

Optimal Design of Truck Carbon Emissions Based on System Dynamics in the Context of Low-Carbon Initiatives

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Abstract:

Currently, environmental pollution and energy shortages are increasingly becoming prominent issues. In the transportation sector, carbon emissions from road freight account for over 60% of the total carbon emissions from road traffic. Electric trucks, with their low carbon emissions and energy consumption, have become a key measure to achieve China's carbon peak and carbon neutrality goals. To address the problem of carbon emission reduction in freight transportation, this study takes Guangdong Province as an example. It conducts an in-depth analysis of the causal relationships among its population economy, vehicle development, and carbon emission subsystems. A system dynamics model for freight transportation carbon emissions is established, and four emission reduction scenarios are set up. Using Vensim software for simulation, the carbon emission reduction potential of electric trucks under different policies is analyzed. The results indicate that controlling fuel trucks is the most effective emission reduction measure, while the significant effects of promoting electric trucks require a longer time period to materialize. The effectiveness of comprehensive multi-scenario control is superior to that of single-policy scenarios. The system dynamics model for freight transportation carbon emission reduction constructed in this study can provide a reference for Guangdong Province's efforts in reducing transportation carbon emissions.

Keywords:

Electric Trucks, System Dynamics, Scenario Analysis, Carbon Emissions

1. Introduction

In recent years, global attention has focused on reducing emissions in transportation due to climate change, pollution, and energy shortages. China's 20th Congress report emphasized advancing clean, low-carbon transport transformation [1]. As a foundational industry, transport is the third-largest carbon emitter, following industry and construction, with road transport accounting for over 80% of sector emissions and road freight contributing more than 60% [2]. Under the "Dual Carbon" strategy and "China VI" standards, optimizing road freight emissions has become a research priority [3].

Guangdong Province, a major economic hub, has the highest transport carbon emissions in China. To meet its 2030 carbon peak goal, Guangdong has intensified emission controls, releasing plans to build a low-carbon transport system [4]. Given

its leadership in low-carbon innovation, studying Guangdong's freight carbon reduction offers insights for nationwide heavy-duty vehicle decarbonization[5].

Existing research on internal combustion engine trucks focuses on route optimization and emission strategies, while studies on electric trucks (ETs) emphasize energy and policy aspects. However, limited research addresses ETs' role in freight carbon reduction, with most studies concentrated on the broader electric vehicle sector [6].

This study develops a System Dynamics model for Guangdong's freight carbon emissions, incorporating population, economy, vehicle, and emission subsystems. Scenario analysis evaluates ET carbon reduction potential under different policies, providing targeted recommendations to advance low-carbon freight development [7].

2. Design of a System Dynamics Model for Freight Transport Carbon Emissions

2.1. Model system boundary

When constructing a system dynamics model, establishing system boundaries is crucial, as it defines the scope of the system involved in the model and its interaction with the external environment. Given the multitude of relevant factors involved in the research subject, it is essential to clearly delineate system boundaries based on the research question and modeling objectives before proceeding with the modeling process, thereby eliminating variables unrelated to the research goals.

Based on the availability of data, the research subjects of this design primarily refer to cargo vehicles with a total mass not exceeding 4.5 tons. These vehicles include two types: one is pure electric trucks, which are powered by rechargeable batteries and driven by electric motors. The models involved include light enclosed trucks (micro vans) and light box trucks (light-duty trucks). Due to their mature technology, they are now widely used in the delivery industry and are simply referred to as "electric trucks." The other type is mild-duty fuel-powered trucks, which are driven by internal combustion engines and are called "fuel trucks." For medium and heavy-duty fuel-powered trucks with a total mass exceeding 4.5 tons, they are classified as other trucks and are not within the scope of this design discussion.

2.2. Basic assumptions of the model

The systematic impact of freight transportation in Guangdong Province on carbon emissions includes three major subsystems: population economy, vehicle development, and carbon emissions. There are close interactions and mutual influences among these subsystems[8]. This design relies on the principles of system dynamics to explore the degree of carbon reduction in freight transportation under the policy background of promoting the development of electric trucks and restricting the development of fuel trucks, and then propose strategies and suggestions to promote the development of China's freight industry towards a clean and low-carbon direction[9]. Considering the complexity of the carbon emission system for freight transportation, many related factors may not be covered during modeling. Therefore, in order to explore the impact of fuel trucks and electric trucks on carbon emissions, this design extracts key structures from complex systems and analyzes them based on the following assumptions:

- (1) Ignore the influencing factors outside the system boundary;

- (2) Assuming there will be no significant policy changes in the short term;
- (3) The social economy and population are showing a sustained and stable growth trend;
- (4) Assuming zero emissions from electric trucks, only the carbon emissions from fuel trucks are considered, without taking into account the carbon emissions during the electricity production process;
- (5) Assuming that 2013-2015 is the cultivation period for the promotion of electric trucks, consider 2016 as the stage of large-scale application of electric trucks;
- (6) Other trucks with a total weight exceeding 4.5 tons, although not included in the study vehicles, are included in the statistical data of the yearbook. Therefore, the vehicle development subsystem includes relevant data for this type of vehicle.

