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An optimal control theory approach for freight structure path evolution post-COVID-19 pandemic

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ABSTRACT

After the outbreak of COVID-19, the freight demand fell briefly, and as production resumed, the trucking share rate increased again, further increasing energy consumption and environmental pollution. To optimize the sudden changing freight structure, the study aims on developing an evolution model based on Markov’s theory to estimate the freight structure post-COVID-19. The current study applies economic cybernetics to establish a freight structural adjustment path optimization model and solve the problem of how much freight transportation should increase each year under the premise that the total turnover of the freight industry continues to grow, and how many years it will take at least to reach a reasonable freight structure. The freight transport structure of China is used to examine the feasibility of the proposed model. The finding indicates that the development of China’s freight transport structure is at an adjustment period and should enter a stable period by 2035 and the COVID-19 makes it harder to adjust the freight structure. Increasing the growth rate of the freight volume of railway and waterway transportation is the key to realizing the optimization of the freight structure, and the freight structure path optimization method can realize the rationalization of the freight structure in advance.

1. Introduction

The carbon emissions generated by the transportation industry account for about 11.5% of the total carbon emissions, and it is one of the four major industries that generate carbon emissions. Compared with railway and waterway transportation, road transportation generates more energy consumption and carbon emissions, while China’s road freight volume accounts for more than 40% all the year round. This data highlights the unreasonable structure of freight transport mainly by road. The coordinated development of the freight transportation structure is essential to promote the development of the optimal transport policy which can provide enhanced access, safety, reduced environmental impact, and improve resilience to accelerate transaction to sustainable economic development [1]. Therefore, in 2018, China proposed the “Three-Year Action Plan for Promoting the Adjustment of Transportation Structure (2018–2020)”, and achieved good adjustment results in 2018–2020. In order to develop green transportation and realize the green transformation of freight transport structure, it is necessary to study the adjustment strategy of China’s freight transport structure under the peak of carbon emissions.

The COVID-19 pandemic has reaffirmed the central role of freight transport in sustainable development, creating new challenges, while also indicating some potential pathways towards sustainability. For example, the improvement of supply chain management capability [2] and the application of IOT (The Internet of Things) technology [3], etc. The outbreak of COVID-19 has partially disrupted the international supply chain, resulting in a slight drop in China’s railway and waterway transportation. With the effective prevention and control of the domestic epidemic in China, the freight demand of major urban agglomerations has recovered and increased, which has made China’s truck freight volume and share rate have risen again, further increasing the difficulty of adjusting the freight structure.

The logit model has been widely used in freight structure forecasting [4] and the model requires many assumptions, such as decision
The adjustment of freight structure is a dynamic and long-term process, and is restricted by many factors. Many scholars have proposed various specific freight structure optimization strategies [9]. studied the effects of policy measures such as subsidies, taxation, pricing, strategic planning and operation, and infrastructure construction on promoting the transition from road transportation to railway transportation [10], emphasized the role of climate finance and carbon pricing in the development of green transportation. But few research have carried out research on the macro freight structure optimization path, especially considering the impact of COVID-19 and the tightening of carbon emission constraints. In this paper, the optimal control theory is used to optimize the freight structure, because this theory can find an optimal control scheme from the control scheme, so that the system can transfer from the initial state to the desired target state. Optimal control theory is a branch of mathematical optimization, that focuses on the conditions and methods that make the control system an optimal benefit or minimal loss [11; Ross, 2009]. Optimal control theory can effectively solve dynamic optimization problems such as freight structure [12] and freight operations research [13, 14].

This paper attempts to answer the following research questions: (1) What is the impact of COVID-19 on the freight structure? (2) How the optimization model can be used to establish the freight structural adjustment path model? (3) Can the carbon emissions of the freight industry be peaked or reduced through the optimization of the freight structure? In order to answer the above questions, the research of this paper is also divided into three parts: (1) This paper constructs the evolution model of freight structure based on Markov chain, and predicts the evolution of freight structure in China after COVID-19; (2) Considering the difference between the current freight structure and the expected freight structure, this paper constructs a freight structure adjustment model based on the optimal control theory, and proposes the path of freight structure optimization; (3) The influence of freight volume, freight energy consumption and freight structure on carbon emission of freight industry is discussed.

