation. The results showed that stability could qualitatively affect the reduction of fuel consumption and emissions, and provide new ideas for reducing fuel consumption and traffic emissions [22].

The above analysis indicated that the current research on fuel consumption and emission models is relatively mature. With the development of CAVs, related scholars have made useful explorations on the fuel consumption and emissions of the transportation system. However, to our best knowledge, there are some issues that need to be further discussed: (1) Some studies only focus on fuel consumption or emissions, and did not discuss the relationship between fuel consumption and traffic emissions under the same scenario. (2) Most researches on traffic scenarios are relatively single, and the impact mechanism of CAVs on fuel consumption and traffic emission under different traffic scenarios is not deeply discussed. (3) Most studies only focus on single-lane freeways. The scenarios do not involve lane-changing behavior, and the impact of vehicle lane-changing on fuel consumption and emission is not considered. Therefore, the impact of CAVs on the fuel consumption and traffic emissions of mixed traffic flows in different traffic scenarios remains to be revealed.

To address these issues, this paper is dedicated to evaluating the impact of the penetration rate of CAVs on the fuel consumption and traffic emission of mixed traffic flow under three classic traffic scenarios: basic road segment with bottleneck zone, a ramp of the freeway, and a signalized intersection. Firstly, the microscopic driving behavior and three car-following modes of mixed traffic flow are analyzed. Secondly, three car-following models were applied to describe these three car-following modes, and the lane-changing model LC2013 [23] was adopted for different traffic scenarios. Then, the VT-micro fuel consumption and emission model is introduced to calculate fuel consumption and traffic emissions in different traffic scenarios. Finally, based on a simulation experiment with SUMO, three traffic scenarios are simulated, and trajectory data are obtained. Based on the VT-micro model, fuel consumption and traffic emissions in different scenarios are calculated and analyzed. Thence, the main contributions of this work are as follows.

(1) The car-following behavior of vehicles in the mixed traffic flow is discussed, and different car-following models are used to describe the car-following characteristics in the mixed traffic flow.
(2) The impact of lane changing on fuel consumption and emission is considered, and lane-changing model LC2013 [23] is applied to different traffic scenarios.
(3) The influence of the penetration rate of CAVs on the fuel consumption and emission of mixed traffic flow under different traffic scenarios is studied.

The remainder of this paper is as follows. The micro-driving behavior, the car-following model, the car-following model, and the lane-changing model are analyzed in Section 2. Section 3 describes fuel consumption and emission models. Simulation analysis was conducted in Section 4, including simulation environment construction and simulation results analysis under different traffic scenarios. Finally, Section 5 summarizes the whole paper and proposes future work.

2. Micro Driving Behavior Analysis

2.1. Mixed Traffic Flow

2.1.1. Car-Following Modes. Considering that it will take a long time to upgrade and deploy CAVs, there will be a mixture of CAVs and HDVs on the road in the future [5, 24, 25]. As shown in Figure 1, there are four car-following modes: (i) HDV-HDV, (ii) HDV-CAV, (iii) CAV-HDV, and (iv) CAV-CAV.

(1) Modes 1 and 2. As shown in Figure 1, the current vehicle of modes 1 and 2 is an HDV. When the front vehicle changes driving behavior (e.g., acceleration and deceleration), the driver of the current vehicle needs to perceive, identify, judge, and take action. Thence, car-following behavior is determined by the human driver.

(2) Mode 3. In this mode, the current and front vehicles are CAV and HDV, respectively. The current vehicle is equipped with the onboard sensing systems (e.g., laser, radar, camera), which can quickly and accurately capture the front vehicle's driving behavior. This mode is called adaptive cruise control (ACC). The ACC system makes the current vehicle closely follow the front vehicle via controlling the accelerator and brake of the vehicle based on the advanced driving assistance system (ADAS).

(3) Mode 4. In this mode, the current and front vehicles are CAVs. The current vehicle can interact with the front vehicle via V2V communication. Therefore, the current vehicle can make synchronous driving behavior changes with the front vehicle. This mode is called cooperative adaptive cruise control (CACC). CACC system can shorten the distance between vehicles as much as possible on the premise of ensuring safety, to improve the traffic capacity of the transportation system.

2.1.2. Proportional Analysis. If it is assumed that the penetration rate of CAVs in the mixed traffic flow is p, then the proportion of HDVs is $1 - p$. Thus, the proportions of car-following modes 1 and 2 are $1 - p$. According to probability theory, the proportions of car-following modes 3 and 4 are $p(1 - p)$ and p^2, respectively. To sum up, the proportions of different car-following modes are shown in Table 1.

2.2. Car-Following Model.

In this paper, the intelligent driver model (IDM) [26], ACC, and CACC models [27, 28] are applied to describe the car-following behaviors of HDVs and CAVs. As shown in Figure 1, the IDM is utilized to simulate modes 1 and 2, and the ACC and CACC are applied to capture modes 3 and 4, respectively. The detailed description of the three car-following models is as follows.

2.2.1. Intelligent Driver Model. In the existing research, the models describing the driver's car-following behavior mainly include stimulus-response model, safety distance model, social force model, and optimal speed model. As a kind of social force model, the IDM [26] can accurately describe the car-following behavior of drivers, and is widely used in the study of micro traffic flow. Therefore, the IDM model is adopted in this paper to describe the car-following behavior of HDVs. The model is defined by equation.

$$a_{i,k+1} = \overline{a}_i\left[1 - \left(\frac{v_{i,k}}{v_f}\right)^{\delta} - \left(\frac{s^*\left(v_{i,k}, \Delta v_{i,k}\right)}{s_i}\right)^2\right], \tag{1}$$

where $a_{i,k+1}$ is the acceleration of the i-th vehicle at $k+1$ time step; $\overline{a}_i$ is the desired acceleration of the i-th vehicle; v_f is the free flow velocity; s^* is the expected distance between the $i-1$-th and -th vehicles; $v_{i,k}$ is the speed of the i-th vehicle at k time step; $\Delta v_{i,k}$ is the speed difference between the $i-1$-th and i-th vehicles at the k time step; $\Delta v_{i,k} = v_{i,k} - v_{i-1,k}$; s_i is the actual distance between the $i-1$-th and i-th vehicles.

The expected distance s^* is determined by the speed of the i-th vehicle and the speed difference of the preceding car, and the calculation equation is:

$$s^*\left(v_{i,k}, \Delta v_{i,k}\right) = s_0 + Tv_{i,k} + \frac{v_{i,k}\Delta v_{i,k}}{2\sqrt{\overline{a}_i\overline{b}_i}}, \tag{2}$$

where s_0 is the minimum headway when stationary; T is the safe time headway; $\overline{b}_i$ is the comfortable deceleration of the i-th vehicle. Referring to Treiber et al. [26], the parameters of IDM are: $\overline{a}_i = 1$ m/s^2, $\overline{b}_i = 2$ m/s^2, $T = 1.5$ s, $v_f = 33.3$ m/s, and $s_0 = 2$ m.

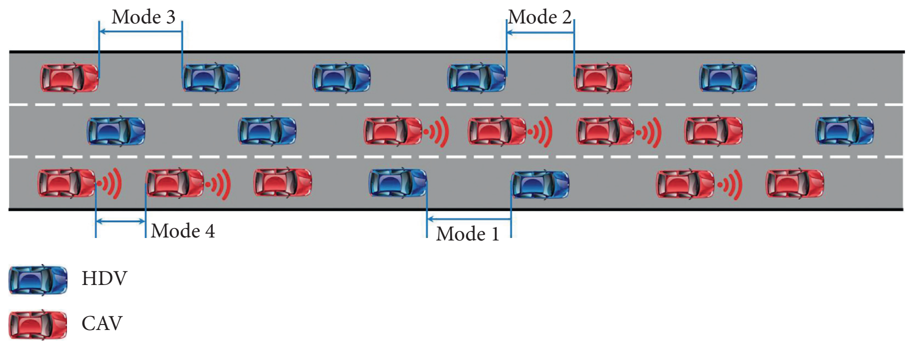


Figure 1: Four car-following modes of the mixed traffic flow.

Table 1: The ratio of the four modes.

Modes		Car-following models	Proportion
1	HDV-HDV	HDV	$1-p$
2	HDV-CAV		
3	CAV-HDV	ACC	$p(1-p)$
4	CAV-CAV	CACC	p^2

2.2.2. Adaptive Cruise Control Model. The ACC system makes the current vehicle closely follow the front vehicle via controlling the accelerator and brake of the vehicle based on the advanced driving assistance system (ADAS). Generally, the ACC system will be equipped with sensing devices, such as laser, radar, camera, etc. These can measure the speed and position difference between the current vehicle and the front vehicle. The ACC system adjusts the current vehicle's speed to keep the desired headway between it and the front vehicle. In particular, when there is no front vehicle, the ACC system will cruise at the designed speed.

The ACC car-following model [27, 28] developed and validated with field data is adopted in this paper. The integrated ACC car-following model is divided into four modes: (i) speed control, (ii) gap control, (iii) gap-closing control, and (iv) collision avoidance. The fourth mode (i.e., collision avoidance) is developed by TransAID [23], which tries to avoid rear-end collisions between adjacent vehicles. The details of the four control modes are discussed below.

(1) Speed Control. The speed control mode aims to keep the preset speed of the vehicle. When the vehicle has no preceding vehicle within the coverage of the sensor or the distance from the preceding vehicle is more significant than 120 m, the speed control mode is activated [28]. The speed control mode calculates the acceleration of the i-th vehicle at k time step and is given by the following equation.

$$a_{i,k+1} = \beta_1\left(v_d - v_{i,k}\right), \tag{3}$$

where v_d is the ideal velocity; $v_{i,k}$ is the velocity of the i th vehicle at k time step; and β_1 is the control gain, which determines the speed deviation rate of acceleration. Xiao et al. [28] suggested that the value is 0.3-0.4 s^{-1}. In this paper, the value of 0.4 s^{-1} was selected.

(2) Gap Control. The gap control mode keeps a constant time gap between the vehicle equipped with ACC and the vehicle ahead. This mode is activated when the gap and speed deviations (vehicle in front) are, respectively, less than 0.2 m and 0.1 m/s. The acceleration of the i-th vehicle at time step $k+1$ is described by the second-order function based on the velocity and gap error with the leading vehicle, which is defined in the following equation.

$$a_{i,k+1} = \beta_2 e_{i,k} + \beta_3\left(v_{i-1,k} - v_{i,k}\right), \tag{4}$$

where $e_{i,k}$ is the gap error of the i th vehicle at k time step; β_2 and β_3 are the control gain for position and velocity deviations. Referring to Xiao et al. [28], the calibration values of control parameters in equation (4) are $\beta_2 = 0.23\,s^{-1}$ and $\beta_3 = 0.07\,s^{-1}$. Furthermore, the gap error $e_{i,k}$ is given by

$$e_{i,k} = x_{i-1,k} - x_{i,k} - \tau_a v_{i,k}, \tag{5}$$

where $x_{i-1,k}$ and $x_{i,k}$ are the positions of the $i-1$-th and the i-th vehicles at time step k, and the τ_d is the desired time gap for the ACC system; its value range is generally 1.1 to 2.2 s. In this study, the value of τ_a is set to 1.3 s.

(3) Closed Gap Control. The gap closure controller realizes the stable transition from speed control mode to gap control mode. This mode is activated when the distance to the vehicle in front is less than 100 m. According to Xiao et al. [28], the gap closure control mode can be presented by setting parameters of equation (4) as $\beta_2 = 0.04\,s^{-1}$ and $\beta_3 = 0.8\,s^{-1}$. Specially, if the distance is between 100 m and 120 m, ACC-equipped vehicles will retain the fore control mode to supply hysteresis in the control loop and stable transition between the two modes.

(4) Collision Avoidance Control. The collision avoidance controller is developed by the TransAID team to prevent vehicle rear-end collision under safe conditions. When the distance to the preceding vehicle is less than 100 m, and the position gap deviation is negative, this mode is activated. Similar to gap-closing control, the collision avoidance control mode can be presented by setting parameters of equation (4) as $\beta_2 = 0.8\,s^{-1}$ and $\beta_3 = 0.23\,s^{-1}$. In simulation, these parameters can ensure the safe operation of ACC vehicles, even in critical events [23].

2.2.3. Cooperative Adaptive Cruise Model. Compared with the ACC system, the CACC system can communicate with each other through V2V communication. Therefore, the CACC system can further improve traffic safety and traffic efficiency. The integrated CACC car-following model is verified by the actual data based on the work of Milanés et al. [29] and Xiao et al. [28, 30]. Similar to the ACC system, the developed control algorithm in the CACC system is divided into four modes: (i) speed control, (ii) gap control, (iii) closed gap control, and (iv) collision avoidance control.