2.3. System causality

By analyzing the causal relationship of the population economic subsystem, it can be concluded that an increase in GDP can drive urban construction and the growth of residents' income, thereby enhancing urban attractiveness and promoting an increase in the total population[10]. With the increase of population, urban development will also be further promoted, thereby driving GDP growth. In this subsystem, GDP is regarded as one of the main factors promoting the overall growth of social interests, therefore, its sustained and stable growth is crucial for the smooth operation of the socio-economic system.

By analyzing the causal relationship of the vehicle development subsystem, it can be concluded that population growth directly drives the growth of freight demand. Therefore, the total number of trucks and the number of newly added and updated trucks have also increased accordingly. Driven by this overall increase, the sales and market share of electric trucks have also been boosted. The government's policy support for electric trucks and restrictions on fuel trucks have further enhanced the market attractiveness of electric trucks, accelerated the growth of electric truck sales, and limited the increase of fuel trucks. Ultimately, these factors work together to gradually increase the market share of electric trucks in the truck industry.

By analyzing the causal relationship of the carbon emission subsystem, it can be concluded that the improvement of the national economic level will lead to an increase in the total freight volume. However, due to the significant energy consumption and carbon emissions generated during the use of fuel trucks, this will exacerbate environmental pollution and thus restrict the development of the national economy. With the improvement of urban economic level, the government can increase the attractiveness of electric trucks and impose restrictions on fuel trucks through policy regulation, promote more consumers to purchase electric trucks, and thus curb the increase of fuel trucks, gradually reducing carbon emissions in freight transportation. In the carbon emission subsystem, enhancing the attractiveness and ownership of electric trucks to reduce the market share of traditional fuel trucks is a key measure that can reduce the overall carbon emissions of freight transportation, promote sustainable development of the ecological environment and urban economy.

2.4. Model Variables and Equations

- (1) Energy consumption calculation model: The calculation parameters for the energy consumption of road motor vehicles are the number of different types of motor

vehicles, the average annual mileage of different types of vehicles, and the energy consumption per hundred kilometers of various types of vehicles. The energy consumption calculation model is shown in equation (2-1):

$$EC_{ij} = P_{ij} \times VKT_i \times FC_{ij} \quad (2-1)$$

In the formula, is the energy consumption of fuel for motor vehicles (measured in standard coal), in millions of tons; The inventory of fuel for motor vehicles, vehicles; For the average annual mileage of motor vehicles, in kilometers; for the energy consumption per hundred kilometers of fuel for motor vehicles, in kilometers, MJ/100km.

(2) CO₂ emission calculation model: The calculation parameters for CO₂ emissions from road vehicles are energy consumption and CO₂ emission factors. The CO₂ emission calculation model is shown in equation (2-2):

$$CE = EC_{ij} \times EF_j \quad (2-2)$$

In the formula, represents the CO₂ emissions of road vehicles, in 10000 tons; The energy consumption of fuel for motor vehicles (measured in standard coal), in millions of tons; For the CO₂ emission factor of fuel like substances, kg/km.

2.5. Model Verification

Within a certain range, the driving restriction coefficient of gasoline trucks is negatively correlated with the carbon emissions of gasoline trucks, while within a certain range, the price of electric trucks is positively correlated with the carbon emissions of gasoline trucks. Therefore, this design adopted two variables, the limit coefficient of fuel trucks and the price of electric trucks, for sensitivity analysis of the model. The analysis results are shown in Figure 1.