2. Literature review

2.1. Freight structure models

The discrete choice models are based mostly on the selection process of freight mode selection, such as the comparison of modes of transport, decision-making criteria, and types of cargo demand [15]. The discrete choice model is one of the commonly used models of freight transportation structure in the literature [16, 17]. The Logit selection model is completely demand-oriented, and studies have shown that even if there is a lack of traffic supply data, the choice of transportation mode predicted by this model is relatively effective [18]. Markov chain is one of the most abundant models for capturing dynamic evolution behavior of random nature. It is of great significance in many branches of science, engineering, and other fields [19, 20], including physics [21, 22], industrial control [23, 24], reliability analysis [25] optimization analysis [26], decision analysis [27, 28, 29], and economics [30]. The above literature shows that the freight structure is predictable, and the Markov chain model has a good predictive ability. The paper by Ref. [31] discussed the comprehensive freight transport models (Freturb and Wiver) and existing city’s transport model were evaluated to understand the difficulties in freight transportation [32], proposed a two-sided matching model, and analyze the impact of suppliers and demanders’ loss aversion on matching result. The paper by Ref. [33] developed four multidimensional resource allocation models aimed to prioritize freight improvement projects for regional, state, and local transportation agencies such that return on investment is maximized. The recent pandemic has also diverted the attention of the researchers towards freight transportation [34], developed location, routing and allocation of medical centers to distribution depots during the COVID-19 pandemic outbreak [35]; discussed the need for versatile mathematical models that can help in distribution of medicines related to COVID-19. To integrate un-certainty in the mathematical model, the paper by Ref. [36] extended the previous work to develop sustainable-resilient health care network related to the COVID-19.

2.2. Freight structure solution approaches

Freight agencies and scholars have proposed a series of ideas and methods for the transformation of freight transportation modes because of the negative externalities of road transportation. In addition to technology and investment means, it is also necessary to increase service levels and quality to guide the growth of railway freight [37]. The premise of multimodal transportation is that the lower transportation cost of a railway or waterway can offset the additional transportation time and handling cost [38]. However, because of the increasing time-line innership requirements of cargo transportation, high value-added, and time-sensitive cargo will not choose multimodal transportation [39]. [40] proposed the inelasticity of freight structure, that is, the irreplaceability of freight mode, especially transportation within 500 km, has strong inelastic characteristics. For example, South Korea’s freight transport is dominated by road transportation. In 2015, South Korea’s freight transport structure (calculated in ton-kilometers) was 76.2% by road [41], further studied the elasticity of the EU’s “revolution waterway” and “revolution railway”. It is worth noting that economic penalties have little effect on the transformation of freight transport mode. The United States, Germany, Japan, and other countries are also developing multimodal automatic freight systems to assist the development of railway and waterway transportation [42, 43]. At the same time, changing the main behavior of freight participants is necessary to achieve the policy goals. Freight policymakers must have a clear prior concept to clearly understand the response of freight participants to the policy [44, 45]. [46] showed that the government’s comprehensive policy measures to reduce road transport can shift 4% of road freight to the railway, even so, it is still the dominant mode of German freight.

3. Modeling

Freight structure refers to the proportion of the five modes of transportation, reflecting the competition and cooperation of the modes of transportation. This section gives the basic concepts and construction principles of the Markov chain model and builds the freight structure, and prediction model. Subsequently, the path optimization model of freight structure was constructed based on the optimal control theory and the results of the evolution of freight structure. Finally, the calculation of energy consumption and carbon emissions in the freight industry is explained.

3.1. Markov chain model analysis

At the beginning of the last century, Russian mathematician Andrei Markov discovered that a class of things in nature exhibits a process of random chance, but when it transitions from the former state to the latter state, a relatively stable transition probability matrix occurs. The transition probability matrix is determined by the recent state of things
and has nothing to do with the past state in the time series. This characteristic is called memory less ness or no aftereffect. The random process with this characteristic is called the Markov process [47]. The change of state is called transition, and the probability associated with different state changes is called transition probability. Markov process analysis is based on the following basic assumptions in a certain period:

1. The transition probability remains relatively stable, that is, the change of freight structure is stable;
2. The number of states is limited and remains unchanged, that is, the number of transportation modes remains unchanged; and
3. The transition of the future state is only affected by the current state and has nothing to do with the previous state, that is, the evolution of the future freight structure depends only on the current freight structure.

From the perspective of the evolution of the freight structure in Europe, America, and Japan, the changes in the freight structure tend to be stable, that is, the changes in the freight structure have obvious Markov process characteristics. Markov models are often used to model the probabilities of different states and the rates of transitions among them. The method is generally used to model systems. Markov models can also be used to recognize patterns, make predictions, and learn the statistics of sequential data. In the current study since we have dynamic data, the use of the Markov model is justified. In addition, the Markov chain analysis model is simple and clear, requiring only recent freight data, the use of the Markov model is justified. In addition, the Markov chain analysis model is simple and clear, requiring only recent freight data, the use of the Markov model is justified.