(1) Speed Control. The speed control mode aims to keep the desired speed predefined by the driver. This mode is activated when there are no preceding vehicles in the sensor coverage area or the time gap is greater than 2 seconds. The acceleration of the i-th vehicle at time step $k+1$ can be obtained by equation.

$$a_{i,k+1} = \beta_4\left(v_d - v_{i,k}\right), \tag{6}$$

where β_4 is the speed control gain. Referring to Milanés and Shladover [27], the value of β_4 is set as $0.4\,s^{-1}$.

(2) Gap Control. The gap control mode keeps a constant time gap between the vehicle equipped with CACC and the vehicle ahead. This mode is activated when the gap and velocity deviations (vehicle in front) are, respectively, less than 0.2 m and 0.1 m/s. The gap control of the CACC model is based on the first-order transfer function of velocity and gap error, which can be defined in the following equation.

$$v_{i,k} = v_{i,k} + \beta_5 e_{i,k} + \beta_6 \dot{e}_{i,k}, \tag{7}$$

where $\dot{e}_{i,k}$ is the first derivative of the gap error $e_{i,k}$. The values of β_5 and β_6 are set to $\beta_5 = 0.45\,s^{-1}$ and $\beta_6 = 0.0125\,s^{-1}$, respectively [31]. The first derivative of the gap error is given by

$$\dot{e}_{i,k} = v_{i-1,k} - v_{i,k} - \tau_d a_{i,k}, \tag{8}$$

where $a_{i,t}$ is the acceleration at time t, and τ_d is the required time gap defined by the CACC controller. The value is 0.6 to 2.2 s, and the value of τ_d in this study is set to 1.0 s.

(3) Closed Gap Control. The gap closure control mode realizes a stable transition from the speed control mode to the gap control mode. This mode is activated when the time distance to the front of the vehicle is less than 1.5 s. The control formula is consistent with equation (7), but the value of the gain coefficient parameter is inconsistent. Referring to Reference [23], the gain coefficient parameter values are $\beta_5 = 0.005\,s^{-1}$ and $\beta_6 = 0.05\,s^{-1}$.

(4) Collision Avoidance Control. The collision avoidance mode prevents vehicle rear-end collision under safe conditions. When the time gap is less than 1.5 s, and the position gap deviation is negative, this mode is activated. The controller's logic is consistent with the gap control and could be expressed by changing the gain coefficients, which are $\beta_5 = 0.45\,s^{-1}$ and $\beta_6 = 0.05\,s^{-1}$ [23].

In summary, both ACC and CACC car-following models contain four control modes, and the parameter values of different control modes can be summarized as shown in Figure 2.

2.3. Lane-Change Model. The lane-change model built-in sumo, namely LC2013 [23], is adopted in this study. The LC2013 model shows three main reasons (strategy, cooperation, and tactics) for changing lanes (right or left) in each simulation time step. The self-vehicle initially checks whether the right lane change is mandatory or required according to the logic described in Figure 3. If the right lane change is not mandatory or unnecessary, the motivation for the left lane change is determined according to the same rules. For details of LC2013, refer to Mintsis [23].

3. Fuel Consumption and Traffic Emissions Model

A variety of fuel consumption and emissions models of traffic systems began to develop a hundred years ago [17, 32, 33]; J. N. [34]. Among them, the VT-Micro model [17, 32, 35] calculates fuel consumption and emissions based on the instantaneous speed and acceleration of the vehicle. In addition, due to the simple structure of the VT-micro model, it is widely used to evaluate vehicle fuel consumption and emissions in traffic research [21, 36]. Thence, this paper selects the VT-micro model to calculate the fuel consumption and emissions in the traffic system. The model can be described as follows:

$$\ln\left(\mathrm{MOE}_e\right) = \sum_{i=0}^{3}\sum_{j=0}^{3} K_{i,j}^{e} v^i a^j, \tag{9}$$

where MOE_e is the fuel consumption and emission rate of the vehicle. i and j are the exponential coefficients of speed and acceleration, respectively. $K_{i,j}^e$ is the regression coefficient under the power i of speed and the power j of acceleration. v and a are the vehicle's speed and acceleration, respectively.

Equation (9) was developed by Ahn et al. [32] to calculate fuel consumption (FC), hydrocarbon (HC), carbon monoxide (CO), and oxides of nitrogen (NOx) of vehicles with different regression coefficient $K_{i,j}^e$. The regression coefficient $K_{i,j}^e$ was calibrated by Ahn et al. [32] using field data collected at Oak Ridge National Laboratory. The calibration regression coefficients have been widely used in a variety of studies [21, 36] to assess fuel consumption and transport emissions, as shown in Table 2.

4. Simulation Analysis

The application of CAVs in different traffic scenarios, and the improvement of fuel consumption and traffic emissions is different. Therefore, this section designs three different traffic scenarios, a basic segment with bottleneck zone, a ramp of the freeway, and a signalized intersection, to study the impact of CAVs on fuel consumption and emissions.

4.1. Simulation Settings. To explore the impact of CAVs on fuel consumption and traffic emissions of different traffic scenarios, three typical traffic scenarios, including a basic segment with bottleneck zone (Scenario 1) , a ramp of the freeway (Scenario 2), and a signalized intersection (Scenario 3), are selected in this study. A simulation environment is developed to verify the impact of different penetration rates of CAVs on the fuel consumption and traffic emissions of the transportation system. The penetration rate of CAVs

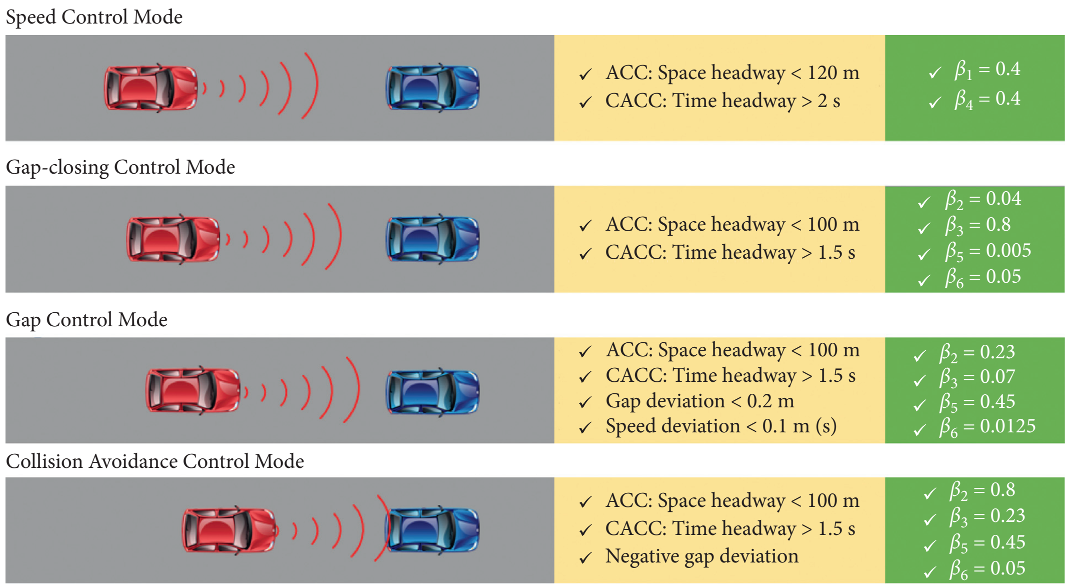


Figure 2: Modes of CACC car-following algorithm.

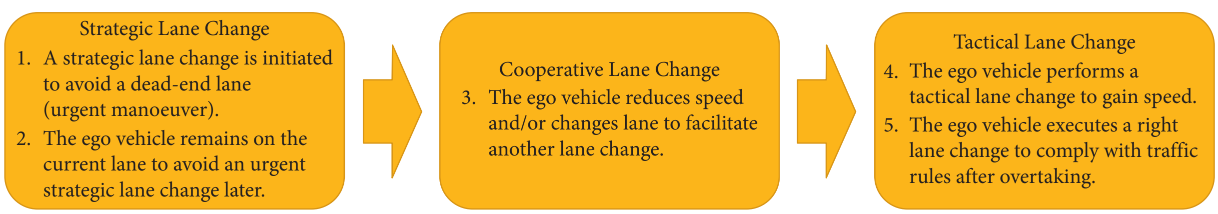


Figure 3: Hierarchy of lane change logic.

Table 2: The regression coefficient $K^e_{i,j}$ in equation (9).

Parameters	Fuel	CO	HC	NOx
$K^e_{0,0}$	−0.679439	0.887447	−0.728042	−1.067682
$K^e_{0,1}$	0.135273	0.148841	0.012211	0.254363
$K^e_{0,2}$	0.015946	0.03055	0.023371	0.008866
$K^e_{0,3}$	−0.001189	−0.001348	−0.000093243	−0.000951
$K^e_{1,0}$	0.029665	0.070994	0.02495	0.046423
$K^e_{1,1}$	0.004808	0.00387	0.010145	0.015482
$K^e_{1,2}$	−0.000020535	0.000093228	−0.000103	−0.000131
$K^e_{1,3}$	5.5409285E−8	−0.000000706	0.000000618	0.000000328
$K^e_{2,0}$	−0.000276	−0.000786	−0.000205	−0.000173
$K^e_{2,1}$	0.000083329	−0.000926	−0.000549	0.002876
$K^e_{2,2}$	0.000000937	0.000049181	0.000037592	−0.00005866
$K^e_{2,3}$	−2.479644E−8	−0.000000314	−0.000000213	0.00000024
$K^e_{3,0}$	0.000001487	0.000004616	0.000001949	0.000000569
$K^e_{3,1}$	−0.000061321	0.000046144	−0.000113	−0.000321
$K^e_{3,2}$	0.000000304	−0.00000141	0.00000331	0.000001943
$K^e_{3,3}$	−4.467234E−9	8.1724008E−9	−1.739372E−8	−1.257413E−8

varies from 0% to 100% in steps of 10%. The schematic diagrams of the three traffic scenarios are shown in Figure 4. In the simulation experiment, the CAVs environment is constructed by SUMO and Python. First, three car-following models with appropriate parameters are built in SUMO, to describe the car-following behavior of different vehicles. Then, the trajectory data of all vehicles are obtained based on Python via the TRACI interface of SUMO. Finally, fuel consumption and traffic emissions of each scene are calculated based on equation (9). In addition, the simulation duration of all scenarios is 1200 s, and the time step of the simulation experiment is 1 s. To avoid the influence of randomness, the different random seeds are adopted in the same experiment to simulate ten times, and the average value of the ten times simulation experiments is taken as the final result.

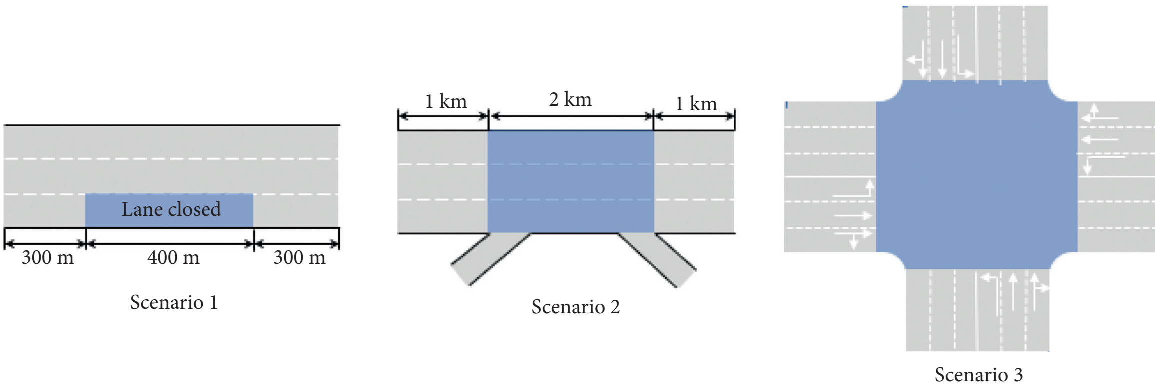


FIGURE 4: The schematic diagrams of the three traffic scenarios.

4.2. Results and Discussions

4.2.1. Basic Road Segment with Bottleneck Zone. The expressway bottleneck zone is usually the sudden point of a traffic accident, and it is a common scenario on the expressway. The road segment is a one-way three-lane expressway of 1 km. Due to accidents or other factors, the rightmost lane is closed at 300 m to 700 m. This indicates that only two lanes are operating normally. In this scenario, the traffic flow rate of the expressway is 700 veh/h/lane. Based on the simulation experiments, the fuel consumption and traffic emissions under different penetration rates of CAVs are obtained, as shown in Table 3.

