Received January 28, 2018, accepted March 17, 2018, date of publication March 27, 2018, date of current version April 23, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2818738

Energy-Efficiency Models of Sustainable Urban Transportation Structure Optimization

YUEZHAO QIANG[1], GUANGDONG TIAN[2,3], (Member, IEEE), YUMEI LIU[2], AND ZHIWU LI[4,5], (Fellow, IEEE)
[1]School of Management, Harbin Institute of Technology, Harbin, 150001, China
[2]Transportation College, Jilin University, Changchun 130022, China
[3]State Key Laboratory of Digital Manufacturing Equipment and Technology, Huazhong University of Science and Technology, Wuhan 430074, China
[4]Institute of Systems Engineering, Macau University of Science and Technology, Macau 999078, China
[5]School of Electro-Mechanical Engineering, Xidian University, Xian 710071, China

(Corresponding authors: Guangdong Tian (tiangd2013@163.com) and Yumei Liu (lymlls@163.com))

This work was supported in part by the National Natural Science Foundation of China under Grants 51775238 and 51575232, and in part by the National Natural Science Foundation of Jilin province of China under Grants 20180101058JC and 20180101056JC.

ABSTRACT With the increasing numbers of cars and trips in cites, energy consumption and environmental pollution have become key problems of urban transport. In particular, the increasing use of private cars not only causes more energy consumption and produces more exhaust, but also makes the transportation structure unbalanced. Thus, a rationalized transport structure must be established and optimized to promote the sustainable development of urban transport. This paper presents some energy-efficiency models of sustainable urban transport structure optimization. Their objective functions are to minimize the energy consumption, and their constraints are carbon dioxide emission and traffic efficiency. The models were solved via the artificial fish swarm algorithm and used to optimize the urban transport structure of Harbin city in China. The results indicate that the models can not only guarantee the benefit of travelers and reduce the carbon emission, but also minimize energy consumption of the urban transportation.

INDEX TERMS Energy efficiency, transport structure, simulation modeling, Internet-of-Things.

I. INTRODUCTION

The number of car ownerships has increased greatly over the past few years with the rapid urban developments. On one hand, these cars provide convenient transportation for passengers; on the other hand, the increase in cars leads to the increase of energy consumption and CO2(carbon dioxide) emission and causes serious environmental pollution. The energy consumption and CO2 emission of urban transportation can affect the transport network structure. Thus, it is necessary to optimize the transport structure to promote the sustainable development of urban transportation [1], [2].

In the past decades, many researchers have addressed optimization issues of the transport structure and proposed various optimization approaches. Generally, these approaches to optimize the urban transport structure are from the perspective of transport efficiency and transport economy. For example, a method based on genetic algorithms was proposed Cortés *et al.* [3] to solve an evolutionary multi-objective dynamic problem of optimizing the real-time operation of public transport systems. Dubois *et al.* [4] designed a transit network by identifying the road routes required for bus operation and built a model to calculate their departure frequencies for minimizing the passenger waiting time. Hasselstrom [5] proposed a programming model to design transit network considering transport efficiency based on choosing the routes and determining the frequencies. Ceder and Wilson [6] described a design method of a mathematical bus-route model, considering the benefit of both passenger and operation. Baaj and Mahmassani [7] proposed a view that hybrid route generation heuristic algorithm can be used to design transit networks and apply the algorithm to the practical cases. Zhao [8] presented a mathematical model for large-scale transit route network optimization to minimize transfers and optimize route directness while maximizing service coverage. Yang *et al.* [9] present an optimization model for a bus network design based on the ant colony algorithm to maximize the direct traveler density. Jaramlillo-Alvarez *et al.* [10] presented a metaheuristics framework for solving the transit routing problem via Genetic Algorithm (GA) to minimize the travel time and the number of transfers simultaneously. Nes *et al.* [11] presented a transit route design method to maximize the number of public transport passengers for a given budget. Pattnaik *et al.* [12] designed an urban transit network model to minimize the total cost that includes users and operators through determining a route configuration with a set of transit routes and the associated frequencies. More models and methods can be found in [13]–[15].

The above-mentioned works have addressed the traditional urban transport structure optimization issues. With increasing environmental pollution, more researchers are focusing on the sustainable transport problem. For example, Bristow *et al.* examined strategic pathways to low carbon personal transportation in Britain and established a 2050 baseline using trend information, forecast and evidence from reviews. They recommended the following: a reduction in the use of motorized transport, the development and purchase of more efficient vehicles, decarbonization of public transportation and reduction of the need for motorized travel [16]. Chen *et al.* [17] recommended the use of low-carbon transportation modes in Shanghai, e.g., strengthening the leadership of government, adjusting the structure, cultivating low-carbon technologies and industries, and developing new-style energy. Nakamura and Hayash [18] summarized the trends and effects of low-carbon measures at the international scale for urban transportation. Sun *et al.* presented a bi-level optimization model for public transit network to maximized the interest of both passengers and operators and minimize the environmental cost by considering low carbon factors. They solved this model via a differential evolution method [19]. Szeto *et al.* [20] formulated a traffic network design problem that takes both vehicle emissions and noise into account. Tian and Liu [21] proposed an transport facilities optimization problem to consider carbon emission. Arild [22] constructd a transport structure optimization model based on the linear programming with two objective functions, i.e., optimizing transport efficiency and minimizing carbon emission.