According to the total probability formula in probability theory and mathematical statistics, the state distribution at the n step is as follows:

\[ S(n) = P[X_n = x_i], \quad (x_i \in I, j = 1, 2, \ldots) = \sum_{i=1}^{T} P[X_0 = x_i, X_n = x_j] = \sum_{i=1}^{T} P[X_0 = x_i] \cdot P[X_n = x_j|X_0 = x_i] = \sum_{i=1}^{T} \pi(i) \cdot P_i(n) \]  

(1)

The state distribution vector at step n is as follows:

\[ S(n) = S(1), S(2), \ldots, S(n), \ldots = S(0) \cdot P(n) \]  

(2)

Let \( X_n = X(n), n \in T = \{0, 1, 2, \ldots\} \) be a homogeneous Markov chain, for any \( u, v \in T \), there is

\[ P_{ij}(u + v) = \sum_{i=1}^{T} P(x_i \cdot P_{ij}(v) (3) \]

Its matrix form is

\[ P(u+v) = [P_v(u+v)] = P(u) \cdot P(v) \]  

(4)

The above equation is the Chapman-Kolmogorov equation, abbreviated as the (C-K) equation. The (C-K) equation is used to determine the n-step transition probability matrix, let \( u = 1, v = n - 1 \), then the recurrence relationship is as follows:

\[ P(n) = P(1) \cdot P(n-1) = P \cdot P(n-1) = \ldots = P^n \]  

(5)

Therefore, after the n-step transfer, the Markov chain analysis model can be expressed as follows:

\[ S(n) = S(0) \cdot P(n) = S(0) \cdot P^n \]  

(6)

The above formula shows that the finite-dimensional distribution state of a homogeneous Markov chain at any time \( n \in T \) is determined by the initial distribution vector \( S(0) \) and the one-step transition probability matrix \( P \). The elements in the transition probability matrix reflect the probability of market participants or consumers retaining, gaining, or losing market shares. The row elements in the matrix represent the retained and lost share probabilities. The column elements in the matrix represent the retained and obtained share probabilities. In an effectively competitive market, these gains and losses can be transferred to each other, that is, if one participant gains or loses a certain market share, other participants will lose or gain that market share.

### 3.2. Path optimization model analysis

This section attempts to apply optimal control theory to establish a freight structural adjustment path optimization model and solve the problem of how much freight transportation should increase each year under the premise that the total turnover of the freight industry continues to grow, and how many years it will take at least to reach a reasonable freight structure. Assuming that the freight system has \( n \) transportation methods, \( x_j(0) (j = 1, 2, \ldots, n) \) is the ratio of the current turnover of j transportation methods to the total turnover, and \( q_j \) is the turnover of \( j \) transportation methods. The reasonable proportion of total turnover, vector \( \alpha = (\alpha_1, \alpha_2, \ldots, \alpha_n) \), is the ideal reasonable structure ratio target vector. Now we need to find a path to keep the total turnover on this path increasing at a certain growth rate. After N periods, adjust \( x_j(0) \) to \( \alpha_j \) and the time are the shortest.

(1) System status. Suppose the state variable \( x_j(k) (j = 1, 2, \ldots, n) \) is the ratio of the turnover of freight mode \( j \) to the total turnover in period \( k \), and the vector \( X(k) = [x_1(k), x_2(k), \ldots, x_n(k)] \) is the structure vector of various freight modes in period \( k \). The control variable \( u_j(k) \) is the growth rate of the turnover volume of freight mode \( j \) in period \( k-1 \) compared to its previous period \( k \), Its vector \( U(k) = [u_1(k), u_2(k), \ldots, u_n(k)] \) is the increase of the turnover of various transportation modes in the \( k+1 \) period compared to the previous period \( k \). Rate vector, \( v(k) \) represents the growth rate of the total turnover in the
\[ \sum_{j=1}^{n} x_j(k) \cdot u_j(k) = \nu(k) \] (11)

\[ m_j(k) \leq u_j(k) \leq M_j(k) \] (12)

where \( m_j(k) \) represents the slowest growth rate of a certain transportation mode, and \( M_j(k) \) represents the fastest growth rate of a certain transportation mode. The value range of \( u_j(k) \) is determined by the matching of supply and demand of a certain freight method, and is also affected by the competition and cooperation among various freight methods in the freight system. On the premise that the total volume of freight turnover remains unchanged, the increase in turnover of one freight mode will inevitably affect the increase in the turnover of other freight modes and is restricted by the increase in the turnover of other freight modes. To facilitate the study of the problem, the growth rate \( \nu(k) \) of total freight turnover is also stipulated as follows:

\[ m_j(k) \leq u_j(k) \leq M_j(k) \] (13)

In the above formulas, \( k = 0, 1, \ldots, N - 1; j = 1, 2, \ldots, n \).

(3) Path optimization model. Based on the above analysis and research, the optimized path model of the transportation structure can be constructed as follows:

\[
\min Z = \sum_{i=0}^{n-1} \sum_{j=1}^{n} \left\{ \frac{x_j(k)[1 + u_j(k)]}{1 + \nu(k)} - \alpha_j \right\}^2
\] (14)

where \( E_{ij} \) represents the energy consumption (standard coal) of the \( i \)-th freight mode in period \( t \), \( T_{ij} \) represents the original consumption of the \( j \)-th energy type of the \( i \)-th freight mode in the period \( t \), and \( \eta_j \) represents the conversion coefficient of converting the original consumption of the \( j \)-th energy type into standard coal.

