Article

Research on Freight Transportation Carbon Emission Reduction Based on System Dynamics

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Abstract: In order to solve the environmental protection problem of carbon emissions in the field of freight transportation, this article proposes to promote the transfer of road freight transportation to railway transportation within a reasonable range by levying carbon emission taxes. To propose an applicable solution, this paper establishes a comprehensive carbon emission system model in the field of road transportation and railway transportation to simulate a closed-loop system as comprehensively as a real transportation system, determines the system elements according to the actual situation, reasonably develops the model hypothesis scheme, and draws out the causal network. On this basis, the system flow diagram and corresponding structural equations are constructed, and the model parameters are estimated. Finally, the paper uses actual data to verify and simulate the system model. A reasonable carbon levy interval has been obtained, and the carbon levy within this interval can promote the transfer of road freight transportation to railway transportation, so as to achieve the purpose of decreasing total carbon emissions of road–rail transportation systems in an orderly way. The innovation of this paper is to construct the carbon emissions of the road–rail system systematically for the first time, and to conduct research and exploration of carbon levies on this basis.

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Keywords: carbon levy; road transportation; rail transportation; environmental protection

1. Introduction

The International Energy Agency (IEA) report shows that 23% of global carbon dioxide emissions come from the transportation industry, only under the electricity and thermal energy industry (Figure 1) [1]. In the carbon dioxide emissions generated by transportation activities, the carbon dioxide generated by the transportation carrier occupies a major share in the transportation process. At present, the main cargo transportation methods are road transportation, railway transportation, water transportation, and air transportation. While road transportation and railway transportation have a large volume, the service objects of the two transportation methods have a large overlap and increase with the transportation distance. The increase in carbon emissions per unit of road transportation is higher than that of rail transportation. Therefore, this could be considered through policies, investment, and other methods to guide the transfer of conditional parts of road freight transportation to railway freight transportation.

At present, energy conservation and reducing carbon emissions are hot topics on a global scale, and many scholars and institutions conduct research on these topics. Scholars have done a lot of work, such as explore the relationship between economic growth, carbon dioxide emissions, and energy consumption [2]. Some use a delayed payment strategy to reduce carbon emissions from supply chains [3]. Others do research to find if environmental innovation is useful for reducing carbon emissions [4,5]. The impacts of human capital on carbon emissions have also been identified [6]. Government and corporate policy guidance can also effectively reduce carbon emissions [7]. The optimization of transportation infrastructure can also have an effect on the reduction of carbon

emissions [8], and through effective energy management, carbon emissions can be controlled [9]. Combining multi-layer logarithmic mean Divisia index (LMDI) decomposition with hierarchical clustering has been used in emission reduction strategies [10]. Through systematic research on the consumption of renewable energy in developing countries, scholars have found ways to reduce carbon emissions [11] and conduct research on the regionality of carbon emissions through regional economic theory [12]. A simultaneous equation model and extended stochastic impacts by regression on population, affluence, and technology (STIRPAT) model based on the $I = P \times A \times T$ equation (IPAT) identity were applied and achieved positive results [13,14], and non-linear gray multi-variable models also have been considered [15]. At the same time, multi-angle research on urban carbon emissions has also been carried out [16]. The research of accounting for carbon emissions in the context of industrial transfer shows the industry impact [17]. Some scholars intend to innovate and improve materials in order to reduce carbon emissions [18]. On the other hand, others consider expanding trade openness and introducing external investment to solve the carbon emission problem [19,20]. Many scholars are using the autoregressive distributed lag (ARDL) cointegration, Granger causality analysis, and dynamic causality analysis to research carbon emissions [21,22]. Various industries also conduct research to reduce carbon emissions, such as cement production [23,24]. Some scholars are also concerned about the clean energy and sustainable development of the transportation industry [25].

Figure 1. Causality diagram.