Table 3 reports that when the traffic flow is mixed with CAVs and HDVs, the CO emission is the highest, while the HC and NOx are lower. Particularly, when the penetration rate of CAVs is 0%, the fuel consumption, CO, HC, and NOx are 15.31 L, 158.33 g, 11.12 g, and 11.56 g, respectively. When the penetration rate of CAVs is 100%, the fuel consumption and traffic emissions are 13.21 L, 153.98 g, 9.12 g, and 9.32 g, respectively. Moreover, to reflect the variation trend of fuel consumption and traffic emissions with the penetration rate of CAVs, Figure 5 is drawn. Figure 5 shows that fuel consumption and traffic emissions all gradually reduce with the increase of the penetration rate of CAVs. When the penetration rate of CAVs is less than 30%, the decrease of CO is relatively small, while the decrease of fuel consumption, HC, and NOx are significant, and the trends are consistent. When the penetration rate is low, most of the CAVs are in the adaptive cruise mode, and the normal operation of HDVs needs to be prioritized, so the decline in fuel consumption, CO, and NOx is small. From the simulation results, when the penetration rate is 60%–70%, the interference between the HDVs and the CAVs is the smallest, resulting in the maximum decrease in fuel consumption, CO, and NOx at this stage. With continuous increase, the optimization space for the coordinated control of CAVs is limited, and the decline in fuel consumption, CO, and NOx tends to be flat.

Based on Table 3, the decrease percentage of fuel consumption and traffic emissions with different penetration rates of CAVs, as shown in Table 4 and Figure 6. Figure 6 shows that when the penetration rate of CAVs is less than 30%, the CO emission declines more slowly. Moreover, when the penetration rate of CAVs is greater than 30%, the CO emission begins to decrease gradually. Compared with CO emission, the downward trends of fuel consumption, HC, and NOx are more consistent. The analysis shows that there is a bottleneck zone in this scenario. When the traffic flow approaches and leaves the bottleneck zone, the vehicle will cause additional acceleration and deceleration due to lane change, whether HDVs or CAVs. In this scenario, when the penetration rate of CAVs is 100%, the four evaluation indices of fuel consumption, CO, HC, and NOx decreased by 13.71%, 2.75%, 17.98%, and 19.36%, respectively. This suggests that the application of CAVs in this scenario has a certain effect on reducing fuel consumption and traffic emissions, but the decline range is small, all less than 20%.

4.2.2. Ramp of Freeway. The ramp of the freeway has a more significant impact on the traffic flow of the main road. The scenario in this section is a basic segment of a one-way three-lane of 4 km. At 1 km, there is a ramp where vehicles enter the freeway, and at 3 km, there is a ramp where vehicles leave the freeway. The traffic flow rate of the freeway and ramp are 1600 veh/h/lane and 120 veh/h/lane, respectively. Based on the simulation experiments, the fuel consumption and traffic emissions under different permeability of CAVs are obtained, as shown in Table 5.

Table 5 indicates that CAVs can effectively reduce fuel consumption and traffic emissions (CO, HC, NOx, etc.). When the penetration rate of CAVs is 0%, the fuel consumption and traffic emissions are 35.34 L, 348.71 g, 25.75 g, and 27.33 g, respectively; when the penetration rate reaches 100%, the fuel consumption and traffic emissions are 32.80 L, 341.36 g, 22.93 g, and 24.14 g, respectively. This means that compared with traditional HDVs, the widespread use of CAVs can reduce fuel consumption and traffic emissions significantly. Furthermore, the fuel consumption and traffic emissions changes under different penetration rates of CAVs and can be plotted, as shown in Figure 7. Figure 7 reports that when the penetration rate of CAVs is below 90%, fuel consumption and traffic emissions decrease as the penetration rate increases gradually; when the penetration rate of CAVs is greater than 90%, the downward trend in fuel consumption and traffic emissions is more

Table 3: Fuel consumption and traffic emissions under different CAVs penetration rates (Scenario 1).

Penetration rate (%)	FC (L)	CO (g)	HC (g)	NOx (g)
0	15.31	158.33	11.12	11.56
10	15.13	158.29	10.94	11.37
20	14.88	158.27	10.65	11.05
30	14.56	158.12	10.31	10.67
40	14.33	157.42	10.10	10.45
50	14.11	157.42	9.87	10.17
60	13.95	156.63	9.73	9.98
70	13.61	156.04	9.40	9.63
80	13.55	155.32	9.38	9.62
90	13.35	154.68	9.21	9.41
100	13.21	153.98	9.12	9.32

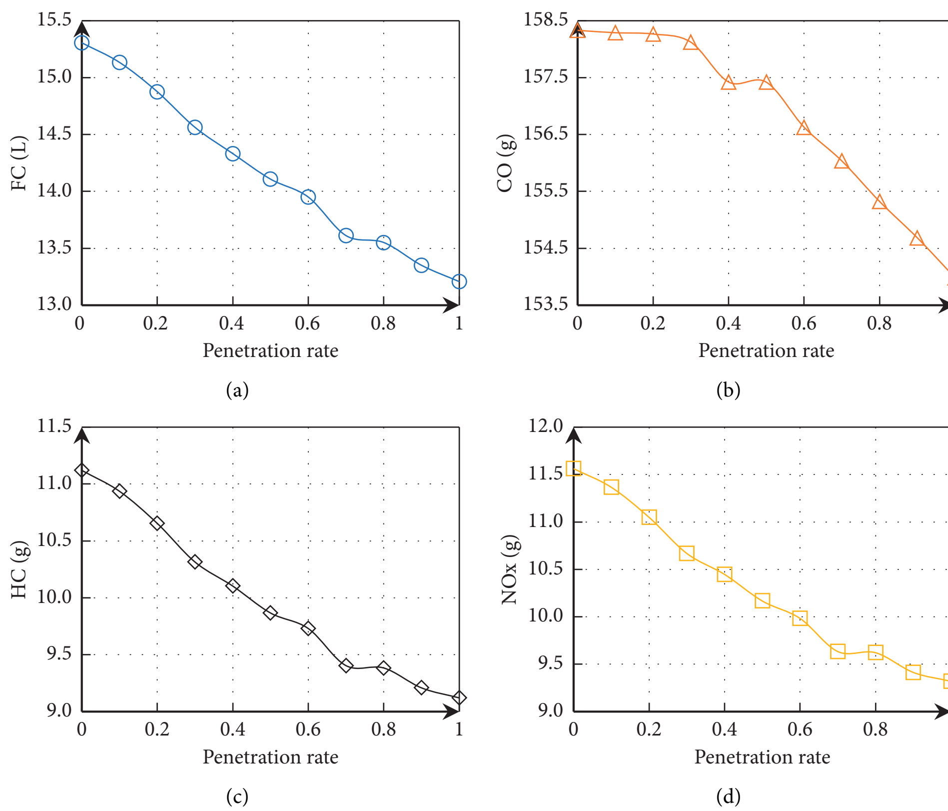


Figure 5: Fuel consumption and traffic emissions under different penetration rates of CAVs (Scenario 1). (a) Fuel consumption. (b) CO. (c) HC. (d) NOx.

significant. This points out that purely CAVs will have a significant impact on vehicle energy saving and emission reduction in this scenario.

Meanwhile, the decrease in fuel consumption and traffic emissions is obtained based on Table 5, as shown in Table 6 and Figure 8. Figure 8 shows that the effects of CAVs on fuel consumption and traffic emissions are the same. As the penetration rate increases, the overall evaluation indicators show a downward trend. In this scenario, the penetration rate of CAVs has a lower impact on CO than the other three evaluation indices, and the trend of change is relatively gentle. The reduction percentage of fuel consumption, CO, HC, and NOx reaches the maximum when the penetration rate of CAVs is 100%, which are 7.18%, 2.11%, 10.93%, and 11.68%, respectively.

The result shows that CAVs can maintain a more stable driving speed and minor headway in the road segments. Meanwhile, CACC vehicles form a platoon during operation. Compared with traditional HDVs, the acceleration and deceleration processes are significantly reduced, thus reducing the fuel consumption and emission of traffic flow. However, in this scenario, when vehicles run near the ramp, an HDV or a CAV will be disturbed by the vehicle in the ramp, resulting in different degrees of acceleration and deceleration behavior. Therefore, in the ramp of the freeway, when the penetration rate of CAVs is 100%, compared with 0%, the decline in fuel consumption, CO, HC, and NOx are relatively low, all lower than 12%.

Table 4: Percentage reduction in fuel consumption and traffic emissions (Scenario 1).

Penetration rate (%)	FC (%)	CO (%)	HC (%)	NOx (%)
0	NA	NA	NA	NA
10	1.13	0.03	1.65	1.70
20	2.81	0.04	4.19	4.44
30	4.86	0.13	7.24	7.73
40	6.36	0.57	9.14	9.64
50	7.83	0.58	11.27	12.07
60	8.86	1.08	12.50	13.66
70	11.07	1.45	15.43	16.68
80	11.47	1.90	15.62	16.78
90	12.78	2.30	17.19	18.58
100	13.71	2.75	17.98	19.39

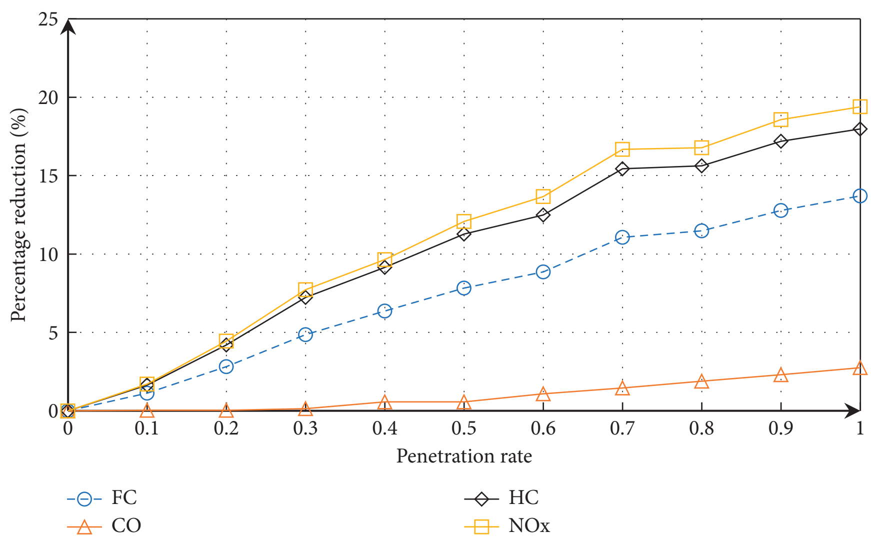


Figure 6: Percentage reduction in fuel consumption and traffic emissions (Scenario 1).

Table 5: Fuel consumption and traffic emissions under different penetration rates of CAVs (Scenario 2).

Penetration rate (%)	FC (L)	CO (g)	HC (g)	NOx (g)
0	35.34	348.71	25.75	27.33
10	35.20	348.13	25.60	27.10
20	35.04	348.09	25.38	26.89
30	34.96	347.55	25.29	26.75
40	34.73	346.97	24.99	26.48
50	34.52	346.44	24.69	26.16
60	34.50	346.19	24.68	26.15
70	34.49	345.49	24.60	26.05
80	34.28	345.48	24.35	25.74
90	34.17	345.43	24.14	25.47
100	32.80	341.36	22.93	24.14

4.2.3. Signalized Intersection. In urban transportation, the signalized intersection is an essential node for vehicle collection, turning, and evacuation. The setting of signalized intersection scenario is of great significance to the study of the characteristics of traffic flow. The scenario here is a two-way three-lane intersection, including three turns: left turn, straight, and right turn. The traffic flow rate of each lane is 220 veh/h. Based on the simulation experiments, the fuel consumption and traffic emissions under different CAVs conditions in this scenario are obtained, as shown in Table 7.