The Chinese government proposes to achieve the peak of carbon emissions in 2030 and achieve carbon neutrality in 2060 to realize the green development of transportation. The carbon emission calculation method of the freight industry can be expressed as follows:

\[ C_{ij} = \sum_{j=1}^{N} C_{ij} \times K_j \] (16)

where \( C_{ij} \) represents the carbon emissions of the freight transport industry of the \( i \)-th freight mode in period \( t \) and \( K_j \) represents the carbon emission coefficient of the \( j \)-th energy type. At the same time, the calculation method of the carbon emission coefficient of the \( j \)-th energy type can be expressed by the following formula:

\[ K_j = o_j \times \left( u_j \times 10^3 \div 10^6 \right) \times \nu_j \times 44/12 \] (17)

where \( o_j \) represents the average low calorific value of the \( j \)-th energy type; \( u_j \) represents the carbon content per unit calorific value of the \( j \)-th energy type; \( \nu_j \) represents the carbon oxidation rate of \( j \)-th energy types.

4. Algorithm

4.1. Algorithm of the Markov chain model

4.1.1. Estimation method of state transition probability

The estimation of the state transition probability is determined based on the recent market or consumer retention rate and the flow of gains and losses. After collecting and researching the literature, four basic methods for estimating the state transition probability are established:

(1) Subjective probability method.

(2) Statistical estimation method. The statistical method is the most commonly used method for estimating the state transition probability. This method calculates the system structure ratio or the frequency of statistical events based on the results of market questionnaire surveys or historical data. When the number of trials is the largest, the frequency can be used as an approximate probability value to estimate the transition probability of state occurrence.
(3) Orthogonal experiment simulation method. First, least squares is used to estimate the orthogonal test factor, determine the normal number according to the size of the experimental factor and the degree of satisfaction of the estimated value, and perform the orthogonal test according to the orthogonal table to determine the objective function. This objective function is used to simulate and perform multiple experimental adjustments. Finally, the ideal parameter estimates are obtained [48].

(4) The secondary planning method. Let \( x(t) \) be the turnover of \( i \) types of freight in period \( t \), then \( X(t) = \sum_{i=1}^{n} x(t) \) is the turnover of various freight methods in \( t \). Total amount. \( W_i(t) = \frac{X_i(t)}{X(t)} \) is the ratio of the turnover of \( i \) modes of freight in period \( t \) to the total turnover of various freight methods in \( t \), then \( W_i(t) = \frac{1}{n} \sum_{i=1}^{n} W_i(t-1) \) is the error term, and \( P_q \) is required to make the sum of squares of the error term \( \sum_{i=1}^{n} \sum_{j=1}^{n} e_i(t) \) reach the minimum and establish a quadratic programming model:

\[
\begin{align*}
\min Z &= \sum_{i=1}^{n} \sum_{j=1}^{n} \left( W_i(t) - \frac{1}{n} \sum_{i=1}^{n} W_i(t-1) \right)^2 \\
\text{s.t.} & \quad \sum_{j=1}^{n} P_q = 1 \\
& \quad P_q \geq 0, i = 1, 2, \ldots, n
\end{align*}
\]  

(18)

The transition probability \( P_q \) is obtained by solving the above quadratic programming model.

4.1.2. Solving steps of the Markov chain model

Step 1 Take the initial feasible solution. Let \( U(k) = [u_1(k), u_2(k), \ldots, u_n(k)]^T \), where \( u_i(k) \) satisfies

\[
\sum_{j=1}^{n} u_j(k) \cdot u_i(k) = v(k)
\]

(22)

\[
m_i(k) \leq u_i(k) \leq M_i(k)
\]

(23)

It can be seen that \( U(k) \) has a feasible solution.

Step 2 Determine whether the conditions meet the requirements. Calculation

\[
x_i(k+1) = \frac{x_i(k) + 1 + u_i(k)}{1 + v}
\]

(24)

Let a predetermined sufficiently small positive number \( \epsilon \). If \( X(k+1) - a^2 \leq \epsilon \), then the optimal structural ratio vector for the \( k+1 \) period is \( X'(k+1) = U(k) \), the entire solution process ends. At this time, \( N = k+1 \); otherwise, if \( X(k+1) - a < \epsilon \), then transfer to the next calculation.

Step 3 Find the feasible descending direction. If \( U(k) \) is not the optimal solution of the above structural optimization model, but only a feasible solution, there must be a sufficiently small positive number \( \lambda(k) \), let \( U(k+1) = U(k) + \lambda(k)D \), \( D \) are the feasible descending directions \( D = [d_1, d_2, \ldots, d_n]^T \) where \( d_j \) takes the value according to the following rules:

When \( j \in \{r+1, \ldots, q\}, d_j = 0 \);
When \( j \notin \{r+1, \ldots, q\}, d_j = [1 + v]E_j \), where

\[
E_j = \frac{a_j}{x_j(k)} - \frac{\sum_{j=1}^{n} \sum_{j=1}^{n} \epsilon_{j,j}}{\sum_{j=1}^{n} \sum_{j=1}^{n} \epsilon_{j,j} \cdot x_j(k)}
\]