The works mentioned above have focused on the sustainable urban transport structure optimization from the perspective of CO2 emission. In fact, in the actual urban transport structure decision-making, a decision-maker may also be concerned about the energy consumption issue. Therefore, the energy management issue of the urban transport structure is addressed. For example, in [23], Poudenx noted that the traditional policy of limiting the use of private cars does not consider the accessibility and comfort of traveling urban residents. To conserve energy and reduce the greenhouse gas emissions, the environmental investment of non-motorized travel modes should be increased, and the new green transport mode should be developed. Solaymani and Kari [24] discussed the impact of energy subsidy on the urban transport structure. The work by in [25] found that the development of sustainable transport systems, such as energy efficient transport systems, should be supported. In addition, Ge *et al.* [26] proposed a model to maximize social welfare of the traffic system by optimizing the traffic signal timings and fuel surcharges and solved the model problem using a simulated-annealing-based solution algorithm. Li *et al.* [27] and Su *et al.* [28] solved the high-speed railway energy-constraint operation problem by calculating the optimal speed profile.

The aforementioned literature on energy management of sustainable transport has mainly focused on the transport energy-efficiency policy and control strategy problems, e.g., advising the government to encourage travelers and operators to use electric cars and proposing some reward and punishment programs to restrict the use of the private cars. Little attention, however, has been paid to the energy-efficiency optimization problem of sustainable urban transport structure. To solve this problem, taking Harbin City in China as an example and considering the impact on the emission of carbon dioxide (CO2) emission and traffic/transport efficiency, this work presents different energy-efficiency models under different constraints of its urban transport structure optimization with CO2 emission and transport efficiency constraints for the first time. The purpose of this work is to find a new method to design the urban transport structure by taking the energy-efficiency, transport efficiency and CO2 emission into full account. Moreover, an artificial fish swarm algorithm (AFSA) is presented to solve the three proposed models.

The remainder of this paper is structured as follows. In Section II, the problem of the models is stated. In Section III, the energy-efficiency models of sustainable urban transport structure optimization are established. Section IV introduces the principle of the proposed algorithm. In Section V, a few cases are presented to test the effectiveness of the algorithm. In Section VI, we conclude our work and describe further research direction.

II. PROBLEM STATEMENT

To build the precise models, the definition of the assumptions and parameters used in this work is essential.

A. TRANSPORT MODE

The transport mode has a great impact on the energy consumption and CO2 emission of urban traffic structure. The previous works only considered traditional traffic/transport modes, e.g., private cars, conventional buses and motorcycles [19]. However, the increasing use of alternative energy cars has affected the urban transport structure. Thus, we must consider these new elements when optimizing an urban transport structure. The main transport modes, including new energy cars, in our work, are as follows: 1) hybrid bus, 2) natural gas bus, 3)conventional bus (i.e., combustion engine bus), 4) natural gas taxi, 5) private car, 6) rail transport, 7) motorcycle and 8) walking and bicycle. Note that the walking and bicycle mode does not exhaust CO2; thus, we combined modes seven and eight as one kind of mode.

B. ASSUMPTIONS

The following assumptions are made in this work:

(1) The urban/city whose transport structure to be optimized is a closed system.

(2) The pollution and resource consumption caused by the transport between cities are ignored.

(3) Transport demand conditions within the city are predetermined.

C. NOTATIONS

(1) i—The modes of passenger transport, $i = 1, 2, 3 \ldots n$.

(2) T_i—The amount of passenger turnover of the ist passenger transport mode, with its unit being million·km/day.

(3) E_i—Energy factor of the ist passenger transport mode, with its unit being MJ/km·per capita, where MJ is million·joule.

(4) R—Equivalent radius of the city, with its unit being km.

(5) V_i—Average speed of the ist passenger transport mode, with its unit being km/hour.

(6) t—The average travel time for urban residents, with its unit being an hour.

(7) C_i—CO_2 emission factor of the ist passenger transport mode, with its unit being g/km·per vehicle.

(8) C_e—The amount of CO_2 emission of per capita in a city, with its unit being ton or t.

D. DEFINITIONS OF TYPICAL EVALUATION PARAMETERS

This work uses the following parameters:

(1) Q—The amount of total energy consumption of the urban passenger transport, defined as

$$Q = \sum_{i=1}^{n} T_i \times E_i \tag{1}$$

(2) C_t—The amount of total CO_2 emission of the urban passenger transport, defined as

$$C_t = \sum_{i=1}^{n} T_i \times C_i \tag{2}$$

(4) C_m—The actual total amount of CO_2 emission in a certain city, defined as

$$C_m = C_{\mathrm{e}} \times T_{\mathrm{p}} \tag{3}$$

where T_{p} is the total amount of population in a certain city.

(5) C_g—The permitted amount of CO_2 emission of urban transport in a certain city, namely, the upper bound of CO_2 emission of urban transport, defined as

$$C_g = g \cdot C_{\mathrm{m}} \tag{4}$$

where g is the CO_2 emission factor of urban transport in a certain city.