Table 7 shows that when the penetration rate of CAVs is 0%, the fuel consumption, CO, HC, and NOx are 29.74 L, 167.38 g, 27.35 g, and 22.47 g, respectively; when the permeability is 100%, the fuel consumption and traffic emissions are 17.58 L, 112.36 g, 17.49 g, and 14.24 g, respectively. In scenario 3, as the penetration rate of CAVs increases, fuel consumption and traffic emissions are all showing a downward trend. The changes in fuel consumption and traffic emissions under different penetration rates are shown in Figure 9. Compared with fuel consumption, HC, and NOx,

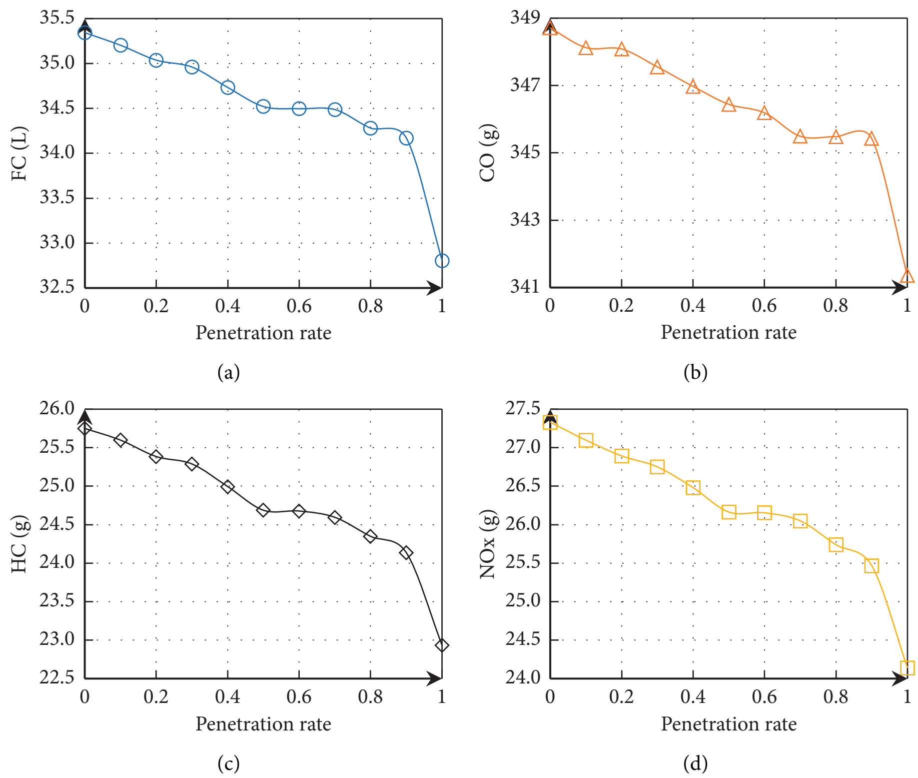


Figure 7: Fuel consumption and traffic emissions under different penetration rates of CAVs (Scenario 2). (a) Fuel consumption. (b) CO. (c) HC. (d) NOx.

Table 6: Percentage reduction in fuel consumption and traffic emissions (Scenario 2).

Penetration rate (%)	FC (%)	CO (%)	HC (%)	NOx (%)
0	NA	NA	NA	NA
10	0.40	0.17	0.59	0.85
20	0.87	0.18	1.42	1.60
30	1.08	0.33	1.79	2.12
40	1.73	0.50	2.93	3.11
50	2.33	0.65	4.13	4.27
60	2.39	0.72	4.17	4.30
70	2.42	0.92	4.48	4.69
80	3.01	0.93	5.44	5.82
90	3.32	0.94	6.26	6.82
100	7.18	2.11	10.93	11.68

CO changes more significantly, and the impact of CAVs on its emission is noticeable. In addition, compared with scenarios 1 and 2, the fuel consumption and traffic emissions in scenario 3 show a linear decrease as the penetration rate of CAVs increases. This means that the use of CAVs can significantly improve fuel consumption and traffic emissions in scenario 3.

Furthermore, the reduction percentages of fuel consumption and traffic emissions under different penetration rates of CAVs is obtained, as shown in Table 8. Meanwhile, Figure 10 provides a more intuitive understanding of the impact of the penetration rate of CAVs on fuel consumption and traffic emissions. It can be seen from Figure 10 that as the penetration rate of CAVs increases, various fuel consumption and traffic emission indicators show a downward trend, and the decline is relatively significant. In scenario 3, the reduction of CO among the four indicators is slightly lower. When the penetration rate of CAVs is 100%, the percentage of CO reduction will reach 32.87%, while the declining percentage of fuel consumption, HC, and NOx reach 40.89%, 36.06%, and 36.64%, respectively.

In scenario 3, the road is relatively more standardized, and there are traffic lights to restrict the traffic flow. Therefore, in this scenario, the advantages of CAVs are more prominent. The four evaluation indicators have a significant decline, reaching more than 32% when the penetration rate of CAVs is 100%.

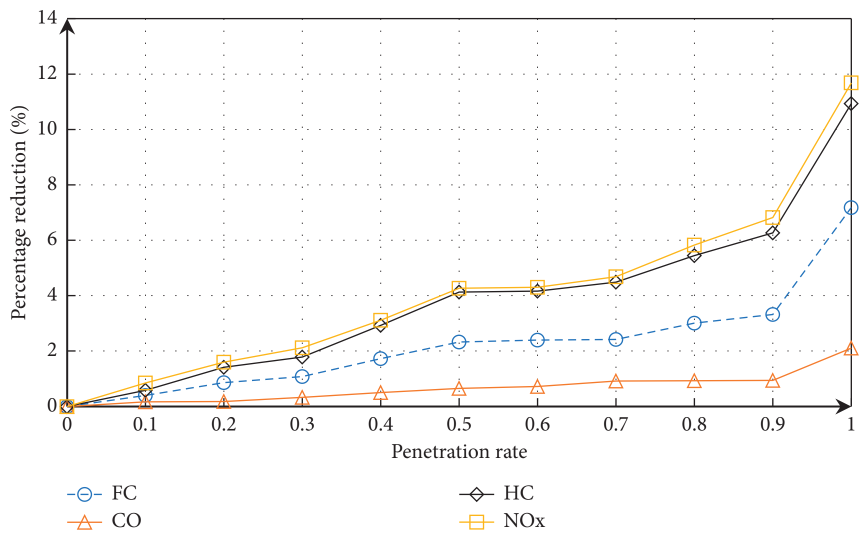
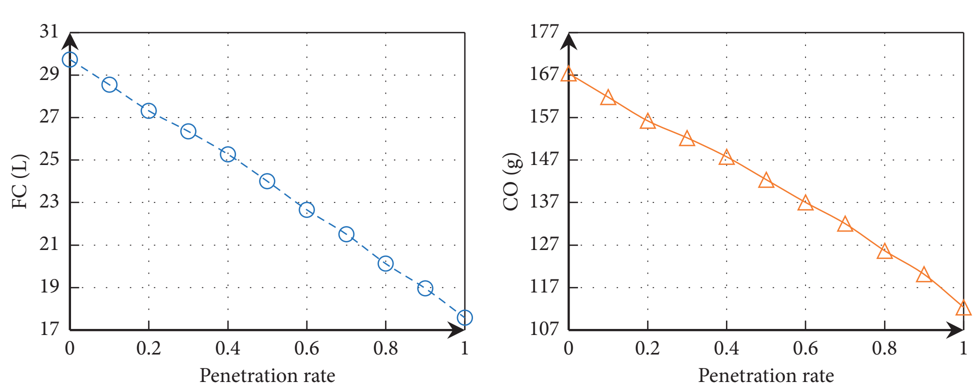


Figure 8: Percentage reduction in fuel consumption and traffic emissions (Scenario 2).

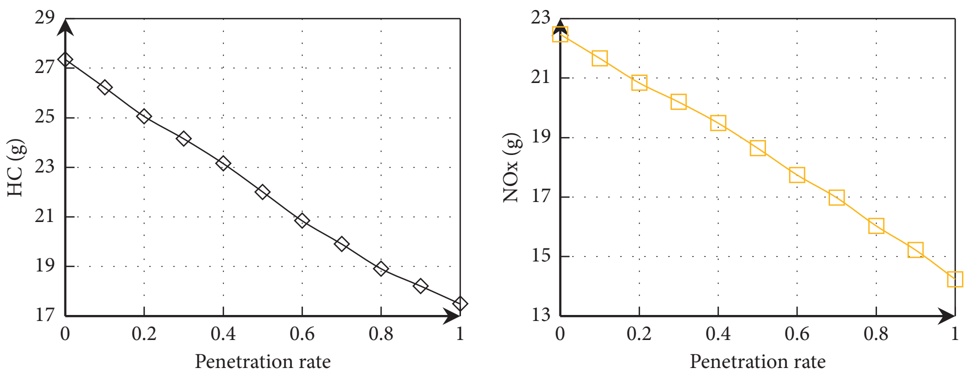
Table 7: Fuel consumption and emissions under different penetration rates of CAVs (Scenario 3).

Permeability (%)	FC (L)	CO (g)	HC (g)	NOx (g)
0	29.74	167.38	27.35	22.47
10	28.55	161.80	26.21	21.66
20	27.32	156.24	25.05	20.84
30	26.35	152.22	24.15	20.19
40	25.27	147.76	23.15	19.48
50	24.00	142.40	22.01	18.64
60	22.66	137.03	20.84	17.74
70	21.51	132.04	19.90	16.98
80	20.12	125.67	18.91	16.03
90	18.96	120.11	18.21	15.22
100	17.58	112.36	17.49	14.24



(a) (b)

Figure 9: Continued.



(c) (d)

Figure 9: Fuel consumption and traffic emission for different permeability of CAVs (Scenario 3). (a) Fuel consumption. (b) CO. (c) HC. (d) NOx.

Table 8: Percentage reduction in fuel consumption and traffic emissions (Scenario 3).

Penetration rate (%)	FC (%)	CO (%)	HC (%)	NOx (%)
0	NA	NA	NA	NA
10	4.01	3.33	4.16	3.59
20	8.14	6.65	8.41	7.27%
30	11.39	9.05	11.71	10.13
40	15.01	11.72	15.36	13.29
50	19.29	14.92	19.55	17.04
60	23.80	18.13	23.80	21.04
70	27.66	21.11	27.23	24.44
80	32.34	24.92	30.88	28.66
90	−36.25	−28.24	−33.43	−32.28
100	−40.89	−32.87	−36.06	−36.64

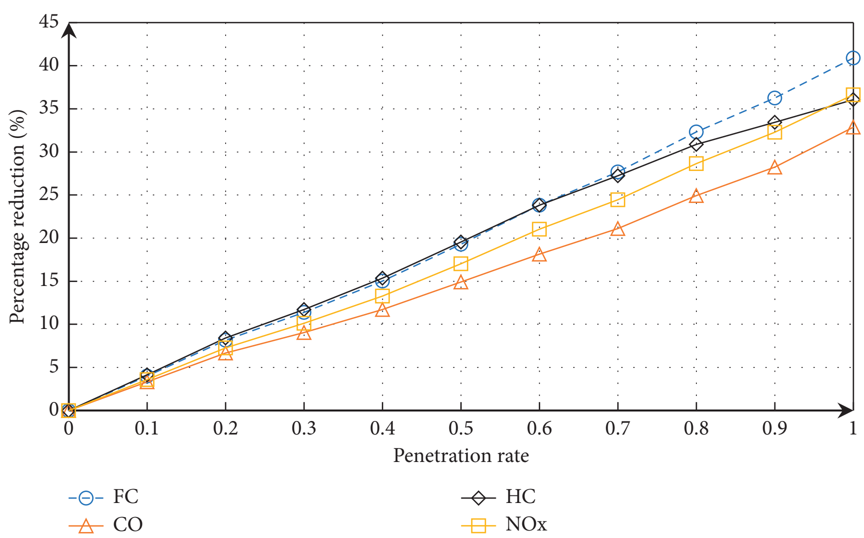


Figure 10: Percentage reduction in fuel consumption and traffic emissions (Scenario 3).

5. Conclusion and Policy Implication

This paper analyzes the fuel consumption and traffic emissions of mixed traffic flow with CAVs in different traffic scenarios. According to the results of the simulation experiment, the conclusions can be obtained as follows:

(1) In different traffic scenarios, CAVs play an effective role in reducing fuel consumption and emissions. With the increase of the penetration rate of CAVs, the declining proportion of fuel consumption and traffic emission increases. This suggests that the widespread application of CAVs can reduce fuel consumption and traffic emission, save resources, and alleviate environmental pollution to a certain extent.

(2) There are certain differences in the impact of CAVs on fuel consumption and traffic emission in different traffic scenarios. In the signalized intersection, the percentage of fuel consumption and traffic emissions reduction both reached more than 32%. However, in the ramp and bottleneck zone of the freeway, when the penetration rate of CAVs is 100%, both fuel consumption and traffic emissions decreased by less than 20%.