(25)

From the definition of \( U(k+1) \), the following formula holds.

\[
\sum_{j=1}^{n} x_j(k+1) \cdot u_j(k+1) = v
\]

(26)

\[
m_i \leq u_i(k+1) \leq M_i
\]

(27)

\[
\sum_{j=1}^{n} \left( \frac{x_j(k+1) + 1 + u_j(k)}{1 + v} - a_j \right)^2 < \sum_{j=1}^{n} \left( \frac{x_j(k) + 1 + u_j(k)}{1 + v} - a_j \right)^2
\]

(28)

Therefore, \( D \) is the feasible descending direction.
Table 1
2015-2019 China freight structure smoothing results.

|       | 2015   | 2016   | 2017   | 2018   | 2019   |
|-------|--------|--------|--------|--------|--------|
| Truck | 46.69% | 45.28% | 43.86% | 42.45% | 41.03% |
| Waterway | 30.24% | 31.27% | 32.29% | 33.31% | 34.34% |
| Railway | 19.14% | 19.55% | 19.95% | 20.36% | 20.77% |
| Pipeline | 3.76%  | 3.26%  | 3.36%  | 3.47%  | 3.68%  |
| Air | 0.17% | 0.17% | 0.17% | 0.18% | 0.18% |

Data source: National Bureau of Statistics.

Step 4 Determine the feasible descending step size \( \lambda(k) \). Let

\[
\lambda_j(k) = \min \left\{ \frac{M_j - v_j d_j}{d_j^r} (1 + v) \right\}, j = 1, 2, \ldots, r
\]

\[
\lambda_j(k) = \min \left\{ \frac{M_j - v_j d_j}{d_j^r} (1 + v) \right\}, j = q + 1, q + 2, \ldots, n
\]

Step 5 In step 4, \( \lambda(k) \) is equal to the j of \( \lambda_j(k) \), corresponding to the feasible descending direction \( D = [d_1, d_2, \ldots, d_n]^T \) where the value of \( d_j \) is 0, and the other \( d_j \) values are the same as above, \( U(k + 1) = U(k) + \lambda(k) \cdot D \). Take \( k := k + 1 \), go to step 2. This iteration continues until the end of the operation.

5. Empirical analysis

5.1. Forecast of the evolution of China’s freight transport structure

5.1.1. Overview of China’s freight transport structure

The evolution of China’s freight transport structure in the 21st century can be roughly divided into three stages: Stage 1, which is the dominant stage of railway transportation from 2000 to 2007, Stage 2, which represents the dominant stage of road transportation from 2008 to 2014, and Stage 3, which represents the freight structure adjustment stage from 2015 to 2021 as shown in Fig. 1.

The adjustment direction of China’s freight transport structure is consistent with Phase 3, which is to increase the proportion of waterway and railway freights and reduce the proportion of road freight. Therefore, Stage 3 is very important to the forecast of the freight structure in the later period of this article. To reduce the noise and fluctuation of the original data, the original data are smoothed first, and the processing results are shown in Table 1. On December 12, 2019, the first patient with the COVID-19 in China was diagnosed in Wuhan. Therefore, this paper first considers the situation in 2015–2019, when the COVID-19 has not yet occurred or has little impact.

5.1.2. Estimate the transition probability matrix

The state transition probability matrix is estimated based on the data in Table 1 and the quadratic programming model in Section 4.1, where \( m = 5, t = 1, 2, 3, 4, n = 5, j = 1, 2, 3, 4, 5 \) represent roads, waterways, railways, pipelines, and air freight modes, respectively, the transition probability matrix \( P \) is obtained as follows:

\[
P = \begin{bmatrix}
P_{11} & P_{12} & P_{13} & P_{14} & P_{15} \\
P_{21} & P_{22} & P_{23} & P_{24} & P_{25} \\
P_{31} & P_{32} & P_{33} & P_{34} & P_{35} \\
P_{41} & P_{42} & P_{43} & P_{44} & P_{45} \\
P_{51} & P_{52} & P_{53} & P_{54} & P_{55}
\end{bmatrix} = \begin{bmatrix}
0.9115 & 0.0714 & 0.0147 & 0.0024 & 0.0000 \\
0.0714 & 0.9286 & 0.0000 & 0.0000 & 0.0000 \\
0.0147 & 0.9853 & 0.0000 & 0.0000 & 0.0000 \\
0.0024 & 0.0000 & 0.0000 & 0.9975 & 0.0001 \\
0.0000 & 0.0000 & 0.0000 & 0.0001 & 0.9999
\end{bmatrix}
\]

Its meaning is shown in Fig. 2.

From the state transition probability matrix, we can see that a substitution relationship exists between truck and waterway and railway transportation, and the substitution between truck and waterway transportation is the largest. Due to the particularity of pipeline transportation and air transportation, no substitution relationship between these two transportation methods and other transportation methods arises.
China's freight transport structure has shown a downward trend in fluctuations. This portion of railway, pipeline, and air freight has increased, and the proportion of waterway transport has continued to grow during 2020–2021. The forecast structure is shown in Table 3.