(3) R_e—The average travel distance of an urban passenger. Transport efficiency of an urban passenger is the possibility of a passenger to reach the destination in the given time. It is required that the average distance of an urban passenger Re should be larger than the equivalent radius of the city R in this work. Re is defined as

$$R_e = \frac{\sum_{i=1}^{n} V_i \times T_i}{\sum_{i=1}^{n} T_i} \times t \tag{5}$$

III. ENERGY-EFFICIENCY MODELS OF SUSTAINABLE URBAN TRANSPORT STRUCTURE OPTIMIZATION

On the basis of the above definitions and assumptions, we build three energy-efficiency models of sustainable urban transport structure optimization, i.e., the energy-efficiency model with the passenger turnover constraint, energy-efficiency model with a CO2 emission constraint, and energy-efficiency model with CO2 emission and the transport efficiency constraints, as presented next in detail.

A. ENERGY-EFFICIENCY MODEL WITH THE PASSENGER TURNOVER CONSTRAINT

In the actual passenger transport process of the urban transport, a decision-maker intends to minimize the energy consumption of passenger turnovers. To solve this problem, we build an energy-efficiency model for sustainable urban transportation structure optimization with the passenger turnover constraint as follows:

$$\begin{aligned} &\min\ (Q) \\ &\text{Subject to}: \begin{cases} T_i^{\min} \le T_i \le T_i^{\max} \\ i = 1, 2, 3, \ldots, \mathrm{n} \end{cases} \end{aligned} \tag{6}$$

where $T_i^{\min}$ and $T_i^{\max}$ are the lower and upper bounds of passenger turnover of the ist passenger transport mode, respectively.

B. ENERGY-EFFICIENCY MODEL WITH A CO_2 EMISSION CONSTRAINT

Traffic exhaust has a great influence on our environment. Regarding traffic suitability, the CO2 emission is considered in the optimal problem of practical urban transport structure. Therefore, a decision-maker must minimize the total energy/fuel consumption of urban transport structure under the specified CO2 emission constraint. The entire model can be established as follows:

$$\begin{aligned} &\min\ Q \\ &\text{Subject to}: \begin{cases} T_i^{\min} \le T_i \le T_i^{\max} \\ C_t \le C_g \\ i = 1, 2, 3, \ldots, \mathrm{n} \end{cases} \end{aligned} \tag{7}$$

where $C_t \le C_g$ is the given CO_2 emission constraint.

C. ENERGY-EFFICIENCY MODEL WITH CO_2 EMISSION AND TRANSPORT EFFICIENCY CONSTRAINTS

In the actual operation of the passenger transport system, the transport efficiency must be considered as an important factor. We should ensure that passengers arrive at their destinations within the prescribed time. Thus, we establish an energy-efficiency model with CO2 emission and transport efficiency constraints for sustainable urban transport structure optimization as follows:

$$\min Q$$
$$\text{Subject to}: \begin{cases} T_i^{\min} \leq T_i \leq T_i^{\max} \\ C_t \leq C_g \\ T_e \geq R \\ i = 1, 2, 3, \ldots, \text{n} \end{cases} \quad (8)$$

where $T_e \geq R$ is the accessibility constraint of a passenger.

IV. SOLUTION ALGORITHM

The artificial fish swarm algorithm (AFSA) has effectively applied to solve many industrial optimization problems, e.g., combinatorial optimization and multiple sequence alignment problems [29]–[33]. Thus, we choose ASFA to solve our models. The fundamentals of ASFA will be introduced next.

A. ARTIFICIAL FISH SWARM ALGORITHM (ASFA)

Similar to other intelligent heuristic algorithms, AFSA is an artificial intelligent swarm algorithm based on simulating the collective foraging behavior of fish groups. ASFA can search for the global optimum by simulating the behaviors of an artificial fish (AF), including preying, swarming and following behaviors [34]. According to the characteristics of ASFA, we can initialize the fish group randomly. We set the searching space to be D-dimensional, with *Fishnum* being the number of fish in the group. The current state vector of an AF group is $Z = (z1, z2, \ldots, zm)$, where $zi(i = 1, \ldots, m)$ is the variable to be optimized. *Visual* is the distance of the visual field of the AF acting. The food abundance of the AF in the current position is described as $Y = F(Z)$, where Y is the objective function. The distance between the *ith* and *jth* individuals of AF can be described as $dij = ||ZjZi||$, where i and j are random fishes. *Step* is the maximum step size of AF. Moreover the ρ $(0 < \rho < 1)$ denotes the degree of congestion. In the algorithm, the number of iterations should be defined as the AF's searching times of food. Moreover, *Maxgen* denotes the upper limit of the number of iterations in this work. Because the maximum problem and minimum problem can be converted into each other by mathematical formulas, we only discuss the maximum problem in this work.