This paper uses the method of system dynamics, and there have been many studies on this method in recent years. Some scholars have conducted in-depth discussions and research on transportation issues using the integrated methods of system dynamics and the analytic network process (ANP) [26,27]. System dynamics has also been applied to the sustainability research of urban development in recent years [28]. The development analysis of the digital platform also uses the method of system dynamics [29]. In natural sciences, the allocation of irrigation resources has also been resolved through system dynamics analysis [30]. System dynamics analysis methods are also widely used in the field of construction engineering and have been applied in the construction and demolition of old buildings [31,32]. Some scholars have used system dynamics models to simulate energy policies and obtained positive feedbacks [33]. System dynamics is also widely used in power grid systems [34]. In the medical field, scholars also use the system dynamics model to study the sharing of medical information and the medical supply chain [35]. A toolkit of designs for mixing discrete event simulation and system dynamics has also been researched and published by scholars [36].

First, some scholars have discussed and studied how to implement carbon tax among the population and gain the public's support for carbon tax [37,38]. Some organizations have analyzed the basis of the carbon tax [39]. Scholars in different fields have conducted research on the collection of carbon taxes from several aspects: the impact on social inequality and the impact on energy, the environment, and the economy [40,41]. One paper

determines the specific value of carbon tax based on the impact of different carbon taxes on carbon emissions [42]. In the field of consumption, some scholars analyze the impact of carbon tax on consumers and retailers from the perspective of revenue sharing and cost sharing [43,44]. There have been many studies on the specific measures of carbon tax collection in recent years. For example, a paper has described research on supply chain network design under an uncertain carbon tax [45]. Research on the economic and environmental integrated model of the multi-stage cold supply chain is ongoing [46]. Scholars use data envelopment analysis to determine the optimal carbon tax rate [47]. Researchers have discussed the impact of carbon tax on industrial production plans under the Industry 4.0 system [48]. Some scholars have optimized the supply chain path selection under the condition of carbon tax [49]. An off-design model to optimize a combined cooling, heating, power, and ground source heat pump (CCHP-GSHP) system considering carbon tax is given [50]. Some scholars have conducted research on supply chain cost-sharing contracts in the context of the carbon tax and have also conducted relevant discussions on the trading of emission rights [51,52]. Spanish scholars discussed the effect of additional taxes on heavy goods vehicles, and the result showed that the additional taxes did not cause freight volume changes or a shift of freight to alternative modes [53]. Italian scholars conducted an economic analysis of the road-to-rail transition at the policy level, and calculated the economic benefits of the policy [54].

Carbon emissions have had a great impact on the global climate and environment. As one of the industries with the greatest carbon emissions, the main trend of the transportation industry will be reducing carbon emissions in the future. In order to coordinate and promote the adjustment of transportation structure, it is an important measure to transfer part of the road freight volume to railway freight. Based on the above background, this paper focuses on roads and railways in the transportation industry, starting from the demand for road-to-rail transportation, and discusses environmental protection investment and carbon tax to increase the demand for road-to-rail transportation. Since this research aims at reducing the impact of carbon dioxide emissions in the road and railway system, it could be a useful resource to assist the government in improving the guidance policy. As the research of road-to-rail transportation does not involve the well-to-tank process, this paper only discusses the tank-to-wheel process in transportation systems.

2. Causality Analysis

2.1. System Element

There are nine system elements considered in this paper: the national economy, environmental investment in railway freight transportation, carbon dioxide emissions, the carbon tax, the road-to-rail freight demand, the incremental volume of railway freight, the decreasing volume of road freight, the railway freight rate, and the incremental railway transportation revenue. Their dimensions and measurement indicators are listed in Table 1 (Dmnl means Dimensionless).

Table 1. System element description.

