

Original Research

Planning Low-Carbon Cold-Chain Logistics Path with Congestion-Avoidance Strategy

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Abstract

To study how traffic congestion affects logistics and transportation in terms of cost and carbon emission and countermeasures, we designed congestion-avoidance strategies to reduce vehicle waiting time and vehicle speed. The delivery time in a day is divided into three periods to calculate the roadway travel time under the congestion avoidance strategy. The mathematical models of cold chain logistics route planning with the objectives of minimizing carbon emissions and total costs are constructed, and the congestion-avoidance strategy is applied to plan the cold chain logistics route. An improved ant colony algorithm is proposed to solve the objective model. The reduced speed strategy generates fewer carbon emissions than the waiting strategy. The cost of distribution under different strategies is influenced by the form of distribution and the size of the customer. The results of the study show that the use of congestion-avoidance strategies can reduce the total cost of distribution and carbon emissions. The waiting strategy is more effective in general logistics, and the speed-reduction strategy is more effective in cold chain logistics. By comparing the carbon emissions generated for various average speeds under the reduced-speed strategy, the optimal driving speed is about 45 km/h.

Keywords: city traffic, congestion avoidance strategies, routing of cold chain logistics, ant colony algorithm, speed reduction strategy

Introduction

With the improvement in living standards, people now are more demanding regarding the freshness of cold chain foods, such as fresh food, which challenges the cold chain logistics distribution system. To maintain the freshness of the distribution foods, refrigerated vehicles should be constantly refrigerated, which generates refrigeration costs and carbon emissions. According to the literature [1, 2], traffic congestion

and changes in distribution vehicle speed affect the quantity of carbon emissions generated by vehicles in cold-chain logistics. Some scholars have addressed transportation delays caused by traffic congestion by avoiding predictable traffic congestion through vehicle-route planning [3]. Vehicle ownership is currently increasing in several countries, and urban road construction planning is imperfect. Many large cities are facing increasingly serious traffic congestion, which increases transportation time during cold-chain logistics distribution, thus affecting carbon emissions and distribution costs. Therefore, it is vital to avoid traffic congestion in the distribution process to optimize economic and environmental benefits.

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The vehicle routing problem (VRP) has been thoroughly studied by many research groups. Today, in the context of green logistics, some research considers carbon emissions in the VRP. Gong et al. [4] developed a mathematical model of multivehicle collocation by considering carbon emissions and time windows. Franceschetti et al. [5] constructed a time-dependent VRP to minimize driver wages and carbon emission costs. The carbon emission problem has been a hot research topic, and many groups have designed carbon emission calculation models to study carbon emissions as a function of carbon taxation or carbon limitation policies. First, Wang et al. [6] used a linear function calculation method for unit fuel consumption to find carbon emissions. Hu et al. [7] first used the cycle evaluation method and input-output method to calculate the range of carbon emissions in each stage of cold chain logistics and established a mathematical model to optimize the carbon footprint. Tao et al. [8] quantitatively analyzed the carbon tax mechanism and used the carbon tax cost as a decision variable for improved quantum bacterial foraging. Li [9] proposed a mathematical model to calculate the cost of carbon emissions and applied it to optimize the cold chain logistics distribution path. Liu et al. [10] proposed a collaborative distribution VRP problem under the carbon tax policy. Wang et al. [11] constructed the lowest-cost green VRP model, compared how carbon taxes affect distribution costs and carbon emissions, and derived the environmental and economic range of carbon taxes to maximize economic benefits.

The transportation process in the VRP inevitably involves traffic congestion. Chen et al. [12] explored how traffic congestion affects cold chain logistics in former warehouses and used the traffic congestion index to quantify the degree of traffic congestion. Qi et al. [13] used the traffic congestion index provided by Baidu Map to describe the actual traffic situation, divided it into multiple time periods to calculate the transportation time method, and applied it to the emergency cold chain. Liu et al. [3] designed a computational model of vehicle speed as a function of time and proposed a method to avoid traffic congestion and temporary traffic congestion. Zhao et al. [14] considered the effects of time-varying traffic volume and road type to construct a model to optimize electric vehicle routing. Poonthalir et al. [15] proposed a computational model to explain how variable speed affects fuel consumption and verified it by showing that variable speed in logistics transportation consumes less fuel than constant speed.

Traffic congestion is often encountered in urban road transport. Zhang et al. [16] proposed a new time-dependent electric vehicle path problem with a congestion charge. If a vehicle enters the peak period, it is required to pay a fixed congestion charge for contributing to the problem. In an urban environment, not only does the travel time change but the travel path also changes from one customer to another. In fact, different paths may be used at different times of the day.

To solve this problem, one approach is to directly use the road network and consider the travel time (or travel speed) for each road segment. Gmira et al. [17] proposed a solution to the time-dependent vehicle path problem that involves a time window, where the travel speed is associated with the road segments in the road network. The effective management of last-mile deliveries is one of the main challenges for online retailers and logistic companies. The main goal is to provide personalized delivery services that meet speed, flexibility, and control requirements and reduce environmental impact. Crowd-sourced shipping is an emerging strategy that optimizes the last-mile distribution process. The main idea is to deliver packages to customers with the help of nonprofessional couriers (called temporary drivers). Pugliese et al. [18] addressed the problem of occasional drivers, time window constraints, and vehicle routing for multiple deliveries. Avoiding traffic-congested roadways is a hot research problem nowadays. Hu et al. [19] studied the VRP with difficult time windows and demand and travel time uncertainty. To solve this problem, we developed a robust optimization model based on a new path-dependent uncertainty set. Ge et al. [20] studied how vehicle path optimization affects carbon emissions as a function of traffic congestion and introduced vehicle-waiting congestion-avoidance strategies. Yan et al. [21] consider two scenarios of recurrent traffic congestion and episodic traffic congestion as well as repetitive and nonrepetitive congestion in a dynamic urban network VRP with real-time traffic information. Kok et al. [22] propose four traffic congestion-avoidance strategies. Liu et al. [23] introduced the waiting traffic congestion avoidance strategy to address the VRP and applied it to show that the waiting strategy avoids traffic congestion, shortens vehicle travel time, and reduces vehicle carbon emissions.