1) PREYING BEHAVIOR

Preying behavior is mainly considered to follow the direction of food, and its goal is to move in the better direction in an iterative manner in the optimization algorithm. Let a current AF state be $Z_{i..}$ We randomly select a new state Zj in this AF's visual field. If the food abundance of Zj is greater than Zi then move a step in that direction; otherwise, select a new state Zj randomly again and decide whether to move or not. If the state cannot be satisfied after trying a default times-value *Try_number*, then move a step randomly. The step moving follows the rule below:

$$\begin{cases} Z_{i+1} = Z_i + Step \times \dfrac{Z_j - Z_i}{\|Z_j - Z_i\|} \times rand() & (Y_j > Y_i) \\ Z_j = Z_i + Visual \times rand() & (Y_j < Y_i) \end{cases} \quad (9)$$

where *rand* () is a random number between 0 and 1.

2) SWARMING BEHAVIOR

In swarming behavior, to ensure survival and avoid harm, fish will naturally gather into groups. An AF at the current state Zi will seek the number of companions (nf) and the central position of companions Zc within its current neighborhood. If $Yc/nf > \rho Yi$, then there is enough food and it is not crowded at the center of the fish group. This behavior can be shown mathematically via the following equation:

$$\begin{cases} Z_{i+1} = Z_i + Step \times \dfrac{Z_c - Z_i}{\|Z_c - Z_i\|} \times rand() & (\dfrac{Y_c}{n_f} > \rho Y_i \ and \ n_f \geq 1) \\ Z_{i+1} = Formula(8) & (\dfrac{Y_c}{n_f} \leq \rho Y_i \ or \ n_f = 0) \end{cases} \quad (10)$$

3) FOLLOWING BEHAVIOR

The following behavior involves a chase to the most active fish nearby and can be understood as a process of moving to the best companion nearby. Let Zi be the current state of the AF that will search the best companion Z_{max} nearby with Y_{max}. If $Y_{max}/nf > \rho Yi$, then the current position of Z_{max} has higher food abundance and there is no crowd around it. Then, the AF will move a step towards Z_{max}; otherwise, execute preying behavior.

The following behavior can be shown mathematically via the following description:

$$\begin{cases} Z_{i+1} = Z_i + Step \times \dfrac{Z_{\max} - Z_i}{\|Z_c - Z_i\|} \times rand() \\ \qquad (\dfrac{Y_{\max}}{n_f} > \rho Y_i \ and \ n_f \geq 1) \\ Z_{i+1} = Formula(8) \\ \qquad (\dfrac{Y_{\max}}{n_f} \leq \rho Y_i \ or \ n_f = 0) \end{cases} \quad (11)$$

4) BULLETIN

Bulletin is used to record the optimal result of AF. Each AF compares its own action-finished state with the bulletin board and decides whether to update or not. If its current state is better than the record of the bulletin board, the value of bulletin will be updated.

On the basis of the above statement, to implement ASFA can be through the following steps.

Step 1) Initialize the parameters of AF, i.e., choose the most suitable value for them.

Step 2) Set the bulletin board to record the current status of each AF and to be ready to record.

Step 3) Implement prey, swarm and follow search-for-good behaviors and obtain the status of each AF.

TABLE 1. Urban transportation structure constitution of Harbin city in china.

T_i	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8
Transp-ort mode	Hybrid bus	Nature-al gas bus	Conv-enti-onal bus	Natu-real gas tax	Privat-e car	Rail traffic	Motor-cycle	Walking and bicycle
Scale (%)	4.8	18	7.2	7	8	0	7	48
E_i *(MJ/km·per)*	0.54	0.79	0.714	5.99	2.795	0.322	1.495	0
V_i *(km/h)*	20	35	40	30	15	8	15	8
C_i *(g/km)*	13.75	50.19	42.91	114.2	128.92	42.03	80.5	0

TABLE 2. Passenger turnover data for each passenger transport mode.

T_i (10^7 per·km/day)	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8
T_i^{min}	5.574	20.9	8.36	3.72	9.57	7.56	1.754	0
T_i^{max}	13.61	51.05	20.42	3.90	35.07	12.96	2.792	8.51

Step 4) Update the optimal value in the bulletin board by comparing the status of the action-finished AF and the bulletin board.

Step 5) Output the best optimal result until the maximum number of iterations is satisfied; otherwise, return to Step 2.

The algorithm has been executed in the MATLAB programming language (R2010b).

V. CASE STUDY

Considering the urban transport structure optimization problem of Harbin City in China, the energy factor Ei, average speed Vi and CO2 emission factor Ci of each passenger transport mode are obtained according to the existing literature [35]; these values are listed in Table 1. Furthermore, we list passenger turnover data of each passenger transport mode of this city, as shown in Table 2. Additionally, $Ce = 8.52\ t/per, Tp = 4600000$, and $g = 0.15$ [36], [37]. Thus, based on Eq. (4), C_m is $16.1 \times 10^4 t$.

The parameters of the AFSA in this work are set below: the number of fish *Fishnum* nf, the maximum number of generations *Maxgen* and the number of exploratory *Try_number* are all given 100; the visual distance *Visual*, the *Step* and the degree of congestion factor ρ are 0.1, 0.05 and 0.618, respectively.

TABLE 3. The results for example 1.