System Element	Remark	Dimension
National economy	GDP	RMB 100 million
Environmental investment in railway freight transportation	Environmental investment in railway freight transport	RMB 100 million
Carbon dioxide emissions	Total CO ₂ emissions from road and rail	10,000 tons
Carbon levy	Carbon levy rate	Dmnl
Road-to-rail freight demand	Road-to-rail demand	Ton-kilometer
Incremental volume of railway freight	Supply and demand ratio of transport efficiency	Ton-kilometer
Decreasing volume of road freight	Supply and demand ratio of transport efficiency	Ton-kilometer
Railway freight rate	Average railway freight rates	Yuan
Incremental railway transportation revenue	Income	(RMB)/Ton-kilometer
		RMB 100 million

2.2. Model Assumption

The model in this paper needs to make the following assumptions to ensure the operation of the model:

1. That macro factors are stable, the indicators develop smoothly, and no major emergency changes cause a certain indicator to change away from the objective growth rate.
2. That the overall development of freight transportation is stable, and the changes in freight volume of other transportation methods will not affect the road–rail freight system studied in this paper.
3. The carbon emission calculation of railway freight transportation only considers the mobile terminal and does not consider the carbon emissions of fixed equipment. Its calculation selects carbon dioxide as an indicator, without considering the indirect emissions of electricity.

2.3. Causality

According to the reality analysis of the causal relationship between the elements of the road-rail system, the causal relationship is shown in Figure 2. The arrows indicate the causal relationship between two elements. The “+” sign in the figure indicates a positive effect, and the change trends of the elements on both sides of the arrow are consistent. The “-” sign indicates a negative effect, and the changing trends of the elements on both sides of the arrow are opposite.

Figure 2. Causality diagram.

In the causality diagram of this paper, the main feedback relationship includes the following three parts.

1. National economy $\xrightarrow{+}$ Environmental investment in railway freight transportant $\xrightarrow{-}$ Carbon dioxide emissions $\xrightarrow{+}$ Carbon levy $\xrightarrow{+}$ Road-to-rail freight demand $\xrightarrow{+}$ Incremental volume of railway freight $\xrightarrow{+}$ Incremental railway transportation revenue $\xrightarrow{+}$ National economy. This is negative feedback. Carbon emissions have greatly affected the global climate and environment. Therefore, the government will adjust environmental protection investment to balance environmental problems. The government will give a certain amount of environmental protection investment by

industry every year to deal with corresponding environmental problems. With the continuous improvement of the national economy, the government's investment in the environmental protection of railway freight will also increase, so the corresponding investment in governance will increase, and carbon dioxide emissions will decrease. In addition, in order to reduce carbon emissions, the government levies a carbon tax based on carbon dioxide emissions. Therefore, compared with road carbon emissions, the railway carbon emissions are relatively low. This will encourage cargo owners to switch from road transportation to railway transportation. So, the demand for road-to-rail freight increases. Considering the freight rates to be invariable will promote the growth of railway freight transport revenue, thereby raising the level of the national economy.

2. Carbon dioxide emissions $\rightarrow$ Carbon levy $\rightarrow$ Road-to-rail freight demand $\rightarrow$ Incremental volume of railway freight $\rightarrow$ Decreasing volume of road freight $\rightarrow$ Carbon dioxide emissions. This is negative feedback. The government levies a carbon tax based on carbon dioxide emissions. Therefore, compared with the road carbon levy, the railway carbon levy is relatively low. This will encourage cargo owners to switch from road transportation to railway transportation. Therefore, the demand for railway freight transportation will increase, and will promote the reduction of freight transportation, so carbon dioxide emissions will be reduced.
3. Carbon dioxide emissions $\rightarrow$ Carbon levy $\rightarrow$ Road-to-rail freight demand $\rightarrow$ Incremental volume of railway freight $\rightarrow$ Carbon dioxide emissions. This is positive feedback. Similar to the second feedback relationship, the government levies a carbon tax based on carbon dioxide emissions. Therefore, compared with the road carbon levy, the railway carbon levy is relatively low. This will encourage cargo owners to switch from road transportation to railway transportation. Therefore, the demand for railway freight transportation will increase. As a result, carbon dioxide emissions will increase.

However, according to the comparative data of carbon dioxide emissions from roads and railways in previous years, because the railway is a cleaner mode of transportation, the carbon dioxide emissions, after the feedback of A and B are superimposed, on the whole show a decreasing trend.