(3) Compared with the ramp and bottleneck zone of the freeway, the reduction in fuel consumption and traffic emissions of the signalized intersection is more significant, up to 32% or more. This means that the application of CAVs has more significant energy-saving and emission-reduction effects on urban transportation.

This paper mainly analyzes the mixed traffic flow's fuel consumption and emissions with CAVs and HDVs based on the micro-driving behavior. Thus, the optimization and coordinated control of the CAVs are not considered in this study. Therefore, the collaborative control and optimization of connected automated vehicles can be considered further to reduce fuel consumption and traffic emissions in future work [37, 38]. Moreover, the trajectory of the CAVs can also be optimized in real-time to achieve the effect of alleviating traffic congestion, fuel consumption, and traffic emissions.

Data Availability

The data used to support the findings of this study are included in the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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Review Article

Automobile Industry under China's Carbon Peaking and Carbon Neutrality Goals: Challenges, Opportunities, and Coping Strategies

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China has already committed to peaking carbon dioxide emissions by 2030 and achieving carbon neutrality by 2060 (referred to as the 30·60 Target), which has brought both daunting challenges and great opportunities to the automobile industry in China. However, there is still a lack of comprehensive and in-depth studies on the challenges, paths, and strategies for reducing carbon emissions to fulfill the 30·60 Target in automobile industries. Therefore, this paper proposes low-carbon development strategies for China's automobile industry. This study's method is to integrate the results from different literature to summarize the status, challenges, opportunities, and refine the coping strategies for carbon emission of the automobile industry. The results indicated that the paths for achieving the 30·60 Target include joint carbon emission reduction by upstream and downstream enterprises inside the industry. It also needs cross-industry and cross-sector coordinated decarbonization outside the industry. Meanwhile, the low-carbon policy and regulation system should be established to provide a direct driving force and fundamental guarantee for the low-carbon development of China's automobile industry.

1. Introduction

To date, thousands of experts and scholars worldwide have proved that global warming is real with all kinds of scientific evidence [1]. A consensus has been reached that the surge in human-caused carbon emissions is the primary cause of global warming. The concept of carbon neutrality is designed to control global temperature rise [2]. China committed to peaking carbon dioxide emissions (CO_2) by 2030 and achieving carbon neutrality by 2060 (the 30·60 Target) in September2020 [3]. China emitted about 10.2 billion tons of carbon in 2020. It accounts for about one-third of global carbon emissions, twice that of the United States and three times that of the European Union [4]. Realizing China's carbon neutrality target is crucial for global carbon neutrality.

The transport sector has contributed about 10% of China's carbon emissions in recent years. Road transport carbon emissions are the primary source of carbon emissions from the transport sector, accounting for about 73% in 2018, as shown in Figure 1 [5]. The carbon emissions of the automobile industry accounted for about 97.8% of the road transport sector in 2020 [6]. The automobile industry is one of the significant energy consumption sectors and greenhouse gas emissions. Meanwhile, the automobile industry has a high potential to reduce carbon emissions due to immature technologies, such as battery manufacturing technologies [7]. Thus, the automobile industry is an essential part of China's efforts to achieve the 30·60 Target [8].

Recently, a new round of scientific and technological revolution is driving the overall restructuring of the automobile industry, which is moving faster with the carbon neutrality goal [9]. The Society of Automobile Engineering of China (China-SAE) in the Energy-Saving and New Energy Vehicle Technology Roadmap 2.0 has planned the time point for the automotive industry to achieve its carbon reduction

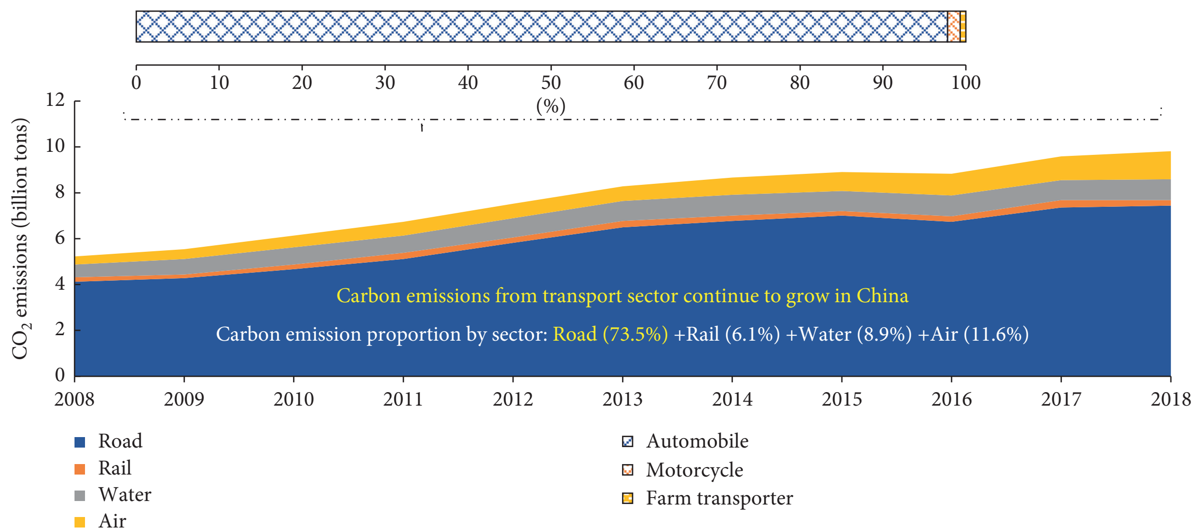


FIGURE 1: Carbon emission of the road transport sector and automobile industry [5, 6] (note: the carbon emissions of the automobile industry account for about 97.8% of the road transport sector in 2020).

goals. It proposed that the automobile industry should peak carbon emissions by 2028 and achieve carbon neutrality by 2050 to smoothly achieve China's 30·60 Target [10]. It means that the automobile industry in China faces daunting challenges under the 30·60 Target.

There are many studies about the carbon emission of the automobile industry while mainly concentrating on three aspects. First, the literature focused on how to calculate the total carbon emission of the automobile industry. Lee et al. explored an eco-control approach for carbon accounting for supply chain management in the automobile industry. This study finds that eco-control can foster alignment between a firm's carbon management strategy and carbon performance measurement and provides useful quantified information for corporate decision-makers [11]. Hao et al. built a bottom-up model to address energy, environmental impacts of greenhouse gas emission reduction from the passenger vehicle fleet. The results indicate that for passenger vehicles, the target of GHG emissions reduction generally synergizes with petroleum security enhancement, urban air quality improvement, and transport cost reduction but conflicts with the targets of rare metal conservation and transport well-being improvement [12]. Second, the literature paid attention to reducing carbon emission technologies. Qiao et al. conducted a comparative study on life cycle CO_2 emission from electric and conventional vehicles in China. The results showed that the CO_2 emissions from the production of an electric range from 14.6 to 14.7 t, 59% to 60% higher than the level of an ICEV, 9.2 t [13]. Wu et al. investigated obstacle identification, analysis, and solutions of hydrogen fuel cell vehicles for application in China under the carbon neutrality target. The results revealed that hydrogen fuel cell vehicles application is one of the effective measures of carbon emission reduction, and the economic, technical, social, and political obstacles should be addressed [14]. Third, the literature investigated the impact of carbon policy on the automobile industry. Du et al. conducted a study focused on policymaking and its impact on the automobile industry in the context of carbon neutrality. They concluded that carbon neutrality is a problem that automobile companies must face and should set targets and time nodes related to carbon neutrality as soon as possible and speed up implementing specific measures [15]. Du et al. studied the costs and potentials of reducing CO_2 emissions in China's transport sector based on the energy system analysis. The results underlined the carbon peak policy while making alternative fuel vehicles (AFV) more efficient, which increases the overall cost of emissions reduction [16].

However, there is still a lack of comprehensive and in-depth studies on the challenges, paths, and strategies for reducing carbon emissions to fulfill the 30·60 Target in automobile industry [17], because of the short time that China has put forward the carbon neutrality goal. Meanwhile, many scholars paid more attention to the basic research on the technologies for reducing carbon emissions from automobiles and calculating carbon emissions throughout the life cycle. [18]. Therefore, it is important to summarize and point out the strategic directions and technology paths toward low-carbon development of the automobile industry from the macro level.

To bridge these gaps, this paper systematically studies the challenges, opportunities, and coping strategies for China's automobile industry to achieve the 30·60 Target. First, the connotation of China's 30·60 Target is interpreted. Second, the current situation, challenges, and opportunities of the automobile industry to reduce carbon emission are analyzed. Finally, the path and direction of the carbon neutrality goal are proposed based on the current situation and development vision of the automobile industry in China.

2. Interpretation of China's 30·60 Target

2.1. Connotations of China's 30·60 Target. Carbon neutrality refers to zero carbon dioxide emissions. It can be achieved by offsetting the total greenhouse gas emissions directly or indirectly. The emissions are generated by enterprises, organizations, or individuals within a certain period by afforestation, energy conservation, and emission reduction. Carbon peaking refers to the steady decline of carbon emissions after reaching a plateau. The process of achieving the 30·60 Target in China is shown in Figure 2, from which we can see the difference between carbon peaking and carbon neutrality goals.

It should be said that the technical difficulty in achieving the goal of peaking carbon emissions by 2030 is relatively low for China. It can be achieved by mainly adopting carbon reduction technologies (referring to technologies for reducing carbon emissions) and partially adopting zero-carbon technologies (referring to the use of clean energy without carbon emissions) [19]. In comparison, the technical difficulty in achieving the carbon neutrality goal by 2060 is exceptionally high. In addition to applying carbon reduction and zero-carbon technologies, it is also necessary to adopt negative carbon technologies (meaning capturing carbon from the environment and sequestering or reusing it, or absorbing carbon from the natural environment using tree planting, etc.) [20]. In addition, according to China's climate management authority up to date, the carbon peaking goal only refers to the peak of carbon dioxide emissions. In contrast, the carbon neutrality goal refers to the neutrality of all greenhouse gases.

Carbon emissions will gradually enter the plateau period with stable fluctuations around the time of achieving the carbon peaking goal, as shown in Figure 2. The more prolonged carbon emissions stay on the peak plateau after reaching the peak, the shorter the window of time to achieve carbon neutrality and the higher the cost of subsequent decarbonization. Therefore, although carbon peaking must precede carbon neutrality from the timeline perspective, the two must complement specific actions. It makes no sense to peak carbon emissions first and go carbon neutral later. It should be emphasized that carbon peaking is a prerequisite for carbon neutrality—the sooner the carbon peaking goal is achieved, the lower the peak emissions value will be. Thus, the sooner the carbon peaking goal is achieved, the better it is for achieving carbon neutrality. At the same time, the time point of entering the carbon emission plateau should be as early as possible as when the carbon peak occurs. It will promote the industrial application of carbon neutrality technologies and increase the time window for carbon neutrality.

Given the above, carbon peaking and carbon neutrality are intrinsically related and fundamentally different. Generally speaking, carbon peaking is an important milestone and critical time point for carbon neutrality. In contrast, carbon neutrality is the ultimate goal of carbon peaking and the fundamental symbol of a complete transformation of the national development model. Moreover, the carbon peaking goal is not as tricky as carbon neutrality. The carbon neutrality goal limits the time and peak value of the carbon peaking goal. It fundamentally rejects the "cheating" path of raising carbon peak value first and lowering it later. Accordingly, the carbon peaking goal will become more challenging and meaningful under the constraints of the carbon neutrality goal. At the current time point, China must reasonably develop a carbon peaking strategy and factor carbon neutrality in its low-carbon energy transition. Only in this way can we ensure that carbon neutrality could be achieved as scheduled after peaking carbon emissions.

In addition, the 30·60 Target will open a new chapter of human civilization. From an energy perspective, it would accelerate decarbonization on the energy supply side, leading to fossil fuels being replaced entirely, and the proportion of renewable energy will be significantly increased [21]. At the same time, the transformation in energy consumption should also be accelerated. A clean electricity-based energy consumption pattern must be established in the future [22]. From the industry perspective, carbon neutrality will accelerate the adjustment and optimization of industrial structures [23]. Specifically, it can be summarized into three aspects. First, the 30·60 Target will drive the upgrading of relevant technologies and the innovation of industrial models. Second, the 30·60 Target will curb energy-intensive industries' expansion and capacities. Third, the 30·60 Target will make the digital economy, high-tech industries, and services the development priorities [24].