T_i (10^7 per·km/day)	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8
Results	8.356	22.33	13.475	3.72	9.57	9.373	2.206	4.18

Example 1: A decision-maker seeks to optimize the urban transport structure of this city with the minimum energy consumption of the passenger turnover. This problem can be translated into solving the following model:

$$\min (Q) \tag{12}$$

$$\text{Subject to}: \begin{cases} 5.574 \le T_1 \le 13.61 \\ 20.9 \le T_2 \le 51.05 \\ 8.36 \le T_3 \le 20.42 \\ 3.72 \le T_4 \le 3.9 \\ 9.57 \le T_5 \le 35.07 \\ 7.56 \le T_6 \le 12.96 \\ 1.754 \le T_7 \le 2.792 \\ 0 \le T_8 \le 8.51 \end{cases} \tag{13}$$

After executing the algorithm, we can obtain the following results. The optimal results of the passenger turnover of each transport mode are shown in Table 3. The lowest total energy consumption of the urban passenger transport satisfying the passenger turnover constraint is 87.116×10^6 kJ.

Example 2: A decision-maker wants to optimize the urban transport structure of this city to obtain the minimum energy consumption of the passenger turnover satisfying the specified CO2 emission constraint. This problem can be translated into solving the following model problem:

$$\min (Q) \tag{14}$$

$$\text{Subject to}: \begin{cases} 5.574 \le T_1 \le 13.61 \\ 20.9 \le T_2 \le 51.05 \\ 8.36 \le T_3 \le 20.42 \\ 3.72 \le T_4 \le 3.9 \\ 9.57 \le T_5 \le 35.07 \\ 7.56 \le T_6 \le 12.96 \\ 1.754 \le T_7 \le 2.792 \\ 0 \le T_8 \le 8.51 \\ \sum_{i=1}^{n} T_i \times C_i \le 16100 \end{cases} \tag{15}$$

After executing the algorithm, we can obtain the following results. The optimal results of passenger turnover of each transport mode are shown in Table 4. The lowest total energy consumption of the urban passenger transport satisfying this carbon constraint is 90.879×10^6 kJ.

Example 3: A decision-maker seeks to optimize the urban transport structure of this city with the minimum energy consumption of the passenger turnover satisfying the specified CO2 emission and transport efficiency constraints. This problem can be translated into solving the model problem

TABLE 4. The results for example 2.

T_i (10^7 per·km/ day)	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8
Results	10.121	27.289	9.723	3.72	10.363	9.262	1.794	6.359

TABLE 5. The results for example 3.

T_i (10^7 per·km/ day)	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8
Results	12.754	28.537	10.998	3.723	9.808	10.25	1.936	6.633

below. Note that $R = 15$ km, which is calculated according to the area of this city [37], and the average urban travel budget time t is 0.86 h.

$$\min\ (Q) \tag{16}$$

$$\text{Subject to}: \begin{cases} 5.574 \le \mathrm{T}_1 \le 13.61 \\ 20.9 \le \mathrm{T}_2 \le 51.05 \\ 8.36 \le \mathrm{T}_3 \le 20.42 \\ 3.72 \le \mathrm{T}_4 \le 3.9 \\ 9.57 \le \mathrm{T}_5 \le 35.07 \\ 7.56 \le \mathrm{T}_6 \le 12.96 \\ 1.754 \le \mathrm{T}_7 \le 2.792 \\ 0 \le \mathrm{T}_8 \le 8.51 \\ \sum_{i=1}^{n} T_i \times C_i \le 16100 \\ \dfrac{\sum_{i=1}^{n} V_i \times T_i}{\sum_{i=1}^{n} T_i} \times t \ge 15 \end{cases} \tag{17}$$

After executing the algorithm, we obtain the following results. The optimal results of passenger turnover of each transport mode are shown in Table 5. The lowest total energy consumption of the urban passenger transport satisfying carbon and transport efficiency constraints is 93.191×10^6 kJ.

Furthermore, for testing the effectiveness of AFSA, the results based on **Example 1** with different given parameters are shown in Table 6. The result of their errors are shown in Table 6, and the relative error is accounted by [(Best value)-(Actual value)]/(Best value) × 100%, where the *Best value* is the minimum value of solution results among all cases, and the *Actual value* is the solution results of the model run each case.

As seen in Table 6, we can draw a conclusion that the relative error does not exceed 0.94% and the result is reasonable and accurate, i.e., AFSA applied to solve our transport structure optimization models is highly satisfactory.

TABLE 6. Comparison of solutions of example 1 with different cases.

Cases	*Fishnum*	*Try_n umbe r*	*Maxgen*	*Actual v alue*	*Optimal value*	*Relative error (%)*
1	100	100	100	87.116	87.116	0.00
2	60	100	120	87.599	87.116	0.55
3	50	120	100	87.283	87.116	0.19
4	80	110	120	87.941	87.116	0.94
5	80	120	130	87.672	87.116	0.64

VI. CONCLUSIONS

Considering the rapid development of the economy and the transportation industry, energy consumption and CO2 emission have been key factors in sustainable development, with transport consumption occupying a large proportion of energy consumption and CO2 emission. For example, the transport activities contribute 8% of the total energy consumption and approximately 20-30% of CO2 emission, and the contribution will continue to grow with the increase of the motorization level in China [38]. The sustainable urban transport structure optimization has an important role to play in energy conservation and emission reduction. This work presented energy-efficiency models built under different constraints of sustainable urban transport structure optimization for the first time, i.e., an energy-efficiency model with the passenger turnover constraints, an energy-efficiency model with a CO2 emission constraint, and an energy-efficiency model with CO2 emission and transport efficiency constraints. By taking Harbin City in China as an example, some practical examples of energy-efficiency optimization for its urban transport structure were presented. Then, an AFSA algorithm was presented to solve these model problems. The results of running and testing the model showed that the AFSA algorithm is feasible and effective when used to solve the proposed optimized transport structure models. Thus, the results can help decision-makers make better decisions. Additionally, the application results showed that our models can not only make transportation convenient and efficient for passengers by selecting their appropriate mode of travel but also ensure that the urban passenger transport satisfies the requirements of low energy consumption and low CO2 emissions.