In summary, although various studies have used congestion-avoidance methods and case validation to address the VRP, the following shortcomings remain in congestion-avoidance applications: (1) Traffic congestion avoidance methods are mostly dynamic-change path studies, whereas, in reality, when no better path exists, the relevant question to study is how to avoid the traffic congestion sections on the current road and at the current point in time. (2) Previous studies [18] have applied the waiting congestion avoidance strategy to the VRP to reduce carbon emissions and distribution costs, but since cold-chain logistics distribution generates refrigeration costs and carbon emissions when vehicles are waiting, the application of the waiting strategy to the cold chain VRP needs to be studied. (3) How driving speed affects carbon emissions should also be further studied as a function of congestion-avoidance strategies. Therefore, we consider how congestion-avoidance strategies involving vehicle waiting and reduced speed affect carbon emission and distribution cost in the cold chain VRP. In addition, we investigate how driving speed affects carbon emission in the case of the reduced-speed congestion-avoidance strategy.

Problem Description

Research Hypotheses

We study the single-distribution-center problem, where the location, service time, time window, and demand quantity are known for each demand point. A single vehicle serves each demand point once. The distribution center is fully stocked with cold-chain goods. The vehicle starts at the distribution center. The assumptions used herein are as follows:

- (1) The same mode refrigerated vehicle is used in all cases, the vehicle is not overloaded, and the driving distance does not exceed the maximum range of the vehicle.
- (2) Severe traffic congestion occurs only between demand points.
- (3) There is severe traffic congestion and waiting stops are made without considering the surrounding parking environment.
- (4) The refrigerated vehicles do not consume fuel during the waiting phase when they are not being driven. However, the refrigeration equipment remains in working condition, which consumes energy.
- (5) Driving on heavily congested roads generates significant carbon emissions due to stop-and-start driving.

Decision-making problem: If confronted with serious traffic congestion while driving, how can you reduce the carbon emissions generated by the vehicle? How can you reduce the total cost of cold chain logistics? How does driving speed affect carbon emissions in cold-chain logistics?

Symbol Description

$M = \{1, 2, \dots, m\}$ is the collection of the number of electric vehicles used. $N = \{0, 1, 2, \dots, n\}$ is a distribution center with a collection of customer points. $W = \{0, 1, \dots, w\}$ is a collection of charging stations. $Z = \{1, 2, \dots, z\}$ is the set of transport product types. P_{11}, P_{21} are the fixed costs per unit of ordinary electric vehicle and electric refrigerated vehicle, respectively. P_{12}, P_{22} are the transportation costs per unit time for ordinary electric vehicles and electric refrigerated vehicles, respectively. P_3 is the price per unit of electricity consumed. P_4 is the charging price per unit of time. P_h is the unit price of product category h . P_5 is the price per unit of product quality. Q, D are the maximum load and maximum driving distance of the electric vehicle, respectively. b is the maximum number of holding tanks per vehicle. $a_{ik}, [B_i, E_i]$ are the arrival time of vehicle k at node i , and the time window of node i , respectively. x_{ij}^k is the 0 – 1 variable, when the electric vehicle k is transported in i, j section, $x_{ij}^k = 1$, otherwise $x_{ij}^k = 0$. y_j^k is a 0 – 1 variable, electric vehicle k if it delivers for customer point j , $y_j^k = 1$, otherwise $y_j^k = 0$. z_i^k is a 0 – 1 variable, $z_i^k = 1$ when Electric Vehicles k is charged at charging station i , otherwise $z_i^k = 0$.

Segment Time Calculation and Traffic Congestion Strategy

Speed Periods and Methods to Calculate Travel Time

A study of driving in a mixed state of congested and fluid traffic [5], the speed is divided into three phases: the average speed v_1 during congestion, the average speed v_2 during the fluid period, and the average speed during the transition between the two periods. The time of day is divided into $T = \{[i_1, j_1], [i_2, j_2], [i_3, j_3], [i_4, j_4]\}$ morning peak, smooth travel time, evening peak, and smooth travel time, respectively. The velocity changes between adjacent time periods, as shown in Fig. 1. To calculate the illustration, let the distance of the vehicle on the travel arc in each time period be d and the departure time be h . The following is an example of the first three time periods used to calculate the travel time t_h :

When $h \leq (i_2 - \frac{d}{v_2})$ or $h \geq j_2$

$$t_h = \frac{d}{v_2} \tag{1}$$

When $(i_2 - \frac{d}{v_2}) < h < i_2$

$$t_h = \frac{d}{v_2} + \frac{v_2 - v_1}{v_1} (i_2 - h) \tag{2}$$

When $i_2 \leq h < (j_2 - \frac{d}{v_1})$

$$t_h = \frac{d}{v_1} \tag{3}$$

When $(j_2 - \frac{d}{v_1}) < h < j_2$

$$t_h = \frac{d}{v_2} - \frac{v_2 - v_1}{v_2} (j_2 - h) \tag{4}$$

Equation (1) calculates the time the vehicle spends at the congestion speed in the morning and evening rush-hour periods but not in transition periods. Equation (2) calculates the time the vehicle spends in the transition between general congestion and fluid traffic. Equation (3) calculates the time the vehicle spends in fluid traffic. Finally, equation (4) calculates the time the vehicle spends in the transition from fluid traffic to congestion.

Fig. 2 shows the vehicle travel time as a function of time. The above method is also used to calculate travel time when a reduced-speed congestion-avoidance strategy during severe congestion.

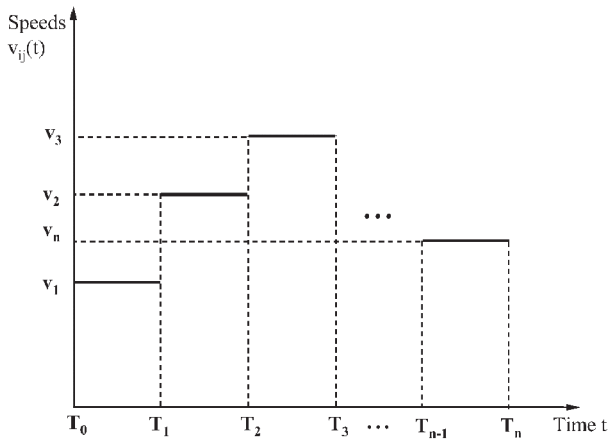


Fig. 1. Vehicle speed as a function of time.