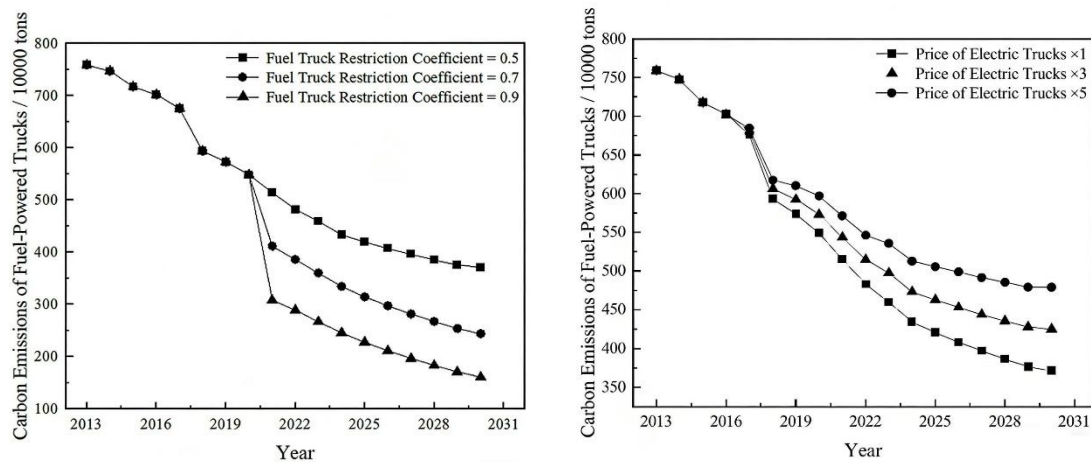


Figure 1. Sensitivity test of dynamic model of freight transportation system in Guangdong Province from 2013 to 2030.

In order to evaluate the accuracy of the model, the population and GDP of Guangdong Province were selected as test variables to test the accuracy of the model. The relevant values and errors are shown in Table 1. According to Table 1, the inspection error rate remains below 10%, with a very small number of errors slightly exceeding 10%. This indicates that the model has high accuracy and reliability and can be used for model emission reduction scenario analysis.

Table 1. Accuracy Test Results of Guangdong Freight Transportation System Dynamics Model.

Year	Population/10000 people			GDP per billion yuan		
	True value	Simulated value	Error/%	True value	Simulated value	Error/%
2013	11270.00	11270.00	0.00	62503.41	62503.41	0.00
2014	11489.00	11343.50	1.27	68173.03	67774.30	0.58
2015	11678.00	11417.40	2.23	74732.44	73016.00	2.30
2016	11908.00	11491.90	3.49	82163.22	78811.00	4.08
2017	12141.00	11566.80	4.73	91648.73	84673.00	7.61
2018	12348.00	11642.20	5.72	99945.22	90972.90	8.98
2019	12489.00	11718.10	6.17	107986.92	97111.40	10.07
2020	12624.00	11794.50	6.57	111151.63	103083.00	7.26

3. Prediction and Scenario Simulation

3.1. Emission Reduction Scenario Design

After constructing and validating a system dynamics model based on data from Guangdong Province, this design simulates different policy effects by adjusting certain variables in the model, and then analyzes the carbon emission reduction effect of freight transportation in Guangdong Province from 2020 to 2030. The setting of emission reduction scenarios is based on relevant literature and local policies, including “controlling fuel trucks (CFT)”, “developing electric trucks (DET)”, “promoting truck renewal (PTR)”, and “improving energy efficiency (IEE)”. This design takes 2020 as the base year to analyze the carbon emission reduction potential of freight transportation in Guangdong Province under different policy scenarios.

3.2. Single scenario control

On the basis of the baseline scenario, this design analyzed the effect of a single emission reduction scenario, as shown in Figure 2.

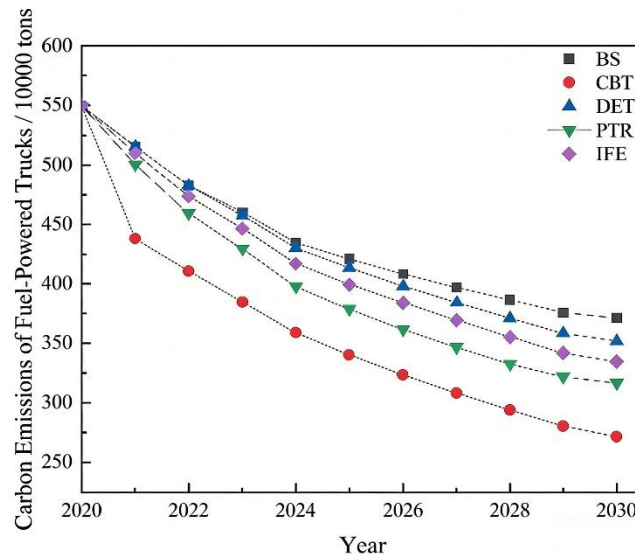


Figure 2. Carbon emissions of freight transportation in Guangdong Province under a single scenario.