3. System Flow Diagram and Structural Equation

3.1. Variable Description

The variable information used in this paper is shown in Table 2.

Table 2. Variable description.

Variable	Abbreviation	Dimension	Remark
GDP	GDP	RMB 100 million	Gross domestic product
Economic growth	EG	RMB 100 million	
Economic reduction	ER	RMB 100 million	
Economic growth coefficient	EGC	Dmnl	Excluding the growth value contributed by road-to-rail income to GDP
Railway freight environmental protection investment	RAFI	RMB 100 million	Environmental pollution control investment allocation by industry
Rail freight environmental protection investment coefficient	RAFIC	Dmnl	Environmental pollution control investment used for environmental pollution control to GDP ratio
Incremental railway transportation revenue	IRR	RMB 100 million	Calculated according to the railway average freight rate
Railway freight rate	RFR	Yuan (RMB)/t·km	
Freight volume	FV	10 ⁸ t·km	

Table 2. *Cont.*

Variable	Abbreviation	Dimension	Remark
Road-to-rail freight volume demand	TVD	$10^8 \text{ t} \cdot \text{km}$	
Road-to-rail transfer ratio	TR	Dmnl	
Incremental volume of railway freight	IVRA	$10^8 \text{ t} \cdot \text{km}$	
Diesel locomotive volume	DLV	$10^8 \text{ t} \cdot \text{km}$	
Electric locomotive volume	ELV	$10^8 \text{ t} \cdot \text{km}$	
Proportion of diesel locomotives	PDL	Dmnl	According to the proportion of diesel locomotives and electric locomotives on the railway
Diesel locomotive unit energy consumption	DLUC	$\text{t}/10^4 \text{ t} \cdot \text{km}$	
Electric locomotive unit energy consumption	ELUC	$\text{kWh}/10^4 \text{ t} \cdot \text{km}$	
Diesel locomotive energy consumption	DLEC	10^4 t	
Electric locomotive energy consumption	ELEC	kWh	
Decreasing volume of road freight	DVRO	$10^8 \text{ t} \cdot \text{km}$	Equal to the incremental volume of railway freight
Diesel vehicle energy consumption	DVEC	10^4 t	
Diesel vehicle unit energy consumption	DVUC	$\text{t}/10^4 \text{ t} \cdot \text{km}$	
Diesel locomotive emission coefficient	DLEMC	Dmnl	
Electric locomotive emission coefficient	ELEMC	Dmnl	
Diesel vehicle emission coefficient	DVEMC	Dmnl	
Carbon dioxide emissions	CDE	10^4 t	
Emission reduction	ED	10^4 t	
Emission growth	EMG	10^4 t	
Environmental protection investment		$\text{RMB } 10^4$	
reduction emission coefficient	EPRC	$\text{t}/100 \text{ million}$	
Carbon levy rate	CLR	Dmnl	

3.2. System Flow Diagram

According to the relationship between various elements in the system, the complete system flow diagram is shown in Figure 3.

3.3. Structural Equation

The structural equation in this paper is used to describe the quantitative relationship between state variables, rate variables, and auxiliary variables. The state variables, rate variables, and auxiliary variables in the system dynamics model correspond to the L equation, R equation, and A equation, respectively.

The L equation includes:

$$GDP.k = GDP.j + DT(EG.jk - ER.jk) \quad (1)$$

$$CDE.k = CDE.j + DT(EMG.jk - ED.jk) \quad (2)$$

The R equation includes:

$$EG.jk = GDP.j \times EGC.j + IRR.j \quad (3)$$

$$ER.jk = RAFI.j \quad (4)$$

$$EMG.jk = ELEM C \times ELEC.k + DLEM C \times DLEC.jk \quad (5)$$

$$ED.jk = DVEM C \times DVEC.k + EPRC \times RAFI.j \quad (6)$$

The A equation includes:

$$RAFI.k = GDP.k \times RAFIC \quad (7)$$

$$IRR.k = RFR \times IVRA.k \quad (8)$$

$$DVRO.k = IVRA.k \quad (9)$$

$$DLV.k = PDL.k \times IVRA.k \quad (10)$$

$$ELV.k = IVRA.k - DLV.k \quad (11)$$

$$DLEC.k = DLV.k \times DLUC.k \quad (12)$$

$$ELEC.k = ELV.k \times ELUC.k \quad (13)$$

$$DVEC.k = DVRO.k \times DVUC.k \quad (14)$$

$$TCD.k = FV.k \times TR.k \quad (15)$$

$$IVRA.k = TVD.k \quad (16)$$

where j and k are time nodes. $Variable.k$ represents the current value of the variable. $Variable.j$ represents the past value of the variable, $Variable.jk$ represents the change in value between j to k of the variable. DT represents the timeline.

In addition to the above equations, the diesel locomotive emission coefficient, electric locomotive emission coefficient, and diesel vehicle emission coefficient are provided in Table 3. The diesel locomotive unit energy consumption, electric locomotive unit energy consumption, and diesel vehicle unit energy consumption are provided in Table 4. The railway freight rate, rail freight environmental protection investment coefficient, and environmental protection investment reduction emission coefficient are determined as constants based on the data of previous years.

Table 3. Carbon dioxide emission coefficient of various energy sources.

	Combustion Value (kJ/kg)	Emission Factor (kgCO ₂ /TJ)	Emission Coefficient (kgCO ₂ /kg)
Diesel fuel	42,652	74,100	3.161
Electricity	—	—	0.604
Petrol	43,070	69,300	2.988

Table 4. Energy efficiency of different modes of transportation.

Year	Railway		Road	
	Diesel Fuel (kg/10 ⁴ t·km)	Electricity (kWh/10 ⁴ t·km)	Petrol (L/10 ² t·km)	Diesel Fuel (L/10 ² t·km)
2001	25.7	113.1	8	6
2002	25.9	110.8	8	6
2003	25.4	110	8	6
2004	25	111.2	8	6
2005	24.6	111.8	8	6.3
2006	24.3	110	7.9	6.5
2007	24.6	109.5	8	6.7
2008	24.9	110.6	8	6.9
2009	25.2	107.9	8	7.1
2010	26.4	102.4	8	7.3
2011	26.5	100.6	8	7.3
2012	26.8	102.1	7.9	7.4
2013	27.3	101.9	7.8	7.4
2014	27.2	103.3	7.8	7.3

In addition, freight volume, economic growth coefficient, proportion of diesel locomotives, diesel locomotive unit energy consumption, electric locomotive unit energy consumption, and diesel vehicle unit energy consumption are set as table functions related to time. Data were obtained from the National Bureau of Statistics of China.

3.4. Model Parameter Estimation

Model parameters and data sources are the main official data from the National Bureau of Statistics of China. The uncollected data are predicted by regression analysis.

3.4.1. Main Parameters

1. Carbon dioxide emissions Carbon dioxide emission coefficients of various energy sources are shown in Table 3.
2. Energy efficiency Energy efficiencies of different modes of transportation are shown in Table 4.
3. Freight volume Freight volumes were extracted from the National Bureau of Statistics of China [55], and are listed in Table 6. What needs to be explained about the freight volumes is that the data coming from freight surveys are often inconclusive. A study by Italian scholars showed the problems in describing the modal split in the freight models based on stated preferences (SPs) and revealed preferences (RPs) [56]. Indian scholars suggested that this can be improved by designing effective survey instruments, data collection strategies to improve response rates, etc. [57].
4. Proportion of diesel locomotives

Proportions of diesel locomotives are listed in Table 5.

Table 5. Proportion of diesel locomotives.

Year	Proportion	Year	Proportion
2000	0.71552	2007	0.648663
2001	0.708659	2008	0.636883
2002	0.709282	2009	0.608359
2003	0.697334	2010	0.547223
2004	0.693079	2011	0.515314
2005	0.684777	2012	0.488051
2006	0.67132	2013	0.456314

Table 6. Freight volume.