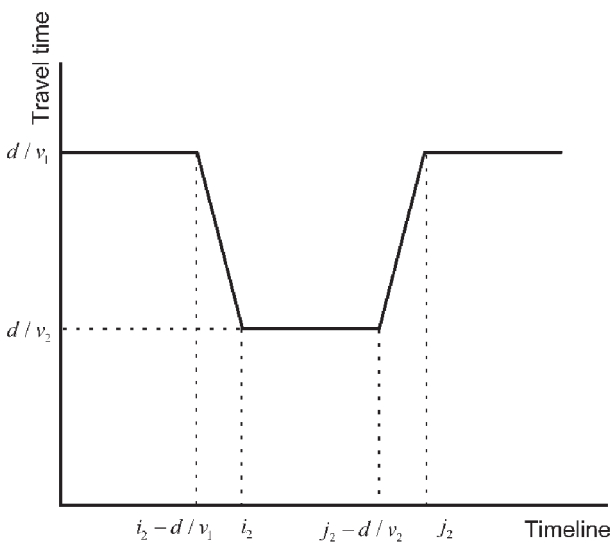


Fig. 2. Vehicle travel as a function of time.

Methods to Avoid Congested Traffic

Road traffic conditions are divided into three types: fluid, general congestion, and severe congestion. In the first two cases, speeds are steady (no acceleration), whereas severe congested causes frequent stop-and-start driving, thereby producing more carbon emissions. Two congestion avoidance methods are used to avoid driving on heavily congested roadways. Figure 3 shows the driving process on road section (i,j).

When the vehicle is driving on the road, according to the Map software knows in real time the congestion state of the road ahead. If severe congestion lies ahead, the estimated time from the current location to the congestion point is T_1 , and the estimated time to spend in congestion is T_2 . If $T_1 > T_2$, the vehicle can continue normally. If $T_1 < T_2$, a traffic-congestion-avoidance strategy is adopted.

(1) Waiting strategies

The waiting time is $T_2 - T_1$. When the vehicle is stopped (i.e., zero speed) and the engine off, the

refrigerated compartment continues to function. After the waiting time, the vehicle is driven at normal speed.

(2) Early reduction of driving speed

The speed is reduced to ensure that no serious congestion is encountered upon arriving at the original congestion point (i.e., $v_{ru} = T_1 v_{ij} / T_2$), the travel time from the front congestion point to the original congestion point is T_2 .

Let v_{ij} be the normal speed of the vehicle on the roadway, v_{ru} be the reduced speed, t_{ij}^t be the average speed over the entire travel time from i to j , t_{ij}^w be the vehicle waiting time from i to j , t_{ru} be the reduced-speed travel time while traveling from i to j , t_{ij} be the total time of the vehicle on road segment (i,j), D_{ij} be the distance of road segment (i,j), and D_{ru} be the distance between the current position and the congestion point.

The following procedure calculates the vehicle time on road segment (i,j) using the congestion-avoidance method:

Step 1. If severe congestion is expected on the road ahead, go to Step 2; otherwise, go to Step 4.1.

Step 2. If the current position is in the congested zone of time $T_1 = D_{ru} / v_{ij} \geq T_2$, then continue to drive normally to the original congestion point. If there is no severe congestion, do not apply congestion avoidance strategies. Go to Step 4.1. Otherwise, if $T_1 < T_2$ go to Step 3.

Step 3: $T_1 < T_2$, if the vehicle continues at the current speed, it will encounter severe congestion, so apply the vehicle-waiting (reduced-speed) congestion-avoidance strategy. Go to Step 3.1 (3.2).

Waiting Strategy

Step 3.1: Waiting strategy. Vehicle waits at the current position with the engine off. The vehicle does not consume energy, but the refrigerated compartment continues to consume energy. Waiting time $t_{ij}^w = T_2 - T_1$, normal-speed travel time is $t_{ij}^t = D_{ij} / v_{ij}$. Go to Step 4.2.

Step 3.2: Speed-reduction strategy. Vehicle travels from its current location to the original congestion point at a reduced speed (i.e., less than the average speed). The reduced travel speed is $v_{ru} = D_{ru} / T_2$, the reduced-speed travel time is $t_{ru} = T_2$, and the normal-speed travel time is $t_{ij}^t = (D_{ij} - D_{ru}) / v_{ij}$. Go to Step 4.3.

Step 4. Calculate the normal speed travel time, the waiting/deceleration time, and the total vehicle usage time after the vehicle travels through sections (i,j).

Step 4.1. Vehicle does not wait or reduce speed. The total vehicle time on road section (i,j) is the normal-speed travel time $t_{ij} = t_{ij}^t = D_{ij} / v_{ij}$.

Step 4.2. The waiting time is $t_{ij}^w = T_2 - T_1$, the normal-speed travel time is $t_{ij}^t = D_{ij} / v_{ij}$, and the total vehicle time is $t_{ij} = t_{ij}^w + t_{ij}^t$.

Step 4.3. The average speed is reduced to $v_{ru} = D_{ru} / T_2$, the reduced-speed travel time is $t_{ru} = T_2$, the normal-speed travel time is $t_{ij}^t = (D_{ij} - D_{ru}) / v_{ij}$, and the total vehicle time is $t_{ij} = t_{ru}^d + t_{ij}^t$.

Mathematical Models

Vehicle Carbon Emission Calculation

The carbon emissions generated in the transportation process are modeled by MEET, so the carbon emission rate (kg/km) generated by driving on the road section (i,j) is

$$C^1_{ijk} = e \times G_{ij} \times \varphi_{ijk} / 1000 \tag{5}$$

Of which

$$e = (110 + 0.000375v_{ij}^3 + 8702 / v_{ij}) \tag{6}$$

$$G_{ij} = \exp[(10.0059v_{ij}^2 - 0.0775v_{ij} + 11.936)w_{ij}] \tag{7}$$

$$\varphi_{ijk} = 0.27\lambda_{ijk} + 1 + 0.0614v_{ij}\lambda_{ijk} - 0.0011v_{ij}^3\lambda_{ijk} - 0.00235\lambda_{ijk}v - 1.33\lambda_{ijk} / v \tag{8}$$

where: The symbol *e* is the carbon emission rate (g/km) without considering road slope or load, *G_{ij}* is the road-slope factor, *w_{ij}* is the road slope (%) of road section (i,j), *φ_{ijk}* is the vehicle load factor, and *λ_{ijk}* is the real-time load ratio of vehicle *k* on road section (i,j).

The carbon emissions (kg) from refrigeration during distribution are calculated by using a published method [24]:

$$C^2_{ij} = Eu_1q_{ij}g_{ij}^k t_{ijk} \tag{9}$$

C_{ijk}² is the carbon emissions from refrigeration, *u₁* is the fuel consumption per unit time of vehicle refrigeration, *q_{ij}* is the cargo capacity on road section (i,j), and *t_{ijk}* is the total driving time of vehicle *k* over road section (i,j).