Table 3
China’s freight structure evolution.

| Mode      | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|-----------|------|------|------|------|------|------|------|
| Truck     | 0.4031 | 0.3732 | 0.3580 | 0.3492 | 0.3344 | 0.3389 | 0.3352 |
| Waterway  | 0.3450 | 0.3589 | 0.3612 | 0.3588 | 0.3549 | 0.3505 | 0.3463 |
| Railway   | 0.2099 | 0.2234 | 0.2347 | 0.2432 | 0.2509 | 0.2577 | 0.2636 |
| Pipeline  | 0.0402 | 0.0426 | 0.0447 | 0.0468 | 0.0488 | 0.0507 | 0.0526 |
| Air       | 0.0018 | 0.0018 | 0.0019 | 0.0020 | 0.0021 | 0.0021 | 0.0022 |

Data source: calculated by the author.

5.1.4. Forecast of evolution of freight transport structure

Using the above analysis, we can predict China’s freight structure from 2020 to 2050. The forecast structure is shown in Table 3.

Table 3 shows that the evolution of China’s freight transport structure is as follows. The proportion of road freight has declined, the proportion of railway, pipeline, and air freight has increased, and the waterway transport has shown a downward trend in fluctuations. This evolution trend is consistent with the evolution of freight transportation in the United States.

The impact of the COVID-19 on passenger transportation is relatively large, and the impact on freight transportation is relatively small, and China’s freight turnover has continued to grow during 2020–2021.

Table 5
Target structure of freight by 2035.

| Mode      | Current structure | Target structure |
|-----------|-------------------|------------------|
| Truck     | 42.39% 34.04% 20.37% 3.33% 0.17% | 35.53% 35.05% 24.56% 4.65% 0.20% |
| Waterway  |                   |                  |
| Railway   |                   |                  |
| Pipeline  |                   |                  |
| Air       |                   |                  |

Data source: National Bureau of Statistics and the author’s calculation.

5.1.3. Analysis of fit test error

As shown in Table 2, this model takes the smoothed 2015 freight structure as the initial state, that is, \( S(0) = (0.4669, 0.3058, 0.1938, 0.0318, 0.0017) \), and the constructed Markov model is used for fitting to test the accuracy of its prediction.

Table 2 further that the relative error of truck, waterway, and railway is within 2%. The error of pipeline transportation is slightly larger, reaching 3.01%, whereas the error of air transportation reaches 6.13%, which may be because the proportion of air transportation is too small. It is caused by the retention of decimals in the calculation process. On the whole, the predicted value is the same as the actual smoothed value, and the fitting effect is good.

According to the evolution of freight structure in 2020–2021, new forecasts can be made for China’s freight structure, and the forecast results are shown in Table 4.

From the comparison between the two, it is found that the impact of the COVID-19 has increased the proportion of truck transportation; it has weakened the proportion of waterway transportation; the proportion of railway and pipeline transportation will decrease in the medium term, and will be further increased in the long run; the impact on air transport has been very limited to little. In the medium term, the COVID-19 has caused the proportion of railway and waterway transportation in China to decrease, while the proportion of truck transportation has increased. This prediction result seems to be contrary to the common sense. The possible reason is that China’s manufacturing industry has developed well in the past two years, and the food processing industry, textile industry, furniture, metal, equipment and other manufacturing industries in the manufacturing industry have large demand for truck transportation. As a result, the proportion of truck transportation has been further increased.

5.2. Optimal route of freight structure

5.2.1. Path optimization model construction

It is assumed that the growth rate of various transportation methods in the future will fluctuate from 0% to 10%, and the freight turnover will achieve an average annual growth rate of 2.3% by 2035. To adjust the freight structure to a reasonable structure, it is necessary to determine what the annual growth rate of various freight modes is under the premise that the total freight turnover growth rate is not less than 2.3%, and how many years of adjustments will be required to achieve a reasonable freight structure. The reasonable structure of the target is shown in Table 5.
5.2.2 Optimized path solving

According to the above model, the optimized route of China’s freight transportation structure is solved, and the result is shown in Fig. 3. The results show that the evolution of freight structure has its regularity, and the adjustment of freight structure can change the evolution of freight structure, but the effect is not large. On the premise that the growth rate of freight turnover remains at 2.3%, it will take at least 13 years for the adjustment of the freight structure to adjust the current structure to the target and reasonable structure. The specific adjustment strategy is to give priority to the development of waterway and railway transportation in five years, develop pipeline transportation under the premise of ensuring the development of waterway and railway transportation, promote the development of air transportation around 2025, and develop air transportation around 2027. The growth rate of transportation was adjusted to about 6%, and then gradually decreased to about 4%. The growth rate of road, waterway, railway, and pipeline transportation was stable at about 2.3%.