However, some limitations remain in our proposed method and model. For example, many uncertain factors have a great influence on the optimization model, e.g., the emission factor of CO2 and the types of urban passenger transport. Thus, the related uncertainty analysis and its industrial application require further discussion [36], [39]–[44].

REFERENCES

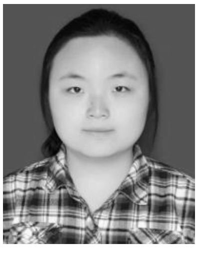
[1] L. Zhang, "The research on low-carbon transport situation and countermeasure in China," *Energy Conservation Technol.*, vol. 1, p. 22, Jan. 2013.

[2] T. Zhang, "Research on urban low-carbon transport development index," *Technol. Econ.*, vol. 32, no. 3, pp. 78–84, 2013.

[3] C. E. Cortés, D. Sáez, F. Milla, A. Núñez, and M. Riquelme, "Hybrid predictive control for real-time optimization of public transport systems' operations based on evolutionary multi-objective optimization," *Transp. Res. C, Emerg. Technol.*, vol. 18, no. 5, pp. 757–769, 2010.

[4] D. Dubois, G. Bel, and M. Llibre, "A set of methods in transportation network synthesis and analysis," *J. Oper. Res. Soc.*, vol. 30, no. 9, pp. 797–808, 1979.