Compared with the baseline scenario, the four emission reduction scenarios have to varying degrees controlled the growth of carbon emissions from freight transportation in Guangdong Province. Especially in the CFT scenario of controlling the travel of

fuel trucks (controlling fuel trucks) and the PTR scenario of updating vehicles by increasing scrap rates (promoting truck renewal), the emission reduction effect is more significant. By 2030, these two scenarios are expected to reduce emissions by 1.0012 million tons and 5.487 million tons respectively compared to the baseline scenario, with emission reduction rates of 26.95% and 14.77%. The DET scenario, which focuses on increasing the traffic volume of fuel trucks (developing electric trucks), has relatively weak emission reduction effects. It is expected to reduce emissions by 192600 tons by 2030, with a reduction rate of 5.18%.

3.3. Dual scenario control

To further explore the carbon reduction effect of the combination scenario, this design paired and combined four single scenarios to evaluate the carbon reduction effect of the dual scenario combination. The results are shown in Figure 3.

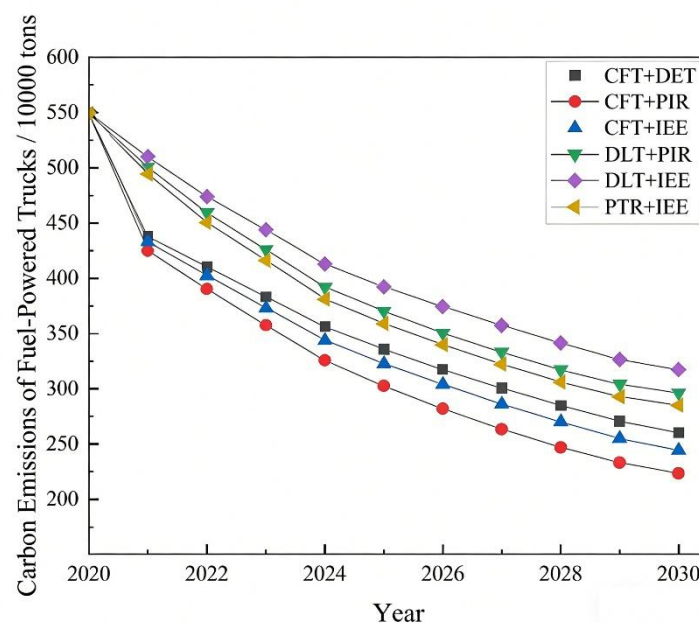


Figure 3. Carbon emissions of freight transportation in Guangdong Province under dual scenarios.

In a single scenario, although the carbon emissions from freight transportation in Guangdong Province have decreased from 2020 to 2030, the reduction in emissions is not significant. However, under dual scenario control, the carbon emissions from freight transportation in Guangdong Province significantly decreased during the study period. Among them, the scenario combination of controlling fuel trucks (CFT) and promoting truck renewal (PTR) has the best effect, and it is expected to reduce emissions by 1.4772 million tons by 2030, with a reduction rate of 39.75%. Next is the scenario combination of controlling fuel trucks (CFT) and improving energy efficiency (IEE), with an expected emission reduction of 1.2697 million tons and a reduction rate of 34.17%.

4. Conclusions

This design is based on the principle of system dynamics to construct a system dynamics model of carbon emissions in freight transportation in Guangdong Province, aiming to analyze the carbon reduction effect of the development of the electric truck industry under different policy influences. This design selects the limit coefficients of

electric and fuel trucks as key parameters for adjusting traffic policies, and takes into account the truck scrap rate and carbon emission factors. Calculate the carbon emissions of freight transportation in Guangdong Province from 2013 to 2020 through system dynamics modeling, and use scenario analysis to predict the carbon emissions from 2020 to 2030. Draw the following conclusion:

(1) Compared to the baseline scenario, the emission reductions for the four emission reduction scenarios of controlling fuel trucks, developing electric trucks, promoting truck renewal, and improving energy efficiency in 2030 are 1.0012 million, 192600, 548700, and 367500 tons, respectively. Under single scenario control, the carbon emission reduction of freight transportation in Guangdong Province has not yet reached 30% in the next decade, with only a slight decrease, which is consistent with the research conclusion of Gao Yongling et al.

(2) At least two emission reduction scenarios are needed for transportation in Guangdong Province to achieve a significant decline by 2030. Under dual scenario control, the most effective emission reduction combination is to control fuel trucks and promote truck renewal. It is expected that by 2030, this combination will reduce carbon emissions by 1.4772 million tons, with a reduction rate of 39.75%; Under the three scenario control, the optimal emission reduction combination is to control fuel trucks, improve energy efficiency, and promote truck renewal. Compared with the baseline scenario, this combination is expected to reduce emissions by 1.6986 million tons by 2030, with an emission reduction rate of 45.71%.

(3) The carbon reduction effect of controlling fuel trucks is the most significant, while the development of electric trucks has slightly less effectiveness, and its obvious effects may take a longer period of time to be reflected.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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