Cost Models

(1) Fixed costs and transportation costs are

$$C_1 = K \times P_1 + P_2 \sum_{k=1}^m \sum_{i=0}^n \sum_{j=0}^n t_{ijk} x_{ij}^k \tag{10}$$

K is the number of vehicles used, *m* is the number of vehicles available *k* = 1, 2, ..., *m*, *P₁* is the fixed cost per unit vehicle, *P₂* is the transportation cost per unit time, *t_{ijk}* is the travel time of vehicle *k* over section (i,j), and *x_{ij}^k* ∈ {0,1} is a binary variable referring to vehicle *k* in section (i,j).

Costs of damaged goods are

$$C_2 = P_3 \alpha_1 \sum_{k=1}^m \sum_{i=0}^n \sum_{j=0}^n x_{ij}^k t_{ijk} q_j + P_3 \alpha_2 \sum_{j=1}^m \sum_{k=1}^m y_j^k q_j t_{jk} \tag{11}$$

where *P₃* is the price per unit quantity of the cold chain product, *q_j* is the demand for the product at customer point *j*, *α₁* is the rate of cargo loss during transportation, *α₂* is the rate of cargo loss during unloading, *y_j^k* ∈ {0,1} is a binary variable; *y_j^k* = 1 if vehicle *k* is delivering to customer point *j*; otherwise, *y_j^k* = 0, and *t_{jk}* is the service time when vehicle *k* is unloading at customer point *j*.

(3) Refrigeration cost

The refrigeration cost is divided into refrigerant costs arising from transportation and unloading. The heat load in the model is calculated by using the empirical formula *Q₁* = *RSΔT* (i.e., the heat load generated by heat exchange inside and outside the refrigerated compartment) [25], where *R* is the heat conduction coefficient of the carriage, *S* is the average surface area of the carriage, and *ΔT* is the temperature difference between the interior and exterior of the carriage, in addition to the heat load generated by the heat leakage of the carriage body, *Q₂* = *βQ₁*, where *β* is the heat leakage coefficient, which is usually in the range 0.1–0.3.

The cooling cost incurred by the vehicle during transport is

$$C_{31} = P_4 \sum_{k=1}^m \sum_{i=0}^n \sum_{j=0}^n x_{ij}^k (Q_1 + Q_2) t_{ijk} \tag{12}$$

and the cooling cost incurred during unloading is

$$C_{32} = P_4 \sum_{k=1}^m \sum_{j=1}^n y_j^k Q_3 t_{jk} \tag{13}$$

so the cooling costs for the entire distribution are

$$C_3 = P_4 \sum_{k=1}^m \sum_{i=0}^n \sum_{j=0}^n x_{ij}^k (Q_1 + Q_2) t_{ijk} + P_4 \sum_{k=1}^m \sum_{j=1}^n y_j^k Q_3 t_{jk} \tag{14}$$

where *P₄* is the cost per unit refrigerant, in addition to the heat load *Q₃* = *μVΔT* generated by opening the door during the unloading process, with *μ* being the frequency of door opening, and *V* is the volume of the refrigerated compartment.

(4) Cost of carbon emissions

The cost of carbon emissions is mainly generated by the fuel consumption of the vehicle and vehicle cooling.

The cost of carbon emissions from fuel consumption while vehicle is on the road is

$$C_{41} = P_5 \sum_{i=0}^n \sum_{j=0}^n \sum_{k=1}^m C^1_{ijk} v_{ijk} t_{ijk} x_{ij}^k \tag{15}$$

The cost of carbon emissions from refrigeration is

$$C_{42} = P_5 \sum_{i=0}^n \sum_{j=0}^n \sum_{k=1}^m C^2_{ijk} \tag{16}$$

The total cost of carbon emissions is

$$C_4 = P_5 \sum_{k=1}^m \sum_{i=0}^n \sum_{j=0}^n x_{ij}^k (C_{ijk}^2 + C_{ijk}^1 v_{ijk} t_{ijk}) \tag{17}$$

where P_5 is the unit carbon tax price, C_{ijk}^1 is the carbon emission rate generated by vehicle driving, and C_{ijk}^2 is the carbon emissions generated by vehicle cooling.

Target Model

The cold chain VRP model to minimize total cost is

$$\begin{aligned} \min C &= C_1 + C_2 + C_3 + C_4 \\ &= K \times P_1 + P_2 \sum_{k=1}^m \sum_{i=0}^n \sum_{j=0}^n t_{ijk} x_{ij}^k + P_3 \alpha_1 \sum_{k=1}^m \sum_{i=0}^n \sum_{j=0}^n x_{ij}^k t_{ijk} q_j \\ &+ P_3 \alpha_2 \sum_{j=1}^n \sum_{k=1}^m y_j^k q_j t_{jk} + P_4 \sum_{k=1}^m \sum_{i=0}^n \sum_{j=0}^n x_{ij}^k (Q_1 + Q_2) t_{ijk} \\ &+ P_4 \sum_{k=1}^m \sum_{j=1}^n y_j^k Q_3 t_{jk} \\ &+ P_5 \sum_{k=1}^m \sum_{i=0}^n \sum_{j=0}^n x_{ij}^k (C_{ijk}^2 + C_{ijk}^1 v_{ijk} t_{ijk}) \end{aligned} \tag{18}$$

The model should satisfy the following constraints:

$$\sum_{k=1}^m \sum_{i=1}^n x_{ij}^k \leq m, \quad i = 0 \tag{19}$$

$$\sum_{k=1}^m \sum_{j=1}^n x_{ij}^k = \sum_{k=1}^m \sum_{j=1}^n x_{ji}^k, \quad i = 0, \quad k = 1, 2, \dots, m \tag{20}$$

$$\sum_{k=1}^m y_i^k = 1, \quad i = 1, 2, \dots, n \tag{21}$$

$$\sum_{i=1}^n q_i y_i^k \leq Q, \quad i \neq j, \quad k = 1, 2, \dots, m \tag{22}$$

$$\sum_{i=0}^n \sum_{j=0}^n d_{ij} x_{ij}^k \leq D, \quad i \neq j, \quad k = 1, 2, \dots, m \tag{23}$$

$$a_{ik} + q_{ik} \geq B_i \tag{24}$$

$$a_{ik} + q_{ik} \leq E_i \tag{25}$$

$$t_{ijk} = t_{ijk}^w + t_{ijk}^t \tag{26}$$

$$t_{ijk} = t_{ruk} + t_{ijk}^t \tag{27}$$

$$T_{ijk} = t_{ijk} + t_{jk} \tag{28}$$

(19) imposes that the number of refrigerated distribution vehicles be not less than the number of distribution routes. (20) imposes that the starting point of a vehicle to complete a distribution mission be a distribution center. (21) imposes that each demand point be served once and by only one vehicle (22) imposes that the total demand of customer points in each distribution route not exceed the maximum carrying capacity of the (23) imposes that the total distribution distance of each distribution route not exceed the maximum distribution range of the refrigerated (24) and (25) impose the time window constraint.(26) and (27) impose the relationship between the total time the vehicle is on the road section and the waiting time (speed-reduction time) and normal-speed driving time. Finally, equation (28) imposes that the distribution process be continuous.