[5] D. Hasselström, *Public Transportation Planning: A Mathematical Programming Approach*. Goteborg, Sweden: Univ. Goteborg, 1981.
[6] A. Ceder and N. H. M. Wilson, "Bus network design," *Transp. Res. B, Methodol.*, vol. 20, no. 4, pp. 331–344, 1986.
[7] M. H. Baaj and H. S. Mahmassani, "Hybrid route generation heuristic algorithm for the design of transit networks," *Transp. Res. C, Emerg. Technol.*, vol. 3, no. 1, pp. 31–50, 1995.
[8] F. Zhao, "Transit network optimization - minimizing transfers and optimizing route directness," *J. Public Transp.*, vol. 7, no. 1, pp. 63–82, 2004.
[9] Z. Yang, B. Yu, and C. Cheng, "A parallel ant colony algorithm for bus network optimization," *Comput.-Aided Civil Infrastruct. Eng.*, vol. 22, no. 1, pp. 44–55, 2007.
[10] P. Jaramlillo-Álvarez, C. A. González-Calderón and G. González-Calderón, "Route optimization of urban public transportation," *Dyna*, vol. 80, no. 180, pp. 41–49, 2013.
[11] R. Nes, R. Hamerslag, and B. H. Immerse, "Design of public transportation networks," *Transp. Res. Rec.*, vol. 1202, pp. 74–82, 1998.
[12] S. B. Pattnaik, S. Mohan, and V. M. Tom, "Urban bus transit route network design using genetic algorithm," *J. Transp. Eng.*, vol. 124, no. 4, pp. 368–375, 1998.
[13] H. J. Carlo, I. F. A. Vis, and K. J. Roodbergen, "Transport operations in container terminals: Literature overview, trends, research directions and classification scheme," *Eur. J. Oper. Res.*, vol. 236, no. 1, pp. 1–13, Jul. 2014.
[14] Y. Sheffi, *Urban Transportation Networks: Equilibrium Analysis with Mathematical Programming Methods*. Englewood Cliffs, NJ, USA: Prentice-Hall, 1985.
[15] Y. Fang, F. Chu, S. Mammar, and M. Zhou, "Optimal lane reservation in transportation network," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 2, pp. 482–491, Jun. 2012.
[16] A. L. Bristow, M. Tight, A. Pridmore, and A. D. May, "Developing pathways to low carbon land-based passenger transport in great Britain by 2050," *Energy Police*, vol. 36, no. 9, pp. 3427–3435, 2008.
[17] W. Chen, G. Luan, and H. Li, "Speed up Shanghai's transportation system developing into low-carbon mode," *Adv. Intell. Transp. Syst.*, vol. 1, no. 4, pp. 95–99, 2012.
[18] K. Nakamura and Y. Hayashi, "Strategies and instruments for low-carbon urban transport: An international review on trends and effects," *Transp. Policy*, vol. 29, pp. 264–274, Sep. 2013.
[19] X. Sun, H.-P. Lu, and W.-J. Chu, "A low-carbon-based bilevel optimization model for public transit network," *Math. Problems Eng.*, vol. 2013, Jun. 2013, Art. no. 374826.
[20] W. Y. Szeto, Y. Wang, and S. C. Wong, "The chemical reaction optimization approach to solving the environmentally sustainable network design problem," *Comput.-Aided Civil Infrastruct. Eng.*, vol. 29, no. 2, pp. 140–158, 2014.
[21] G. Tian and Y. Liu, "Energy-efficient models of sustainable location for a vehicle inspection station with emission constraints," *IEEE Trans. Autom. Sci. Eng.*, vol. 12, no. 1, pp. 238–243, Jan. 2015.
[22] A. Vold, "Optimal land use and transport planning for the greater oslo area," *Transp. Res. A, Policy Pract.*, vol. 39, no. 6, pp. 548–565, 2005.
[23] P. Poudenx, "The effect of transportation policies on energy consumption and greenhouse gas emission from urban passenger transportation," *Transp. Res. A, Policy Pract.*, vol. 42, no. 6,pp. 901–909, 2008.
[24] S. Solaymani and F. Kari, "Impacts of energy subsidy reform on the Malaysian economy and transportation sector," *Energy Policy*, vol. 70, pp. 115–125, Jul. 2014.
[25] S. Fu, H. Wen, J. Wu, and B. Wu, "Cross-networks energy efficiency tradeoff: From wired networks to wireless networks," *IEEE Access*, vol. 5, pp. 15–26, 2017.
[26] X.-Y. Ge, Z.-C. Li, W. H. K. Lam, and K. Choi, "Energy-sustainable traffic signal timings for a congested road network with heterogeneous users," *IEEE Trans. Intell. Transp. Syst.*, vol. 15, no. 3, pp. 1016–1025, Jun. 2014.
[27] X. Li, C.-F. Chien, L. Li, Z. Gao, and L. Yang, "Energy-constraint operation strategy for high-speed railway," *Int. J. Innov. Comput., Inf. Control*, vol. 8, no. 10(A), pp. 6569–6583, 2012.
[28] S. Su, X. Li, T. Tang, and Z. Gao, "A subway train timetable optimization approach based on energy-efficient operation strategy," *IEEE Trans. Intell. Transp. Syst.*, vol. 14, no. 2, pp. 883–893, Jun. 2013, doi: 10.1109/TITS.2013.2244.
[29] X.-L. Li and J.-X. Qian, "Studies on artificial fish swarm optimization algorithm based on decomposition and coordination techniques," *Chin. J. Circuits Syst.*, vol. 1, pp. 1–6, Jan. 2003.
[30] X.-L. Li, F. Lu, G.-H. Tian, and J.-X. Qian, "Applications of artificial fish school algorithm in combinatorial optimization problems," *Chin. J. Shandong Univ. (Eng. Sci.)*, vol. 5, p. 015, Oct. 2004.
[31] Z. Huang and Y. Chen, "An improved artificial fish swarm algorithm based on hybrid behavior selection," *Int. J. Control Autom. Syst.*, vol. 6, no. 5, pp. 103–116, 2013.
[32] M. Neshat, G. Sepidnam, M. Sargolzaei, M. Sargolzaei, and A. N. Toosi, "Artificial fish swarm algorithm: A survey of the state-of-the-art, hybridization, combinatorial and indicative applications," *Artif. Intell. Rev.*, vol. 42, no. 4, pp. 965–997, 2014, doi: 10.1007/s10462-012-9342-2.
[33] W.-H. Yang, "An improved artificial fish swarm algorithm and its application in multiple sequence alignment," *J. Comput. Theor. Nanosci.*, vol. 11, no. 3, pp. 888–892, 2014.
[34] Y. Gao, L. Guan, and T. Wang, "Optimal artificial fish swarm algorithm for the field calibration on marine navigation," *Measurement*, vol. 50, pp. 297–304, Apr. 2014.
[35] H. Cai and S.-D. Xie, "Determination of emission factors from motor vehical under different emission standards in China," *Acta Scientiarum Naturalium Univ. Pekinensis*, vol. 46, no. 3, pp. 319–326, 2010.
[36] G. D. Tian, H. H. Zhang, Y. X. Feng, D. Q. Wang, Y. Peng, and H. F. Jia, "Green decoration materials selection under interior environment characteristics: A grey-correlation based hybrid MCDM method," *Renew. Sustain. Energy Rev.*, vol. 81, pp. 682–692, Jan. 2018.
[37] S. L. Jin, "Carbon dioxide emissions characteristics, trends and policy orientation," Inf. Center Develop. Res. Center State Council, Tech. Rep., 2010.
[38] D. He *et al.*, "Energy use of, and CO_2 emissions from China's urban passenger transportation sector—Carbon mitigation scenarios upon the transportation mode choices," *Transp. Res. A, Policy Pract.*, vol. 53, pp. 53–67, Jul. 2013.
[39] G. Tian, M. Zhou, J. Chu, and Y. Liu, "Probability evaluation models of product disassembly cost subject to random removal time and different removal labor cost," *IEEE Trans. Autom. Sci. Eng.*, vol. 9, no. 2, pp. 288–295, Apr. 2012.
[40] G. Tian, M. Zhou, and P. Li, "Disassembly sequence planning considering fuzzy component quality and varying operational cost," *IEEE Trans. Autom. Sci. Eng.*, to be published, doi: 10.1109/TASE.2017.2690802.
[41] H. Zheng, Y. Feng, and J. Tan, "A hybrid energy-aware resource allocation approach in cloud manufacturing environment," *IEEE Access*, vol. 5, pp. 12648–12656, 2017.
[42] D. W. Chen, R. Chen, Y. D. Li, and T. Tang, "Online learning algorithms for train automatic stop control using precise location data of Balises," *IEEE Trans. Intell. Transp. Syst.*, vol. 14, no. 3, pp. 1526–1535, Sep. 2013.
[43] Y. Feng, Z. Hong, Z. F. Zhang, Z. X. Zhang, and J. Tan, "Interval analysis and DEMATEL-based reliability apportionment for energy consumption optimization with energy Internet," *IEEE Access*, vol. 5, pp. 4769–4778, 2017.
[44] M. Rani, S. Dhok, and R. Deshmukh, "A systematic review of compressive sensing: Concepts, implementations and applications," *IEEE Access*, vol. 6, pp. 4875–4894, 2018.