From the enterprise perspective, the core competitiveness of enterprises will change. Low-carbon manufacturing and low-carbon products become the necessary ability for enterprises to win competitive advantages [25]. At the same time, the development concept and business model of enterprises will also change. Enterprises must carry out low-carbon operations throughout the life cycle of the products. They should consider carbon emissions during product use and energy use during the product life cycle, including the production process. Carbon trading management will be the basis for effective business operations in the future. Companies with high-carbon emissions must spend a lot of money buying carbon credits to avoid losing out to the competition. It is expected that in the future, low carbon emissions will become a new economic norm and trade barrier in the world. Companies with high carbon emissions will be shut out of the market [26]. From the perspective of society, there will be fundamental changes in the way people produce and live. The whole society needs to develop a low-carbon culture. Everyone should have a low-carbon consciousness and start a green and economic low-carbon lifestyle.

2.2. Challenges Facing China in Achieving the 30·60 Target. As the world's second-largest economy, China has a daunting task to achieve the 30·60 Target. Figure 3 shows the fossil fuel-related carbon dioxide emissions and the carbon neutralization goal planning of major countries in the world [27, 28]. According to China's carbon emission trend and carbon neutrality plan, its challenges in achieving the 30·60 Target can be summarized as a "tight schedule and heavy task" compared with other countries.

The schedule is tight. China is now the world's largest carbon emitter, while the buffer time from carbon peaking to carbon neutrality is just 30 years. The time gap between carbon peaking and carbon neutrality in most developed countries is 50–60 years [28]. China's goal of achieving

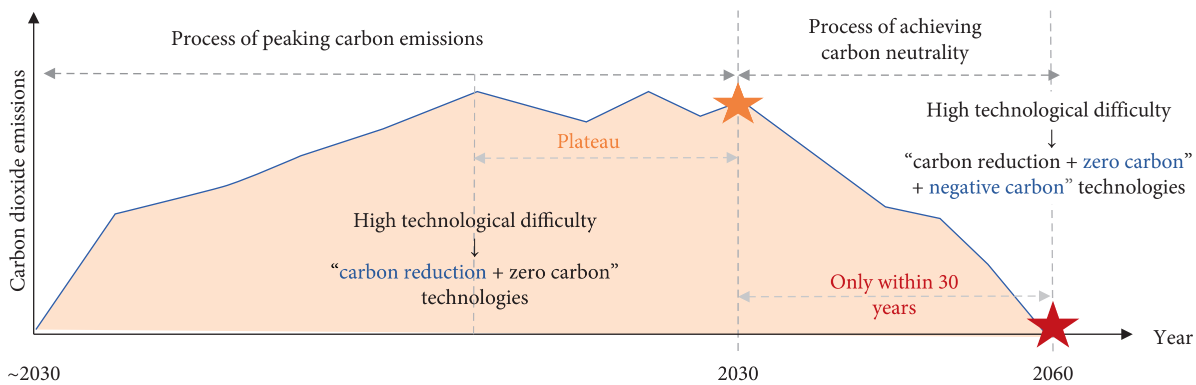
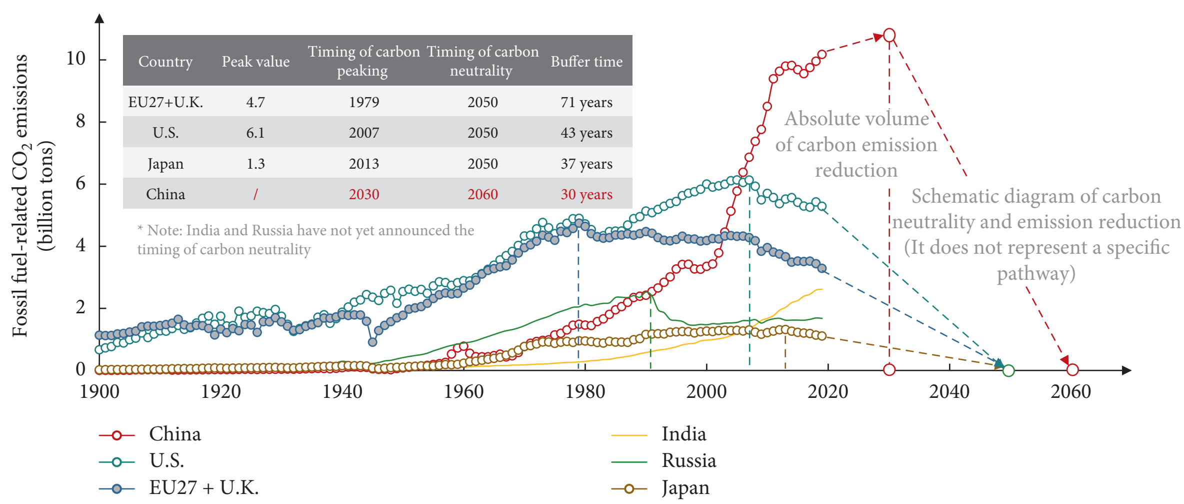


Figure 2: The process of achieving the 30·60 target in China.



Country	Peak value	Timing of carbon peaking	Timing of carbon neutrality	Buffer time
EU27+U.K.	4.7	1979	2050	71 years
U.S.	6.1	2007	2050	43 years
Japan	1.3	2013	2050	37 years
China	/	2030	2060	30 years

Figure 3: Fossil fuel-related carbon emissions and carbon neutrality plans of major countries in the world [27, 28].

carbon neutrality by 2060 has exceeded the expectations of many international experts. It means that a country like China must control the increase and eliminate the stock of CO_2 within 40 years. However, China is developing where its emissions are far from peaking. This challenge is unprecedented for China.

The task is heavy. First, China's carbon emissions have topped the world, as shown in Figure 3. China accounts for about one-third of global carbon emissions, twice that of the United States and three times that of the European Union [4]. At the same time, neither China's industrialization nor urbanization has yet reached its peak. The demand for life services is also in the stage of rapid growth. Many new production capacities and services will be needed to meet the growing needs of the national economy and people's livelihood in the future. If China does not change its development model, carbon emissions will grow further.

Second, the 30·60 Target is an unprecedented and complex national system project involving multiple fields and factors. If any one of them is not fully implemented or linked to the others, it is impossible to achieve carbon neutrality. Therefore, China must think comprehensively and advance as a whole. The government should adopt a top-down approach for strategic deployment and a bottom-up approach for tactical support to implement decarbonization orderly and systematic.

Third, the high-carbon economy itself has development inertia and technological limitations. It is not easy to completely abandon the original development model. At present, China's adoption of low-carbon energy and energy efficiency is relatively low. It is difficult to change the economic growth model in a short time. New products and services require new energy for support, which means China needs to decarbonize both incremental fuels.

Fourth, to achieve the 30·60 Target, economic growth and people's livelihood should be considered. A low-carbon transition at the expense of economic growth is not desirable. China must continue to meet the growing needs of its 1.4 billion people for a better life. It is the prerequisite for implementing carbon peaking and carbon neutrality actions and achieving the 30·60 Target. As a result, China's low-carbon transition is more challenging than expected.

To sum up, the essence of China's 30·60 Target is the innovation of science and technology, reconstruction of social infrastructure, and transformation of the country's economic development model. These involve the simultaneous transformation of the country's energy mix, industrial structure, industrial foundation, and the accompanying transformation of social infrastructure and cultural environment. It is a grand strategy that concerns the fate of the country.

2.3. Overall Strategies to Achieve China's 30·60 Target. Experts and scholars have reached a basic consensus on achieving the carbon neutrality goal for China. A concerted effort must be made from six aspects, such as emission reduction from the source, energy substitution, energy-saving, efficiency improvement, recycling, process transformation, and carbon capture [29].

First, we need to pay attention to the following points in the direction and principle of low-carbon development. On the one hand, the universality of the climate problem determines that it is difficult to achieve global temperature control targets through bottom-up emission reduction. Top-down planning is inevitable. On the other hand, the carbon peaking goal and carbon neutrality goal should be considered simultaneously and cannot be separated. It is the basic principle that must be followed [30].

Second, attention needs to be paid to the scope and manner of achieving the carbon neutrality goal. On the one hand, carbon neutrality is reflected in production activities, lifestyle, and values. It is important to emphasize that lifestyle changes are also essential for achieving carbon neutrality. Efforts should be made to encourage society to advocate a green and economic lifestyle. On the other hand, future economic growth should be based as much as possible on carbon-neutral technologies to avoid the costs of subsequent replacement of high-carbon models.

Finally, specific measures to achieve carbon neutrality need to be considered. First, energy supply-side reform needs to be accelerated. The methods include increasing the proportion of renewable energy, building a new energy mix dominated by zero-carbon electricity, and vigorously promoting energy storage technology and industrial layout to ensure a balanced power grid [31]. Second, energy demand-side reform needs to be strengthened. We will comprehensively promote terminal electrification, emission reduction from the source, and energy efficiency improvement in industrial, transportation, and construction sectors [32]. Third, the whole process of industrial production needs to be improved. Targeted measures such as material substitution, technological innovation, process improvement, and equipment transformation should be adopted for the possible carbon emissions in each link [33].

In general, the technologies for achieving the 30·60 Target can be divided into three categories. One is carbon reduction technologies, which are mainly a matter of technological advancement. These technologies include energy efficiency improvements, resource recovery, process innovation, and fuel/feedstock substitution [29]. The second type is zero-carbon technologies, which are mainly about energy substitution. If carbon-based fossil fuels dominate the energy mix, it is impossible to achieve carbon neutrality no matter how many carbon reduction technologies are used [34]. To achieve this goal, China must promote energy decarbonization, including introducing renewable, nuclear, and biomass energy. It should form an energy supply system that contains renewable energy sources and energy storage carriers.

Meanwhile, electric and hydrogen energy should become the primary terminal energy sources. Under this prospect, electric and hydrogen energy will become the leading carriers of human energy in the future. The production, storage, transportation, and use of electric and hydrogen energy will become increasingly critical [35].

The third type is negative carbon technologies, which refer to recycling carbon emissions from human activities. They belong to the scope of carbon sinks, divided into two main types: natural and artificial carbon sinks [36]. Natural carbon sinks include ocean carbon sinks and agroforestry carbon sinks, achieving carbon sequestration through oceans, forests, and so on. This approach is less costly but has limited potential. Artificial carbon sinks refer to carbon capture, storage, and utilization technologies. This approach is costly and requires breakthroughs in the technologies. There is not much application space in the short term, but it is the key technology to achieve carbon neutrality in a long time [37]. Moreover, these technologies will also expand the space for the human use of fossil fuels.

The above explains the strategic thinking, severe challenges, significant opportunities, and overall implementation strategies of China's 30·60 Target. The following will focus on the coping strategies for achieving the 30·60 Target in the automobile industry in China.

3. Coping Strategies for the Automobile Industry under the 30·60 Target

Carbon emissions from the transport sector are an integral part of the total carbon emissions of the world and every country. Figure 4 shows the predicted carbon emissions reduction of all sectors of China's transport sector to achieve carbon neutrality [4, 38]. As we can see from the figure, although the total amount of carbon emissions in China is higher than that in the United States, the carbon emissions from the transport sector in China are still lower than that of the United States. The transport sector contributed 11% of China's carbon emissions in 2020, well below 37% in the United States and 24% globally. It shows that the transport sector in China is still not saturated. There is still a lot of space for development in the future. It also means enormous pressure and potential room for carbon reduction in the transport sector in China.

To achieve carbon neutrality by 2060, China's transport sector will need to reduce carbon emissions by 75 to 80 percent from the 2015 level, according to the research by Energy Foundation in China on China's mid-and long-term plan for low-carbon development and transformation of its transport sector [38]. Broken down by sector, road transport needs to cut emissions by 81.2 percent, civil aviation by 3.3 percent, and waterways by 5.6 percent to meet the goal. Therefore, the emission reduction of the transport sector should prioritize road transport. In this sense, as an essential part of road transport, the automobile industry will be the key to achieving the carbon neutrality goal in China's transport sector [6].