The corresponding mathematical model to minimize carbon emissions is

$$\min \sum_{k=1}^m \sum_{i=0}^n \sum_{j=0}^n x_{ij}^k (C_{ijk}^2 + C_{ijk}^1 v_{ijk} t_{ijk}) \tag{29}$$

with constraints (19)–(28).

Algorithm Research

The VRP is an NP-hard problem, and VRP with time windows considering traffic congestion and congestion-avoidance strategies is even more complicated. This problem is difficult to solve accurately and efficiently. Ant colony algorithms are heuristic algorithms with the advantages of positive information feedback and distributed computation and can solve various complex combinatorial optimization problems. Therefore, an improved ant colony algorithm is used to solve the VRP. The algorithm is ameliorated as follows: (1) Given that vehicles have different speeds at different driving times, the calculation of the acceleration at different times and the calculation of travel time are embedded in the algorithm. (2) The congestion-avoidance method introduced above is integrated into the ant colony algorithm. (3) To prevent the ant colony algorithm from falling into a local optimum and to enhance the global nature of the ant colony algorithm search, we introduce the adaptive pheromone heuristic factor and the expectation heuristic factor.

The specific steps of the improved ant colony algorithm are as follows:

Step 1. The start parameters and variables are set to divide the time of day when the vehicle works into four time periods: morning and evening peak, between morning and evening peak, and after evening peak.

Step 2. Construct feasible solutions (i.e., construct the paths of all ants).

Step 2.1. Select ant by ant and customer by customer.

Step 2.2. The method for calculating travel time on road sections for different time periods combined with

traffic congestion avoidance methods is used. Calculate the travel time and waiting time of vehicles on the road section.

Step 2.3. Design the state transfer probability of each ant m from i to j with a combination of deterministic and stochastic choices:

$$j = \begin{cases} \arg \max \{ [\tau_{is}]^\alpha [\vartheta_{is}]^\beta [w_{sk}]^\lambda [G_{sk}]^\chi \}, & \text{if } \zeta \leq \zeta_0 \\ P_{ij}^m, & \text{else} \end{cases} \quad (30)$$

$s \in \text{allowed}_m$, $0 < \zeta < 1$ is a random number, and $0 < \zeta_0 < 1$ is a control variable:

$$P_{ij}^m = \begin{cases} \frac{[\tau_{ij}]^\alpha [\vartheta_{ij}]^\beta [w_{jk}]^\lambda [G_{jk}]^\chi}{\sum_{s \in \text{allowed}_m} ([\tau_{is}]^\alpha [\vartheta_{ij}]^\beta [w_{sk}]^\lambda [G_{sk}]^\chi)} & j \in \text{allowed}_m \\ 0, & \text{else} \end{cases} \quad (31)$$

where allowed_m is the set of nodes allowed to be visited by the ant next, τ_{ij} is the information heuristic factor α , β , λ , and χ are the importance of each heuristic factor, ϑ_{ij} is the visibility heuristic factor, w_{jk} is the vehicle waiting time factor, and G_{jk} is the width of the customer point time window.

Step 2.4. Determine whether the selected path satisfies the time and load constraints.

Step 3. The objective function is calculated, and the path with the best objective value for each generation is compared for storage.

Step 4. The global pheromone is updated using the update formula of the standard ant colony algorithm, and the pheromone intensity is solved using the ant perimeter model.

Step 5. The end condition of the algorithm is that the iterations reach a predefined maximum number of iterations, and the result is output.

Example Analysis

Example Data and Parameter Settings

No standard experimental data on the cold-chain VRP problem of congestion avoidance are available, so the data of demand point coordinates, time window, service time, and demand quantity dimensions in c101 and r101 arithmetic cases are selected from the Solomon database for the experiment. The data that meet the test requirements are set.

In accordance with the city's morning and evening peak traffic, the morning and evening peak time periods are set to 7:00-9:00 and 17:00-20:00, respectively. The morning and evening peak normal driving state is general congestion, and the speed is taken as 25 km/h according to the city traffic rules. The other time periods are considered to have fluid traffic, with a speed range of 30-60 km/h. The first two calculations assume 45 km/h.

To compare the effectiveness of different congestion-avoidance strategies, multiple severe congestion situations were set in the above two time periods. The severe congestion time is set to [10, 25] min, the speed is below 10 km/h, and more carbon emissions are generated due to the start-and-stop driving.

The ant colony algorithm was coded on a computer processor operating at 2.20 GHz, with 4 GB of memory, and running MATLAB (R2018b). Table 1 lists the parameters of the model.

Experimental Results Analysis

Congestion-Avoidance Strategies to Lower Carbon Emissions

Data set c101 belongs to the centralized distribution arithmetic, whereas dataset r101 belongs to the random distribution arithmetic. To compare the variation between carbon emissions more significantly, the first 30 sets of data in r101 were selected for the experiment. The improved ant colony algorithm was used to solve the cold-chain VRP with the goal of minimizing carbon emissions under different congestion-avoidance strategies. The first 30 data in r101 were selected for the experiment. Fig. 3 shows the distribution roadmap. The experimental results are shown in Table 2. NV is the number of vehicles used, TD is the total distance traveled by the vehicle (km), TT is the total vehicle travel time (min), TCC is the total CO₂ emissions (kg), DCC is the carbon emissions generated by driving (kg), and RCC is the carbon emission generated by refrigeration (kg).

The results listed in Table 2 lead to the following conclusions:

(1) NV shows that, in the randomly distributed data, each route is more affected by time constraints, resulting in more vehicles being used. TD and TT show that the total distance traveled without congestion-avoidance strategies is shorter. However, the travel time is significantly longer, mainly due to excessive congestion.

(2) For DCC, DS and WS are significantly less than NS, which is mainly due to the lower driving speed and frequent starting and stopping during severe congestion, resulting in more CO₂ production. The reduced-speed strategy generates more carbon emissions than the wait

Table 1. Model parameter.