Year	Freight Volume (10 ⁸ t·km)	Year	Freight Volume (10 ⁸ t·km)
2000	44,320.5	2010	141,837.4
2001	47,709.9	2011	159,323.6
2002	50,685.9	2012	173,804.5
2003	53,859.2	2013	168,013.8
2004	69,445	2014	181,667.7
2005	80,258.1	2015	178,355.9
2006	88,839.85	2016	186,629.5
2007	101,418.8	2017	197,372.7
2008	110,300	2018	204,686.2
2009	122,133.3	2019	199,287.1

3.4.2. Other Parameters

The rest of the parameters are listed in Table 7.

Table 7. Proportion of diesel locomotives.

Parameter	Value	Remark
RFR	0.1551	-
RAFIC	0.0001	Calculated according to the share ratio of the railway transportation
EPRC	68.9	-

4. Model Checking and Simulation Analysis

4.1. Model Checking

4.1.1. Structural Suitability Test

1. Dimensional consistency test The main data of the variables in this paper were obtained from historical statistical data. The data are true and valid. VENSIM software was used to check the dimensional consistency and pass the test.
2. Extreme condition test This part takes the GDP rate equation as an example. If the growth rate is set to 0, only railway transportation revenue growth caused by the road-to-rail transition will be achieved. The simulated output GDP curve (Test1 curve) has a gentle growth, which is consistent with the actual situation, as shown in Figure 4.

Figure 4. Extreme condition test.

4.1.2. Correlation Test

It is necessary to check the established system model and judge whether the system is effective by comparing the simulated data of the system with the actual data. This part takes the GDP as an example for a consistency comparison, and the increased transportation income of the road-to-rail transportation is adjusted to 0 to obtain simulation data. As shown in Table 8, the error of the indicator data is within the acceptable range. Error comparisons are listed in Table 8. Using SPSS software for analysis, the Pearson correlation coefficient of the two sets of data is 0.999, and the significance level is less than 0.01, passing the correlation test.

Table 8. Error comparison.

Year	Actual Data	Simulation Data	Error	Year	Actual Data	Simulation Data	Error
2001	110,863	110,863	0	2011	487,940	455,609	−0.06626
2002	121,717	122,563	0.006951	2012	538,580	539,431	0.00158
2003	137,422	134,562	−0.02081	2013	592,963	595,415	0.004135
2004	161,840	151,924	−0.06127	2014	643,563	655,536	0.018604
2005	187,319	178,919	−0.04484	2015	688,858	711,475	0.032833
2006	219,439	207,087	−0.05629	2016	746,395	761,563	0.020322
2007	270,092	242,596	−0.1018	2017	832,036	825,229	−0.00818
2008	319,245	298,595	−0.06468	2018	919,281	919,552	0.000295
2009	348,518	352,934	0.012671	2019	990,865	1,016,750	0.026124
2010	412,119	385,296	−0.06509				

4.2. Simulation Analysis

In this system dynamics model, carbon dioxide emissions refer to the balanced emissions in an environment where only road transportation and railway transportation are used, without considering the impact of other transportation methods and social factors on carbon emissions.

4.2.1. Initial State

To better explore the guiding role of the policy, this paper sets the initial state carbon levy rate of the system to 0, and the environmental protection investment of railway freight to 0. The carbon dioxide emissions are increasing year by year.

4.2.2. Railway Freight Environmental Protection Investment

Set three states:

State 1: Initial state.

State 2: Increase the railway freight environmental protection investment, with an investment coefficient of $5.6e + 07$ (obtained based on historical data).

State 3: Add railway freight environmental protection investment, with an investment coefficient of $7.6e + 07$.

From the curves in Figure 5 of the comparison of the three states, it can be seen that increasing environmental protection investment can reduce carbon dioxide emissions to a certain extent. This is also the reason why the government has always insisted on using funds for environmental protection management. The carbon dioxide emissions are reduced as the investment coefficient increases.