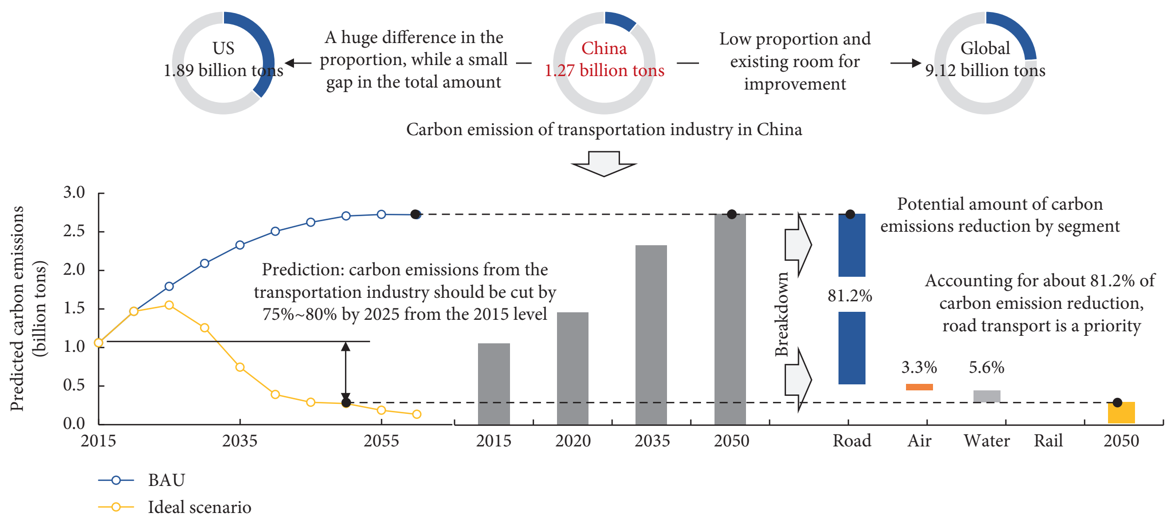


Figure 4: The role of the road transport (automobile industry) sector in achieving the 30·60 target in China [4, 38].

In addition, the automobile industry, as a comprehensive manufacturing industry, has a long industrial chain, involves a wide range of fields, and consumes a lot of energy. The automobile industry is a pillar and a carrier in the national economy. Its low-carbon and the zero-carbon transition are also more representative and vital for China.

3.1. Challenges to the Automobile Industry under the 30·60 Target. Compared with other industries, the automobile industry faces three significant challenges in achieving the 30·60 Target.

First, the automobile industry is large and attracts great attention in China. Car ownership per thousand in China is not yet saturated, and carbon emissions from its automobile industry will continue to grow for the foreseeable future. There are 292 million cars in China (as of the second quarter of 2021). China will have nearly 550 million cars by 2050, predicted by Hao et al. [39]. It implies a complex incremental substitution and de-stocking in China's automobile industry. The effect of low-carbon and zero-carbon transformation in the automobile industry will symbolize China's compliance with the international commitment of achieving the 30·60 Target. It is because that the automobile industry is highly concerned and dominant. For example, China is the world's largest market for new energy vehicles, and it is still growing at a high speed. Moreover, the market penetration rate of new energy vehicles has reached 15% in July 2021, which has attracted global attention [40].

Second, the global economic and trade mechanism has changed, and has increasingly fierce low-carbon competition. The current international political and economic environment is increasingly uncertain. Countries are likely to develop stricter trade policies around carbon emissions, creating new trade barriers. Regulations such as carbon border regulation mechanisms, carbon footprints, carbon leakage laws, etc., will limit the manufacturing model with high carbon emissions and be used for low-carbon emissions. It will affect a country's automobile industry [41]. Taking carbon leakage laws as an example, the European Union is currently discussing legislation to examine the carbon emissions of products from the whole life cycle perspective, which is expected to be implemented in 2023.

With the introduction of carbon leakage laws, those products produced in high-carbon regions will not be allowed to be sold in the relevant legislative areas, or high carbon taxes will be required to be paid. Even if low- or zero-carbon technologies are used in the production process, more attention needs to be paid to electric vehicles with relatively high carbon emissions in the production process [42]. It suggests that automobile enterprises should carry out low-carbon manufacturing and develop low-carbon products in shifting to a low-carbon market. Otherwise, they will not win the competition in the future [43].

Third, the automobile industry alone cannot solve the problems concerning the 30·60 Target. Due to its high interconnection with other industries, the automobile industry cannot achieve carbon neutrality on its own. For example, 90% of the carbon emissions in the production stage of the automobile come from indirect emissions of high-carbon electricity [44]. Only the adoption of clean energy can accelerate the process of carbon neutrality in the automobile industry. Therefore, the sustainable competitiveness of the automobile industry can only be guaranteed by the coordinated cross-industry development in China.

In short, the automobile industry is likely to be forced to accelerate the pace of achieving the 30·60 Target because of its high carbon emissions and high profile [10]. In this regard, the Chinese government and the automobile industry must have sufficient understanding and expectations.

3.2. Identification of Key Factors Affecting Carbon Emissions in the Automobile Industry. Carbon emissions of automobiles mainly cover the automobile manufacturing, use, and recycling stages [13]. By analyzing the life-cycle carbon emissions of automobiles, this paper summarizes the key factors affecting carbon emissions in the automobile industry, as shown in Figure 5.

The factors affecting carbon emissions in the automobile use stage include vehicle carbon emission intensity, structure and level of car ownership, vehicle miles traveled, and carbon emission factors of fuels [45]. Therefore, the following ways can be adopted to reduce the carbon emission intensity in the automobile use stage. First, it can reduce vehicle carbon emission intensity by improving engine thermal efficiency and using hybrid technologies [46] and alternative fuels [47]. These tasks can be completed by automobile companies alone. On the other hand, improving traffic efficiency and reducing congestion can improve the fuel economy of the automotive. Improvements in these jobs will depend on the transport sector. Second, it can optimize the structure and level of car ownership [48]. Examples include reducing the sales of high-carbon cars and increasing low-carbon cars. Measures should be taken to curb the purchase of and accelerate the elimination of high-carbon cars. Realizing these needs requires a change in people's low-carbon lifestyles [49]. Third, it can reduce vehicle miles traveled. For example, private car trips should be minimized, and people should be encouraged to use buses and subways more often [50]. Besides, we should reduce the use of road transport and increase rail or waterway transport [51]. Meanwhile, optimizing urban planning, increasing the frequency of shared trips, and reducing the number of unnecessary trips are also ways to reduce the vehicle miles traveled [52]. Fourth, it can lower the carbon emission factors of fuels. For example, it should conduct low carbon fuel production to lower the carbon emission factors of fuels.

The factors affecting carbon emissions in the automobile manufacturing stage include energy consumption and material consumption per unit of automobile product manufactured [13]. Therefore, on the one hand, carbon emissions in the automobile manufacturing stage can be reduced by cutting the energy consumption per unit of product manufactured. For example, it can be achieved by reducing fossil fuel consumption, increasing production efficiency, and reducing high-carbon manufacturing processes. On the other hand, it can reduce the material consumption per unit of product manufactured, such as lowering the consumption of high-carbon raw materials [53].

The factors affecting carbon emissions in the automobile recycling stage mainly include the reduction of carbon emissions from vehicle recycling and material recycling [54]. Generally speaking, recycling will significantly reduce carbon emissions from automobile manufacturing. Thus, some scholars have classified carbon emissions in the automobile recycling stage and the material consumption in the automobile manufacturing stage. The control of carbon emissions in the automobile manufacturing and recycling stages mainly depends on the automobile industry. Still, it can only be effectively implemented under the premise of cost control [55].

3.3. Coping Strategies for the Automobile Industry to Achieve Carbon Peaking and Carbon Neutrality Goals. From the above analysis, it can be seen that the automobile industry should not fight alone in the long journey toward carbon peaking and carbon neutrality goals. In contrast, it should coordinate effectively with other related industries and fields. Decarbonization is a systematic change for the automobile industry.

Inside the automobile industry, carbon emission reduction must be achieved through the linkage between the upstream and downstream of the industrial chain, including design, procurement, production, use, recycling, service, and other links. And decarbonization must be achieved across the industrial automobile chain and throughout the life cycle [56]. Outside the automobile industry, decarbonization of the automobile industry must be achieved through cross-industry and cross-sector collaboration [57]. The energy industry needs to provide zero-carbon energy for the automobile industry. The transport sector should provide low/zero-carbon mobility application scenarios in the automobile industry. It requires establishing a low-carbon policy and regulation system with carbon trading as the core, which will provide the most direct driving force and fundamental guarantee for the low-carbon and decarbonization transformation of the automobile industry. The coping strategies for the automobile industry to achieve the carbon peaking and carbon neutrality goals are as shown in Figure 6.

Therefore, the coping strategies for the automobile industry to achieve carbon peaking and carbon neutrality goals can be summarized as follows. The carbon emission reduction in the automobile industry needs to be centered on the carbon emission reduction throughout the life cycle; it should be based on the coordinated decarbonization of multiple industries and sectors and finally supplemented by negative carbon technologies.

3.3.1. Inside the Automobile Industry: Carbon Emission Reduction throughout the Life Cycle. To achieve carbon emission reduction throughout the life cycle, the automobile industry should take the following measures. The first is to reduce carbon emissions in the production process, including energy efficiency improvement, process innovation, fuel/raw material substitution, and green energy use. According to the China Automobile Technology and Research Center calculations, the amount of carbon emissions in the automobile production stage in China is maintained between0.06 and 0.07 billion tons per year [44]. The second is to change the use of carbon products, including energy conservation and efficiency improvement and operational efficiency improvement [58]. In particular, low-carbon/zero-carbon products should be used more intensively to dilute their production's energy and emissions' costs [59]. At the same time, the product's service life should be extended as much as possible. In the past, this was mainly to reduce costs while reducing production to reduce carbon emissions in the

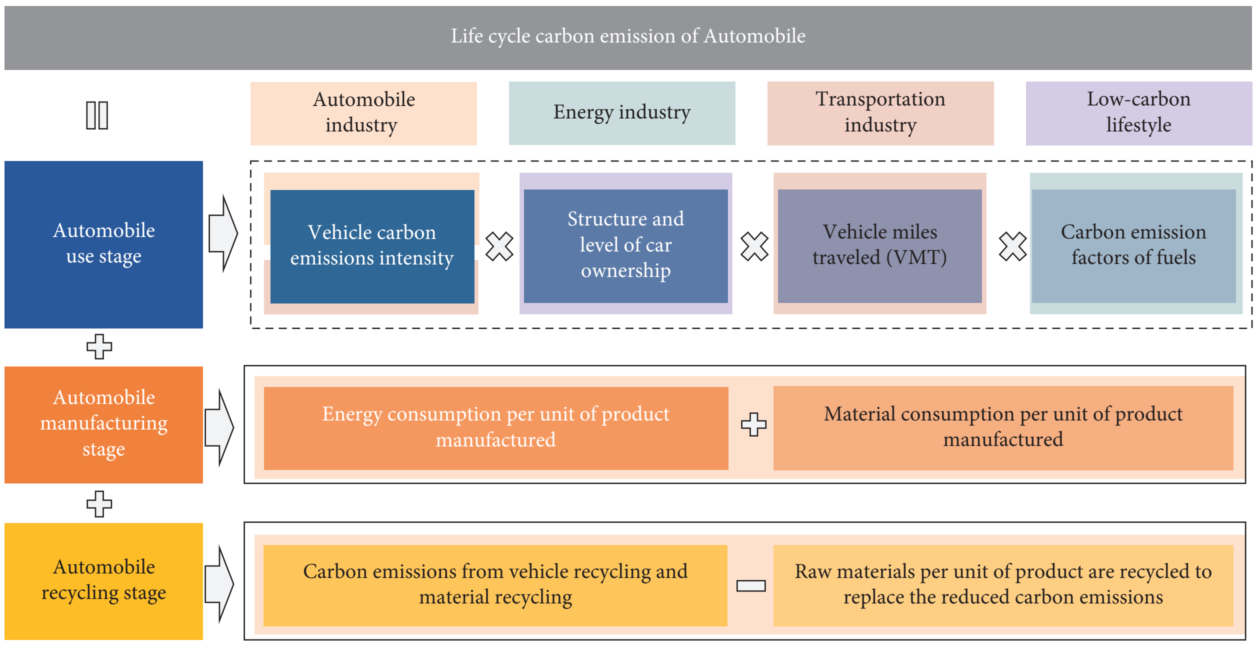


Figure 5: Identification of key factors affecting carbon emissions in the automobile industry.