Parameters	Parameter values	Parameters	Parameter values
P_1	100 yuan/veh	Q_1	280
P_2	1 yuan/min	Q_2	56
P_3	1yuan/kg	Q_3	129
P_4	15 yuan/h	μ_1	22.5 L/100 km
P_5	0.2 yuan/kg	E	2.63 kg/L
α_1	0.012	α_2	0.014

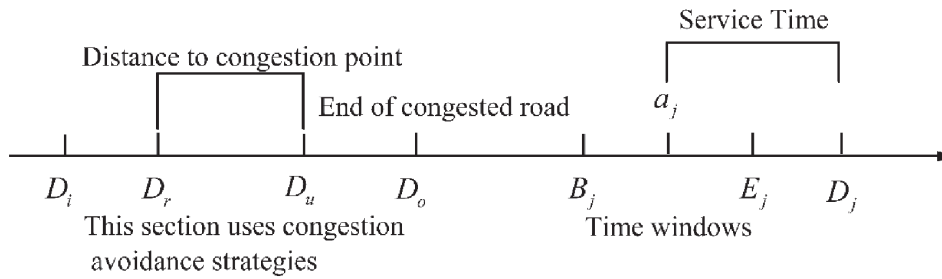


Fig. 3. Vehicle driving process.

Table 2. Carbon emissions under different congestion-avoidance strategies. NV is the number of vehicles used, TD is the total distance traveled by the vehicle (km), TT is the total vehicle travel time (min), TCC is the total CO₂ emissions (kg), DCC is the carbon emissions generated by driving (kg), and RCC is the carbon emission generated by refrigeration (kg).

R101	DS	WS	NS
NV	11	12	13
TD	947.42	930.17	925.57
TT	1184.27	1240.22	1322.24
TCC	1148.22	1150.02	1391.46
DCC	392.18	342.26	547.34
RCC	756.04	807.76	844.12

strategy, although the total driving time is shorter. This is mainly because the wait strategy does not produce driving CO₂ emissions when the engine is off while waiting without moving. Also, waiting avoids severe congestion, and the driving speed is not reduced in other phases, resulting in less CO₂ production.

(3) RCC shows that refrigeration produces carbon emissions. For RCC, DS<WS<NS. Since cold chain

goods must be kept fresh regardless of congestion or waiting, the refrigerated truck needs to be in the refrigeration state all the time, so the carbon emissions from refrigeration is mainly related to the total driving time.

(4) TTC shows that using the congestion-avoidance strategy reduces total carbon emissions, with the speed-reduction strategy producing fewer emissions than the vehicle-waiting strategy. From this, we conclude that the vehicle-waiting strategy is more effective for the general VRP, whereas the speed-reduction strategy is recommended for the cold-chain VRP, as is further verified by the following experimental results.

Impact of Congestion-Avoidance Strategies on Distribution Costs

The first 30 and 50 sets of data from the c101 arithmetic cases with a centralized distribution were selected for the experiment. The improved ant colony algorithm was used to solve the cold chain VRP problem to minimize the total cost with different congestion strategies applied. Fig. 5 shows the optimal roadmap for the two groups of data with the reduced-speed strategy. The experimental results are shown in Table 3. TC is total cost, TG is fixed cost and transportation cost, TH

Table 3. Results for different congestion avoidance strategies with total cost as the objective. TC is total cost, TG is fixed cost and transportation cost, TH is cargo damage cost, TZ qis refrigeration cost, TTC is total carbon emission cost, TDC is carbon emission cost generated by driving, and TRC is carbon emission cost generated by refrigeration.

	DS		WS		NS	
C101	30	50	30	50	30	50
NV	3	7	3	6	3	7
TT	206.17	628.81	247.41	665.79	257.72	676.58
TC	985.69	2015.93	1041.75	1964.28	1064.87	2099.08
TG	506.17	1328.81	547.41	1265.79	557.72	1376.59
TH	33.97	39.05	34.46	39.48	34.59	39.62
TZ	399.35	526.14	411.73	537.24	414.81	540.48
TTC	46.18	121.93	48.13	121.75	57.73	142.39
TDC	19.86	41.65	16.55	36.74	24.83	56.01
TRC	26.32	80.28	31.58	85.01	32.90	86.38

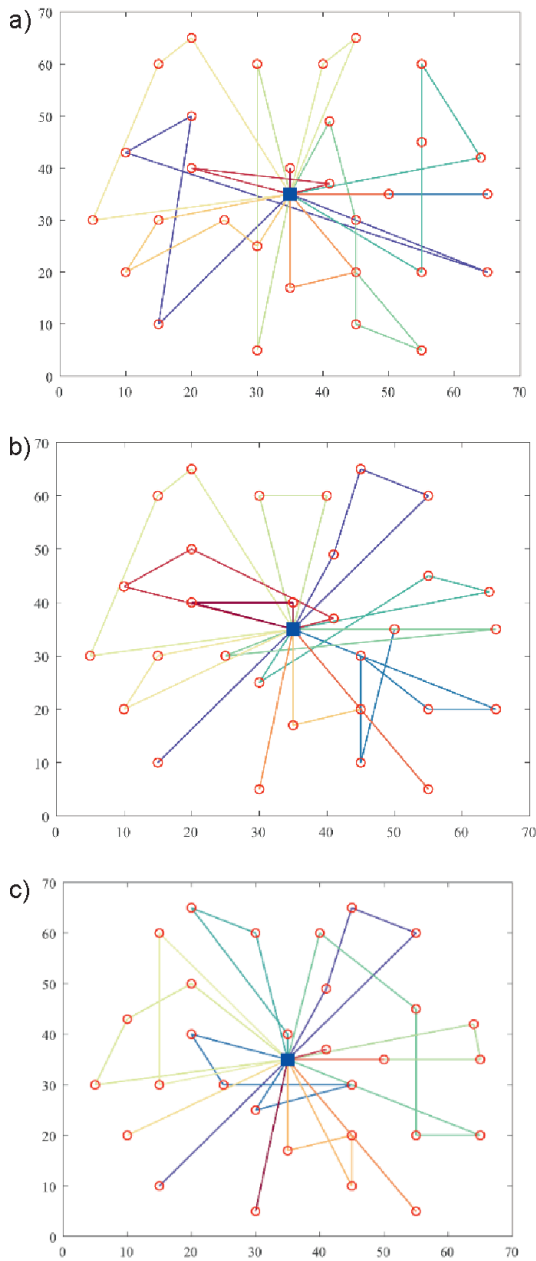


Fig. 4. Roadmap for different congestion strategies

is cargo damage cost, TZ qis refrigeration cost, TTC is total carbon emission cost, TDC is carbon emission cost generated by driving, and TRC is carbon emission cost generated by refrigeration.