We consider two scenarios following the uncertainty of future freight turnover and the growth rate of freight mode. In the first situation, the maximum growth rate of freight mode remains unchanged, and the growth rate of freight turnover changes. The simulation results are shown in Fig. 4. When the growth rate of freight turnover decreases to 2%, the adjustment speed of the freight structure also slows down accordingly because the growth rate of freight turnover limits the speed of adjustment of freight mode, which leads to the extension of the time for optimization of freight structure to 14 years. When the growth rate of freight turnover increases to 2.6%, the adjustment of the freight structure accelerated and the optimization time was shortened to 12 years. The simulation shows that the increase in freight turnover can slightly accelerate the optimization of freight structure.

In the second situation, the growth rate of freight turnover remains unchanged, and the maximum growth rate of freight transportation changes. The simulation result is shown in Fig. 5. When the maximum growth rate of freight transportation mode is reduced to 8%, the optimization time of freight structure is extended to 14 years, whereas the maximum growth rate of freight transportation mode is increased to 12%, the optimization time of freight structure is
shortened to 11 years. The simulation shows that the key to speeding up the optimization of freight structure is to change the growth rate of freight mode.

5.3. Carbon emission analysis

China’s energy consumption is dominated by coal, and thus, China adopts standard coal as the energy consumption calculation standard, that is, various energy sources are converted into standard coal according to their calorific value. The original consumption and standard coal conversion coefficient of each energy type in the freight industry are from the China Energy Statistical Yearbook. The conversion factor of 10,000 tons of standard coal is shown in Table 6.

| Energy type  | diesel fuel | gasoline | kerosene | fuel oil | electricity | raw coal | natural gas | liquefied petroleum gas | coke | crude |
|--------------|-------------|----------|----------|----------|-------------|----------|-------------|------------------------|------|-------|
| Conversion factor | 1.4571 | 1.4714 | 1.4714 | 1.4286 | 1.229 | 0.7143 | 12.14 | 1.7143 | 0.9714 | 1.4286 |

Table 6: Conversion coefficients between energy consumption and 10,000 tons of standard coal.

From the point of view of the total carbon emissions from freight transportation, there is a trend of year-on-year growth from 2010 to 2018, from 560 million tons in 2010 to 870 million tons in 2018, with an average annual growth rate of about 5.59%. Until 2018, when the Chinese government implemented the “Three-Year Action Plan for Promoting Transportation Structural Adjustment (2018–2020)”, the carbon emissions of the freight transport industry 2019 were reduced by 20%, which was the same as that in 2012, as shown in Fig. 6.

This paper divides freight energy consumption into two cases for prediction: energy consumption prediction when freight structure remains unchanged and energy consumption prediction when freight structure changes to compare the effects of freight structure changes on freight energy consumption.
increase in freight turnover leads to a 1% increase in energy consumption. The relationship between the two is a straight line that starts from the origin with a slope of 1. That is, a 1% growth rate of freight turnover. The relationship between the growth rate of freight energy consumption and the growth rate of freight turnover is set at an average annual growth rate of 2.3%, and the growth rate of freight turnover in China from 2010 to 2019 is shown in Fig. 7.

The functional relationship between the two is

\[ ER = 0.961R_{FT} + 0.007 \]  

where \( ER \) is the growth rate of freight energy consumption and \( R_{FT} \) is the growth rate of freight turnover. The relevant parameter tests are shown in Table 8.

The regression equation and model parameters passed the test, and the fit was good. The verification results are consistent with the theoretical analysis. Thus, when the freight structure and energy intensity remain unchanged, the freight energy consumption is only affected by the freight turnover, and the function graphs of the two are a straight line with a slope of 1 and a zero-crossing point.

When the freight structure and energy intensity remain unchanged, assuming that the average annual growth rate of freight turnover from 2017 to 2035 is 2.3%. The forecast results of freight energy consumption in 2035 are shown in Table 9.

Without changing the freight structure and energy intensity, China’s freight energy consumption will reach 210.54 million tons of standard coal in 2035, and the average annual growth rate of energy consumption from 2019 to 2035 will be 2.6%. Assuming that the energy consumption structure remains unchanged, carbon emissions will reach 1.034 billion tons. If so, the goal of energy conservation and emission reduction in China will not be achieved, and energy consumption will not peak in 2035.

5.3.2. Energy consumption forecast based on freight volume growth and energy intensity reduction

Freight energy consumption shows a downward trend from the perspective of the evolution of China’s freight energy consumption. Assuming that the future energy intensity continues to decline at the current trend, the freight energy intensity in 2035 is shown in Table 10.

Assuming that the freight structure remains unchanged, the growth of freight turnover is set at an average annual growth rate of 2.3%, and the energy consumption intensity is reduced as shown in Table 10, the forecast results of China’s freight energy consumption are shown in Table 11.