Figure 5. Carbon dioxide emissions in different railway freight environmental protection investment scenarios.

Therefore, increasing railway freight environmental protection investment is an effective policy to reduce carbon emissions in the transportation industry.

4.2.3. Carbon Levy

Since no unified carbon levy standard documents have been issued at present, for comprehensive consideration and pilot applications, the initial carbon levy rate is set to 0.1. When carbon dioxide emissions are less than 200 million tons, the carbon levy rate can be appropriately reduced.

Set four states:

State 1: Initial state.

State 1: Carbon levy rate 0.1.

State 1: Carbon levy rate 0.2.

State 1: Carbon levy rate 0.2.

It can be seen from Figure 6 that the levy of carbon can promote the growth of the demand for road-to-rail transportation, and enterprises will change the mode of transportation due to transportation cost considerations. At the same time, it can be seen from Figure 7 that the carbon tax has a certain impact on carbon dioxide emissions. However, when the carbon levy rate is 10% and 20%, carbon dioxide emissions show a downward trend, but when the carbon tax rate is 30%, carbon dioxide emissions increase instead. This shows that the higher carbon levy rate is not better, it needs to have a certain limit.

Figure 6. Road-to-rail freight volume demand with different carbon levy rates.

Figure 7. Carbon dioxide emissions with different carbon levy rates.

5. Discussion

From our paper's analysis, it can be seen that current policies, such as increasing investment in environmental pollution treatment by industry, have a good effect on reducing carbon emissions in the transportation industry. However, it is also necessary to understand that to further implement investment and increase governance efforts, not only should analysis of investment theory be used, it also needs to be improved in combination with practice.

In addition, the formulation of transportation carbon tax is still in the theoretical stage in most regions, and no specific policy formulation or implementation has been carried out. From the simulation experiment in our research, we can also see that there are certain difficulties in determining the carbon levy rate, and it can be concluded that a higher carbon levy rate may not be better. Using the simulation and calculation methods proposed in our paper, the final reasonable range of the carbon tax rate should be between 10 and 20%. Exceeding this range will cause the transfer of short-distance transportation on roads to railway transportation. This situation will increase the carbon emissions of railway transportation and increase the carbon emissions of the entire system. Therefore, follow-up carbon tax research is still worthy of further discussion.

The system dynamics model we studied has been established and its applicability has been verified. In future research, this model can be used to quickly analyze the changes in the transportation–environment system. It is not only limited to the study of road-to-rail transition, but also provides a tool for other studies within the framework of the system.

In the past year, a road-to-rail transition has been widely carried out at the policy level in China, and all data are complete. It is expected that the carbon levy policy will also be implemented in the next 2–3 years. The specific implementation effect will appear, which can test and verify the model in our research. It is a very good research material for the carbon levy policy and environment.

As one of the most beneficial measures to combat global warming, the proposal of a carbon levy is welcomed all over the world. For example, resolution 763 proposed by a cross-party panel of the US House of Representatives in January 2019 paved the way for the carbon levy. As a market-driven tool, carbon levies have different policy guidelines in different countries. Countries take into account factors such as GDP level, the ratio of railway, road, and water freight, and the difference between state-owned and private-owned transportation. The ranges of the carbon levy ratio will be different. These can be simulated and calculated by the system dynamics model proposed in our research. For example, we substitute Japan's GDP data into this model, for example, and find that the sensitivity to changes in transportation volume caused by the carbon levy decreases. However, due to the lack of data on other factors, it is impossible to conduct further

research. We hope that scholars from other countries can conduct further research or collaborations.

This article has two major contributions:

- Establishing a complete road–rail freight volume–carbon emissions system dynamic relationship system which can be used in research in related fields.
- Analyzing the impact of environmental protection investment on freight volume transfer and carbon emissions.

In further research, the authors will consider water transportation in the research system based on the current road–rail transportation system framework, making the research more complete. The specific reasonable transportation tax rate of carbon will be researched more accurately and deeply.

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