The results listed in Table 3 lead to the following conclusions:

(1) The total cost and carbon emissions when using a congestion-avoidance strategy are significantly lower in the 30 and 50 sets of data in c101. This indicates that using a congestion avoidance strategy proposed in this paper when the congestion ahead is predicted in real-time by the mapping software can save distribution costs for logistics companies and reduce carbon emissions.

(2) The TH cargo loss cost shows that, because the refrigerated truck always maintains the refrigeration

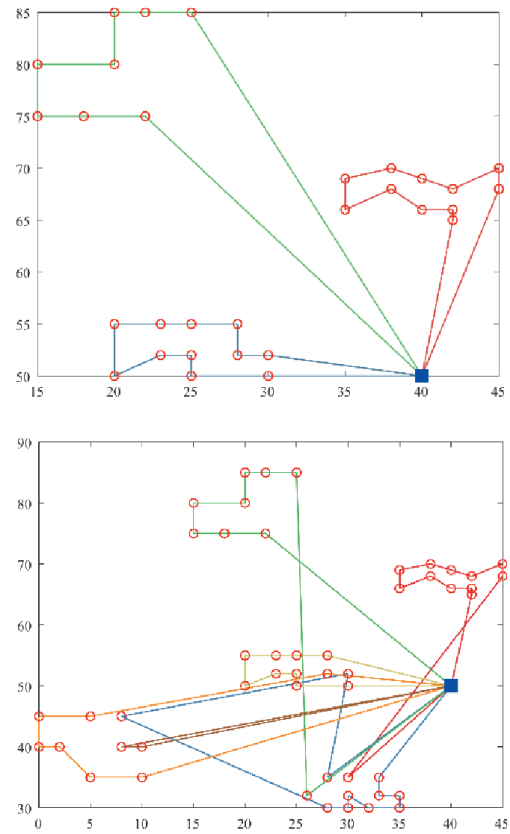


Fig. 5. Optimal roadmap for two data sets.

state in the distribution process and the refrigeration is improved, the change in cargo loss cost with time is subtle, and the fraction of the total cost decreases.

(3) The reduced-speed congestion avoidance strategy generates more carbon emissions while driving and fewer for cooling compared with the vehicle-waiting strategy. The carbon-emission costs between the two data sets are similar. In the 30 sets of data in c101, the total carbon emission cost is slightly less when using the speed-reduction strategy. In the 50 sets of data in c101, the total cost of the vehicle-waiting strategy is slightly less. However, the total cost of the speed-reduction strategy is significantly less for both data sets, mainly because the total driving time is significantly less for the speed-reduction strategy, resulting in lower transportation and refrigeration costs. Therefore, in the cold chain logistic distribution, the congestion avoidance strategy is chosen to reduce carbon emissions and achieve low-carbon logistics. To save distribution costs and maximize economic benefits, the reduced-speed congestion avoidance strategy is thus chosen.

Impact of Congestion Speed on Carbon Emissions

In the above experiments, both the general congestion speed and the fluid speed are set to assumed values. The speed under general congestion is set to a constant value because the speed is lower during the morning and evening peak hours and is generally not

Table 4. Carbon emissions for various speeds under the speed reduction strategy.

V	30	40	45	50	60
NV	12	11	11	12	11
TD	942.75	938.66	947.42	930.42	903.68
TT	1346.79	1235.07	1184.27	1192.85	1221.19
TCC	1305.78	1197.48	1148.22	1156.53	1184.01
DCC	445.99	409.07	392.18	395.02	404.40
RCC	859.79	788.47	756.04	761.51	779.61

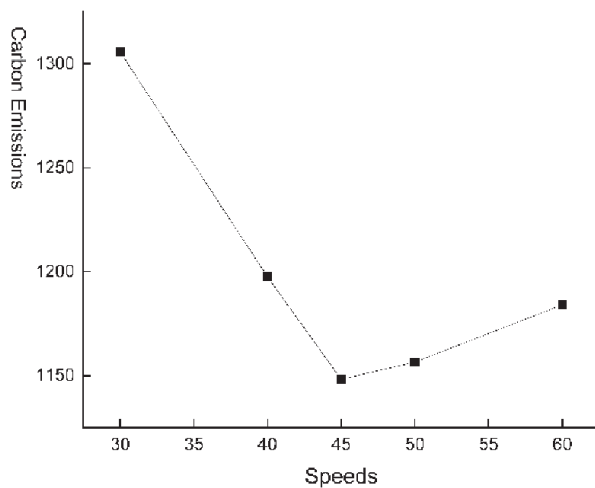


Fig. 6. Trend of carbon emissions generated at different speeds.

subject to subjective control. To study how average speed affects carbon emissions in the cold-chain VRP when using the reduced-speed congestion-avoidance strategy, the speeds of the fluid times were set to (30, 40, 45, 50, and 60) km/h. The experimental data are r101 arithmetic. The experimental results are shown in Table 4. Fig. 6 graphs the carbon emissions as a function of speed.

This is mainly due to more congestion because the speed is too fast in normal driving. Anticipating the congestion ahead allows the vehicle to reduce speed in a shorter distance, which will slightly extend the driving time and increase carbon emissions. Therefore, a reasonable speed is required to ensure that carbon emissions are minimized. In this model, the most effective speed for energy savings and emission reduction is 45 km/h.

Conclusions

Severe traffic congestion in the VRP can result in increased carbon emissions and travel times. To avoid congested roads, a vehicle-waiting congestion-avoidance strategy and a speed-reduction congestion-avoidance strategy are proposed and applied to the

cold-chain VRP. The experimental results show that the congestion-avoidance strategy reduces transportation time and carbon emissions in the cold-chain VRP. The speed-reduction congestion-avoidance strategy is more suitable for the cold-chain VRP, whereas the vehicle-waiting congestion-avoidance strategy is more suitable for the general logistics VRP. The optimal driving speed is determined from the carbon emissions generated from the cold-chain logistics distribution as a function of vehicle speed. The results of this study show the practical significance of studying congestion avoidance in the cold-chain VRP, which can improve environmental and economic benefits. Combining real-time variations of the vehicle path with congestion-avoidance strategies in the VRP is a future research avenue worth exploring to mitigate traffic congestion. In the future, it will also be possible to study changes such as the power consumption of electric vehicles when adopting congestion avoidance strategies.