YUEZHAO QIANG is currently pursuing with the School of Management, Harbin Institute of Technology His research interests include intelligent decision-making and information management.

GUANGDONG TIAN (M'16) received the B.S. degree in vehicle engineering from the Shandong University of Technology, Zibo, China, in 2007, and the M.S. and Ph.D. degrees in automobile application engineering from Jilin University, Changchun, China, in 2009 and 2012, respectively. He is currently an Associate Professor with the Transportation College, Jilin University, and holds a post-doctoral position at the State Key Laboratory of Digital Manufacturing Equipment and Technology, Huazhong University of Science and Technology. He is also a Founding Member of sustainable production and service automation in the IEEE Robotics and Automation Society. His research interests include remanufacturing and green manufacturing, green logistics and transportation, intelligent inspection and repair of automotive, decision-making, and intelligent optimization. He has published over 90 journal and conference proceedings papers in the above research areas, including the IEEE Transaction on Automation Science and Engineering, the IEEE Transaction on Cybernetics, and the IEEE/ACM Transactions on Computational Biology and Bioinformatics. He is invited to organize several conferences and service a Session Chair, including ICAMechS 2015 and CASE 2016. He serves as a Frequent Reviewer for over 20 international journals, including the IEEE Transaction on Automation Science and Engineering, the IEEE Transactions on Systems, Man, and Cybernetics-Part A, *IEEE Intelligent Transportation Systems*, and so on. He is listed in Marquis Who's Who in the World, 30th Edition, in 2013.

YUMEI LIU received the Ph.D. degree from Jilin University, Changchun, China, in 2006. In 2007, she was a Visiting Scholar with the University of Bath, where she was appointed as a Guest Professor. She is currently a Senior Visiting Scholar with UIC, USA and a Professor with the Transportation College, Jilin University. She has hosted two projects supported by the National Science and technology Support Program, one project by the National 863 Plan, two projects supported by the National Natural Science Foundation, and 14 projects supported by the National Science Foundation of Jilin Province. She has completed over 40 research projects in total. She has authored or co-authored over 86 papers. She has obtained 30 national invention patents. She has received the National Invention Patent Excellence Award, the Jilin Province Patent Excellence Award, and the Pittsburgh International Invention Exhibition Invention Award. She currently serves as an Expert of Youth Thousand Plans, an Evaluation Expert of the Central Organization Department Outstanding Scientific and Technical Personnel, and an Expert of National 863 Plans. She was a recipient of the Jilin Province Science and Technology Progress Award and the first, second, and third prizes of the Science and Technology Award of CHTS.

ZHIWU LI (M'06–SM'07–F'16) received the B.S. degree in mechanical engineering, the M.S. in automatic control, and the Ph.D. degree in manufacturing engineering from Xidian University, Xi'an, China, in 1989, 1992, and 1995, respectively. He joined Xidian University in 1992. Over the past decade, he was a Visiting Professor with the University of Toronto, Technion–Israel Institute of Technology, the Martin Luther University of Halle-Wittenberg, the Conservatoire National des Arts et Métiers (Cnam), Meliksah University, King Saud University, and the University of Cagliari. He is currently with the Institute of Systems Engineering, Macau University of Science and Technology, Taipa, Macau. His current research interests include Petri net theory and application, supervisory control of discrete event systems, work flow modeling and analysis, system reconguration, game theory, and data and process mining. He is a member of the Discrete Event Systems Technical Committee of the IEEE Systems, Man, and Cybernetics Society, and the IFAC Technical Committee on Discrete Event and Hybrid Systems from 2011 to 2014. He was a recipient of the Alexander von Humboldt Research Grant, the Alexander von Humboldt Foundation, Germany, and Research in Paris, France. He is the Founding Chair of the Xi'an Chapter of the IEEE Systems, Man, and Cybernetics Society. He serves as a Frequent Reviewer for over 60 international journals, including *Automatica*, and a number of the IEEE Transactions, as well as many international conferences. He is listed in Marquis Who's Who in the world, 27th Edition, in 2010.