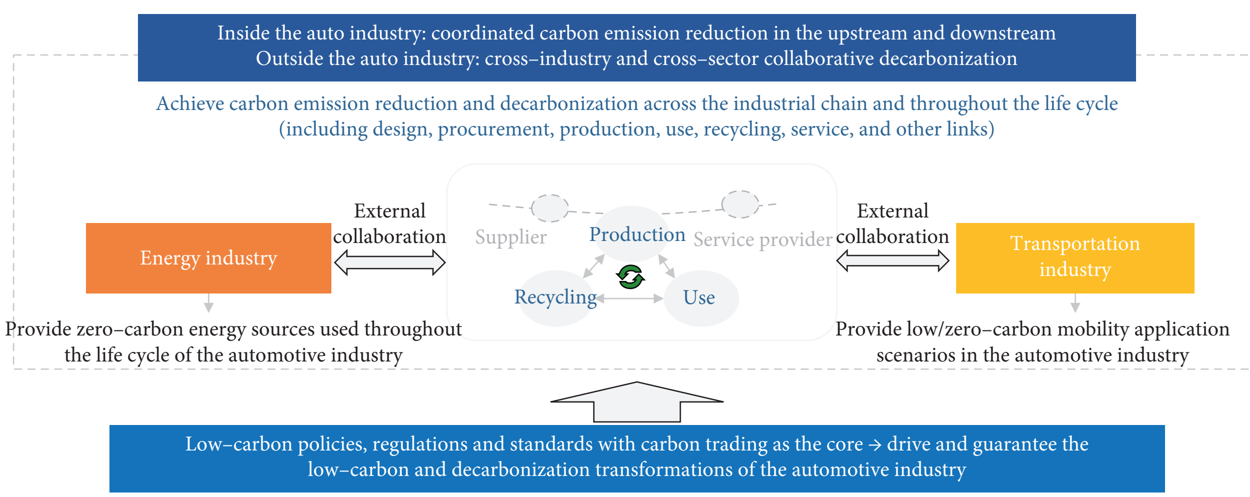


Figure 6: Coping strategies for the automobile industry to achieve carbon peaking and neutrality goals.

future [60]. In addition, in the structure of car ownership in China's automobile industry, commercial vehicles and passenger cars account for 16.7% and 83.3%, respectively. However, the corresponding carbon emissions account for 56% and 44%, respectively. Therefore, commercial vehicles will be an essential field of carbon emission reduction in the transport sector in the future [61]. Low-carbon technologies for commercial vehicles should be promoted in the future. For example, promoting the adoption of fuel cells in commercial vehicles is a good move.

The third is to reduce carbon emissions through recycling, including improving the efficiency of material recycling and developing a circular economy. Material recycling means that the production of raw materials can be reduced. It will effectively reduce the carbon emissions of raw material production from mining, processing to application. The carbon emissions from electric vehicles can be cut by 8%–11% through recycling (from Grave to Cradle stage) [62]. In particular, the recycling of power batteries will significantly reduce the overall carbon emissions of electric vehicles [63]. Fourth, the carbon emission reduction target of the automobile industry can be achieved by reducing the carbon emissions of the supply chain. Specific methods include material substitution and process innovation. The former solves the carbon emission problem of the upstream industrial chain from the source of materials while the latter effectively reduce carbon emissions in the production process of components [64]. For example, many automobile enterprises have carried out low-carbon supply chain management through collaboration with suppliers [11].

3.3.2. Outside the Automobile Industry: Cross-Industry and Cross-Sector Collaborative Decarbonization. In terms of external cooperation, efforts are mainly reflected in the cross-industry and cross-sector coordinated decarbonization. First, carbon emission reduction in the automobile industry can be realized by optimizing the structure of the energy industry. For example, the share of clean energy can be steadily increased [65]. At the same time, the development of electric vehicles and hydrogen fuel cell vehicles should be taken into account in the future to increase the consumption of renewable energy. In addition, efforts should be made to break through the challenges facing vehicle-to-grid (V2G) technology and business models to promote the development of a smart grid [66]. Second, the structural optimization and redistribution of the transport sector can reduce the carbon emissions of the automobile industry. For example, we can continuously enrich the application scenarios of low-carbon/zero-carbon automobile products and improve their usage intensity and operational efficiency. In the future, the barriers between smart cars, smart transportation, and smart cities can be broken down to realize the large-scale low-carbon application of smart electric vehicles. Finally, carbon emissions can be eliminated through negative carbon technologies. Some hard-to-eliminate carbon emissions in the automobile industry can be neutralized through reforestation and the application of carbon capture, storage, and utilization technologies.

3.3.3. Establishment of a Low-Carbon Policy, Regulation, and Standard System with Carbon Trading Policy as the Core. The policy, regulation, and standard system are essential drivers for the transformation of automobile power and the development of the automobile industry [67]. The carbon peaking and carbon neutrality goals have put forward new requirements for the integrity of the automobile industry's policies, regulations, and standards. It is necessary to further improve the policies, regulations, and standards for the automobile industry.

First of all, automobile test and evaluation standards are the foundation of the automobile industry's policy, regulation, and standard system. Specifically, passenger vehicle fuel economy test standards for passenger cars provide a benchmark for the quantitative evaluation of vehicles' energy consumption. Meanwhile, they also serve as the basis for the implementation of incentive policies, such as the corporate average fuel consumption (CAFC) and new energy vehicle (NEV) credits policy for passenger car enterprises (i.e., the CAFC & NEV dual credits policy) in China's automobile industry. However, the current automobile test and evaluation standards are still not perfect, especially for the energy consumption standards for new energy vehicles, calling for the formulation of life cycle-based evaluation methods as soon as possible. On the other hand, China still faces a shortage of test standards and policies for commercial vehicles. After all, commercial vehicles contribute more than half of the carbon emissions in the automobile industry. It is necessary to establish a system for evaluating the average fuel consumption of commercial vehicle enterprises as soon as possible.

Second, fiscal and tax incentive policies can reduce the incremental cost of promoting new energy vehicles. It can accelerate the market-based development of new energy vehicles [68]. At present, the existing incentive policies mainly include fiscal subsidies, purchase tax exemption, and right-of-way policies for new energy vehicles. To further promote the low-carbon development of the automobile industry in the future, it is necessary to establish a comprehensive fiscal and tax policy system for the automobile industry from the perspective of the whole life cycle, which should include the production, consumption, and usage stages.

Third, based on controlling the fuel economy of enterprises, the corporate average fuel consumption of the CAFC & NEV dual credits policy has been issued to promote the development of new energy vehicles [69]. In recent years, the CAFC & NEV dual credits policy has achieved notable results in promoting the development of new energy vehicles. However, the fuel economy of conventional cars is falling rather than rising due to the implementation of the CAFC & NEV dual credits policy. It needs to be optimized and adjusted in the future. It is suggested that the NEV credit policy should be phased out in due course according to industrial development. At the same time, the CAFC credit parameters should be determined in a scientific manner to ensure the gradual decrease of the average fuel consumption of automobile enterprises.

Finally, neither fiscal and tax incentive policies nor the CAFC & NEV dual credits policy is directly related to carbon emissions; they only indirectly affect the carbon emissions of the automobile industry. In the future, the automobile industry needs to establish a policy, regulation, and standard system with carbon emission control policy as the core, as shown in Figure 7. The automobile industry's carbon emission control should aim to achieve the low-carbon development of the automobile industry and promote the development of energy conservation, emission reduction, and efficiency enhancement in the automobile industry in China.

Policies directly related to carbon emission control include carbon tax and carbon trading policies [70]. The carbon tax policy takes the carbon dioxide emissions from automobiles as the evaluation standard. It controls the application of high-carbon fuels and high-carbon automobile products by levying corresponding taxes and fees on vehicle fuels and vehicle purchases. The carbon trading policy is an instrument that endows carbon dioxide with a commodity property to achieve energy conservation and carbon emission reduction based on market regulation. It can control the total amount of carbon emissions [71]. Compared with foreign carbon trading policies, the carbon market in China lacks control over emissions from vehicles in public use. Some localities could try carbon-sharing programs to incentivize people to stop using conventional vehicles or switch to alternative energy sources [72].

In general, compared with the carbon tax policy, the carbon trading policy has the advantages of a definite emission reduction effect, flexible response measures for enterprises, lower

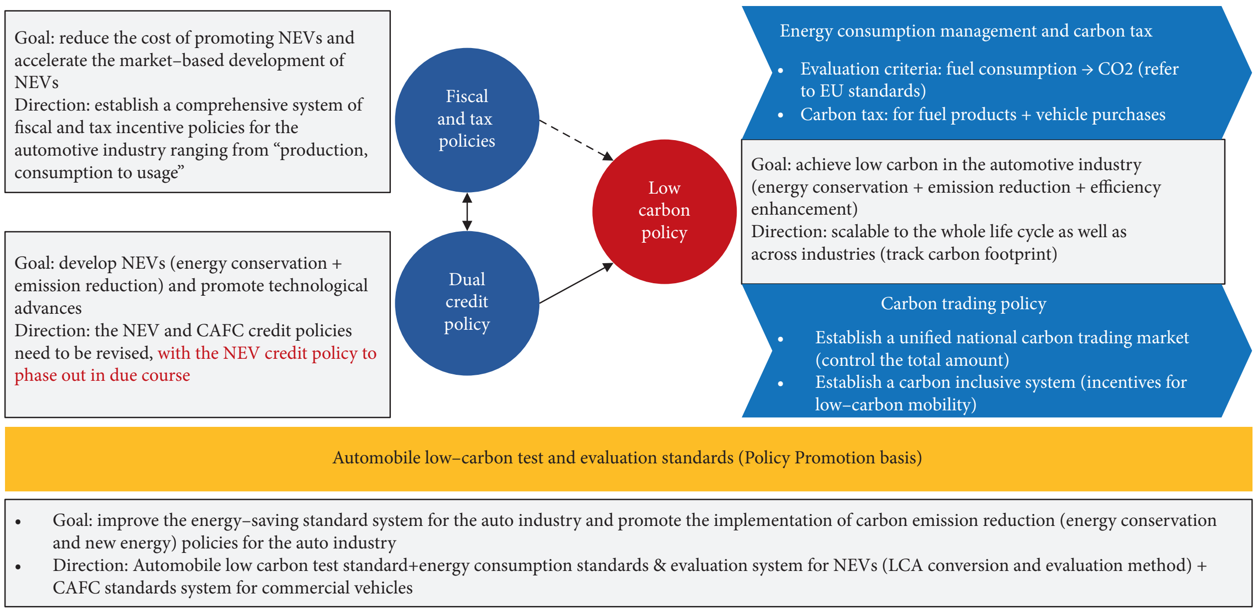


Figure 7: The low-carbon policy, regulation, and standard system with carbon trading policy as the core.

cost of emission reduction for the whole society, and low resistance to policy implementation. Therefore, the Chinese government should prioritize establishing a unified carbon trading market, incorporate the transport sector into the carbon trading market as soon as possible, and carry out relevant basic research on the transport sector's entry into the carbon trading market. Finally, it is suggested that China needs to improve the automobile test and evaluation standards, establish fiscal and tax incentive policies based on the whole life cycle consideration, and switch the dual credits policy to a carbon control policy. It is important to ensure the low-carbon transformation of the automobile industry. China should establish a low-carbon policy, regulation, and standard system with carbon trading as the core as soon as possible.

4. Conclusion

This paper systematically studies the challenges and opportunities brought about by the 30·60 Target and the coping strategies for the automobile industry. Through analysis, the following conclusions are drawn:

(1) Achieving the 30·60 Target is an environmental issue and a development issue. More importantly, it is a significant issue concerning human survival mode. It should be the fundamental starting point for all relevant emission reduction efforts of the country. In this sense, achieving carbon neutrality is a must. Achieving the 30·60 Target will mainly rely on carbon reduction technologies in the short term. At the same time, zero-carbon and negative carbon technologies will be necessary for the medium and long term. In the future, carbon emission reduction will become the most critical issue in China's social development, while the cost and other related issues will be of secondary importance.

(2) The automobile industry contributes a significant portion of carbon emissions to road transport and is an essential link in China's efforts to achieve the 30·60 Target. In particular, the automobile industry must effectively collaborate with other related industries and sectors to achieve carbon neutrality. The paths include joint carbon emission reduction by upstream and downstream players inside the industry and cross-industry and cross-sector coordinated decarbonization outside the industry. Meanwhile, the low-carbon policy and regulation system should be established to provide a direct driving force and fundamental guarantee for the low-carbon development of the automobile industry in China.

(3) Achieving the 30·60 Target is a systematic national project that is highly complex and interconnected. As the leader, adequate means, and carrier of national economic transformation and upgrading, the automobile industry should bear the brunt to achieve the carbon peaking and carbon neutrality goals. In the future, the automobile industry must make concerted efforts with other related industries from the whole life cycle perspective. Only in this way can the automobile industry effectively support China's historical transformation toward low-carbon and zero-carbon development.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Authors' Contributions

F.Z. and Z.L. designed the whole study; X.L. conducted data collection; X.L and H.Z. performed the modeling, analyzed the results, and wrote the paper; H.Z. and Z.L. revised and edited the paper. All authors have read and agreed to the published version of the paper.

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