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Conflict of Interest

The authors declare no conflict of interest.

Author's Contributions

Conceptualization: Aobei Zhang, Data curation: Aobei Zhang, Ying Zhang, Formal analysis: Aobei Zhang, Ying Zhang, Yanqiu Liu, Jiaqi Hou, Jihui Hu, Software: Aobei Zhang, Ying Zhang, Yanqiu Liu, Methodology: Aobei Zhang, Jiaqi Hou, Jihui Hu, Validation: Aobei Zhang, – original draft: Aobei Zhang, Ying Zhang, Yanqiu Liu, Writing – review & editing: Aobei Zhang, Ying Zhang, Yanqiu Liu, Jiaqi Hou, Jihui Hu.

References

1. GUO X.L., ZHANG W., LIU B.B. Low-carbon routing for cold-chain logistics considering the time-dependent effects of traffic congestion. *Transportation Research Part D: Transport and Environment*, **113**, 103502, **2022**.
2. LUO H.Y., DRIDI M., GRUNDER.O. A branch-price-and-cut algorithm for a time-dependent green vehicle routing problem with the consideration of traffic congestion. *Computers & Industrial Engineering*, **177**, 109093, **2023**.
3. LIU C.S., KOU G., ZHOU X.C., PENG Y., SHENG H.Y., ALSAADI F.E. Time-dependent vehicle routing problem with time windows of city logistics with a congestion avoidance approach. *Knowledge-Based Systems*, **188**, 104813, **2020**.
4. GONG M.Z., LIU S. Study on Cold Chain Logistics with Time Windows Based on Carbon Emissions Considering Simultaneous Pick Up and Distribution//2019 8th International Conference on Industrial Technology and Management (ICITM). *IEEE*, 301, **2019**.
5. FRANCESCHETTI A., DEMIR E., HONHON D., WOENSEL T.V., GILBERT L., MARK S. A metaheuristic for the time-dependent pollution-routing problem. *European Journal of Operational Research*, **259** (3), 972, **2017**.
6. WANG S., TAO F., SHI Y. Optimization of location–routing problem for cold chain logistics considering carbon footprint. *International journal of environmental research and public health*, **15** (1), 86, **2018**.
7. HU B., HUANG B.T., LIU Z., GUO H.X., CHEN Z., Shi L.H. Optimization Model of Carbon Footprint of Fresh Products in Cold Chain from the Energy Conservation and Emission Reduction Perspective. *Mathematical Problems in Engineering*, **2021**.
8. TAO N., LU A., DUAN X.D. Optimization of cold chain distribution path of fresh agricultural products under carbon tax mechanism: A case study in China. *Journal of Intelligent & Fuzzy Systems*, **40** (6), 10549, **2021**.
9. LI J.Y., FAN L.N., Dong D.Y. A new route optimization approach of cold chain logistics distribution based on fresh agricultural products//2018 Chinese Control And Decision Conference (CCDC). *IEEE*: 6652, **2018**.
10. LIU G.K., HU J.Y., YANG Y., XIA S.M., LIM M.K. Vehicle routing problem in cold Chain logistics: A joint distribution model with carbon trading mechanisms. *Resources, Conservation and Recycling*, **156**, 104715, **2020**.
11. WANG S.Y., TAO F.M., SHI Y.H., WEN H.L. Optimization of vehicle routing problem with time windows for cold chain logistics based on carbon tax. *Sustainability*, **9** (5), 694, **2017**.
12. CHEN J.X., LIAO W.Z., YU C.W. Route optimization for cold chain logistics of front warehouses based on traffic congestion and carbon emission. *Computers & Industrial Engineering*, **161**, 107663, **2021**.
13. QI C., HU L. Optimization of vehicle routing problem for emergency cold chain logistics based on minimum loss. *Physical Communication*, **40**, 101085, **2020**.
14. ZHAO Z.X., LI X.M., ZHOU X.C. Distribution route optimization for electric vehicles in urban cold chain logistics for fresh products under time-varying traffic conditions. *Mathematical Problems in Engineering*, (2020), **2020**.
15. POONTHALIR G., NADARAJAN R. A fuel-efficient green vehicle routing problem with varying speed constraint (F-GVRP). *Expert Systems with Applications*, **100**, 131, **2018**.
16. ZHANG R.Y., GUO J.M., WANG J.W. A time-dependent electric vehicle routing problem with congestion tolls. *IEEE Transactions on Engineering Management*, **69**(4), 861, **2020**.
17. GMIRA M., GENDREAU M., LODI A., POTVIN J.Y. Tabu search for the time-dependent vehicle routing problem with time windows on a road network. *European Journal of Operational Research*, **288** (1), 129, **2021**.
18. PUGLIESE L.D.P., FERONE D., FESTA P., GUERRIERO F., MACRINA G. Solution approaches for the vehicle routing problem with occasional drivers and time windows. *Optimization Methods and Software*, **37** (4), 1384, **2022**.
19. HU C., LU J., LIU X., ZHANG G. Robust vehicle routing problem with hard time windows under demand and travel time uncertainty. *Computers & Operations Research*, **94**, 139, **2018**.
20. GE X.L., RAN X.F., Study on the optimization of pollution routing problem with time-varying traffic congestion. *Industrial Engineering and Management*, **25** (03), 75, **2020**.
21. LI Y.F., GAO Z.Y., LI J. Vehicle routing problem in dynamic urban network with real-time traffic information. *Systems Engineering-Theory & Practice*, **33** (07), 75, **2013**.
22. KOK A.L., HANS E.W., SCHUTTEN J.M.J. Vehicle routing under time-dependent travel times: the impact of congestion avoidance. *Computers & operations research*, **39** (5), 910, **2012**.
23. LIU C.S., SHEN L.Z., SHENG H.Y., LV X.Y., QU Y.P. Research on low-carbon time-dependent vehicle routing problem with traffic congestion avoidance approaches. *Control and Decision*, **35** (10), 2486, **2020**.
24. JI Y.H., DU J., WU X.Q., QU D., YANG D.Q. Robust optimization approach to two-echelon agricultural cold chain logistics considering carbon emission and stochastic demand. *Environment, Development and Sustainability*, **23**, 13731, **2021**.
25. ZHANG L.Y., TSENG M.L., WANG C.H., XIAO C., FEI T. Low-carbon cold chain logistics using ribonucleic acid-ant colony optimization algorithm. *Journal of Cleaner Production*, **233**, 169, **2019**.