Table 11 shows that China’s freight energy consumption in 2035 will be reduced to 164.3829 million tons of standard coal, which is 22% lower than the forecast based on the increase in freight volume. Assuming that the energy consumption structure remains unchanged, carbon emissions will also decrease by 22% with the reduction of energy consumption.

5.3.3. Freight energy consumption forecast based on freight volume growth, energy intensity reduction, and freight structure optimization

Assuming that China’s freight structure in 2035 is the result predicted in this paper, combined with the above forecast of the freight volume and the reduction of unit energy consumption, the freight energy consumption of China in 2035 can be predicted. The prediction results are shown in Table 12.

Table 12 shows that China’s freight energy consumption in 2035 will be 132.3369 million tons of standard coal. In the case of optimizing the freight structure, compared with the 210.54 million tons of standard coal predicted based on the increase in freight volume before the optimization of the freight structure, and the 164.3829 million tons of standard coal predicted based on the increase in freight volume and the reduction in energy consumption, the reduction was 37% and 19%,
respectively. In terms of transportation mode, the energy consumption reduction comes mainly from road transportation, which is 44% and 29% lower than the previous road transportation energy consumption forecast. If the energy consumption structure remains unchanged, carbon emissions will also be reduced accordingly. In addition, this energy consumption is lower than the freight energy consumption of 139.1494 million tons of standard coal in 2019. That is, China can reduce energy consumption and achieve the goal of peaking and reducing carbon emissions in the freight industry through the optimization of the freight structure.

6. Conclusion and implications

This paper uses Markov’s theory to construct a freight transport structure evolution model to predict the evolution of freight structure after the COVID-19 and realize the optimization of freight structure. Based on the results of the evolution of the freight structure, a path optimization model of the freight structure is constructed to enable the freight structure to adjust to a reasonable structure. Finally, taking the evolution and optimization of China’s freight transport structure as an example, this paper predicts the evolution of China’s freight transport structure from 2020 to 2050. The forecast shows that the occurrence of the COVID-19 has made the sharing rate of truck freight higher, while the proportion of railway and waterway transportation has decreased, which has exacerbated the difficulty of adjusting the freight structure. Takes the results of the evolution of China’s freight transport structure in 2035 as the goal, a method to optimize the freight structure is proposed, which verifies the practicability and reliability of the freight structure route optimization model. To analyze the factors that affect the optimization of freight structure, this paper studies the influence of the growth rate of freight turnover and the growth rate of freight mode share on the optimization of freight structure. The simulation shows that the change in the growth rate of the freight turnover has little effect on the optimization of the freight structure, and the increase in the growth rate of the share of specific freight modes, especially railway and waterway transportation, is the key to the optimization of the freight structure. In this paper, the Markov chain model is applied to the forecast of freight structure, and the prediction results of the Markov chain are optimized by data smoothing, which further enriches the application scope of the Markov chain. From the perspective of route optimization, this paper realizes the method innovation of optimal control theory and proposes new ideas for the optimization of freight transport structure. The specific conclusions are as follows:

1. By adjusting the route, the freight structure can be optimized. The adjustment strategy is to give priority to the development of waterway and railway transport in five years, develop pipeline transport on the premise of ensuring the development of waterway and railway transport, and then promote the development of air transport around 2025. The growth rate of freight turnover is expected to reach about 6% annually by 2027, and then gradually reduce to about 4%. The growth rate of highway, waterway, railway and pipeline transport will be stable at about 2%.

2. In order to analyze the factors affecting the optimization of freight structure, this paper studied the influence of freight turnover growth rate and freight mode share growth rate on freight structure optimization. The simulation shows that the change of freight turnover has little impact on the optimization of freight structure, and the increase of the share of specific freight modes (especially railway and waterway transportation) is the key to achieve the optimization of freight structure.

3. The research on the prediction of freight energy consumption in 2035 showed that when the freight structure and energy consumption intensity are unchanged, the growth rate of freight energy consumption is equal to the growth rate of freight turnover, then China’s freight energy consumption in 2035 will be 210 million tons of standard coal and carbon emissions will be 1.034 billion tons; Considering the reduction of energy consumption intensity, China’s energy consumption will be reduced to 164 million tons of standard coal in 2035, and the carbon emission will be reduced 22% accordingly. Through the optimization of freight transport structure, China’s freight transport energy consumption in 2035 will be 132.3369 million tons of standard coal. This energy consumption is lower than that of 139.1494 million tons of standard coal in 2019, that is, through the optimization of freight transport structure, the goal of reducing energy consumption and carbon emissions can be achieved.

The evolution of freight structure is predicted under the assumption that China continues to implement the policies of “Road to Waterway” and “Road to Railway”. It has a certain idealized tendency and does not necessarily conform to the evolution of freight structure in reality. The freight structure optimization model is also based on theoretical analysis. Whether it can be realized or not also needs to consider the investment amount, location and other factors. Considering more realistic factors can further enhance the applicability of the model, which is the direction of future research.

Data availability

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

Declaration of competing interest

The authors declare that they have no conflicts of interest.

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