



Effect of urban traffic-restriction policy on improving air quality based on system dynamics and a non-homogeneous discrete grey model

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Abstract

With the acceleration of urbanization, traffic congestion and vehicle exhaust pollution are becoming increasingly serious problems. Focusing on the problem of urban pollution from vehicle exhaust, this study used system dynamics to establish an urban congestion mitigation and emission-reduction management model. Specifically, a nonlinear function that integrates system dynamics and a non-homogeneous discrete grey model (SD-NDGM) was used to construct an algorithm, which improved the accuracy of the model. Thereafter, the mid- and long-term effects of the restriction policy were explored. The main findings from dynamic model simulations were as follows: All types of restrictions alleviated traffic congestion to varying degrees, but “odd and even” restrictions had more obvious effects, with an average annual reduction rate of 43.53% in the number of motor vehicle trips. The driving-restriction policy had a time effect, significantly reducing the number of vehicle trips in the short term. However, it could have negative effects in the long term (e.g., agglomeration effect, emission-reduction paradox), and it does not fundamentally solve traffic and environmental problems. Thus, it could only be used as a phased policy, not a long-term measure. The purchase-restriction policy controlled excessive increases in the number of private cars, but it had little effect in terms of solving environmental problems. Compared with a single policy, the combination of public-transport development and driving-restriction policy not only reduced traffic congestion, air pollution, and air quality health indexes by 29.13%, 52.63%, and 54.63%, respectively, but also improved environmental carrying capacity by 294.26%. A combined approach can therefore be said to have certain benefits for society, health, and the environment.

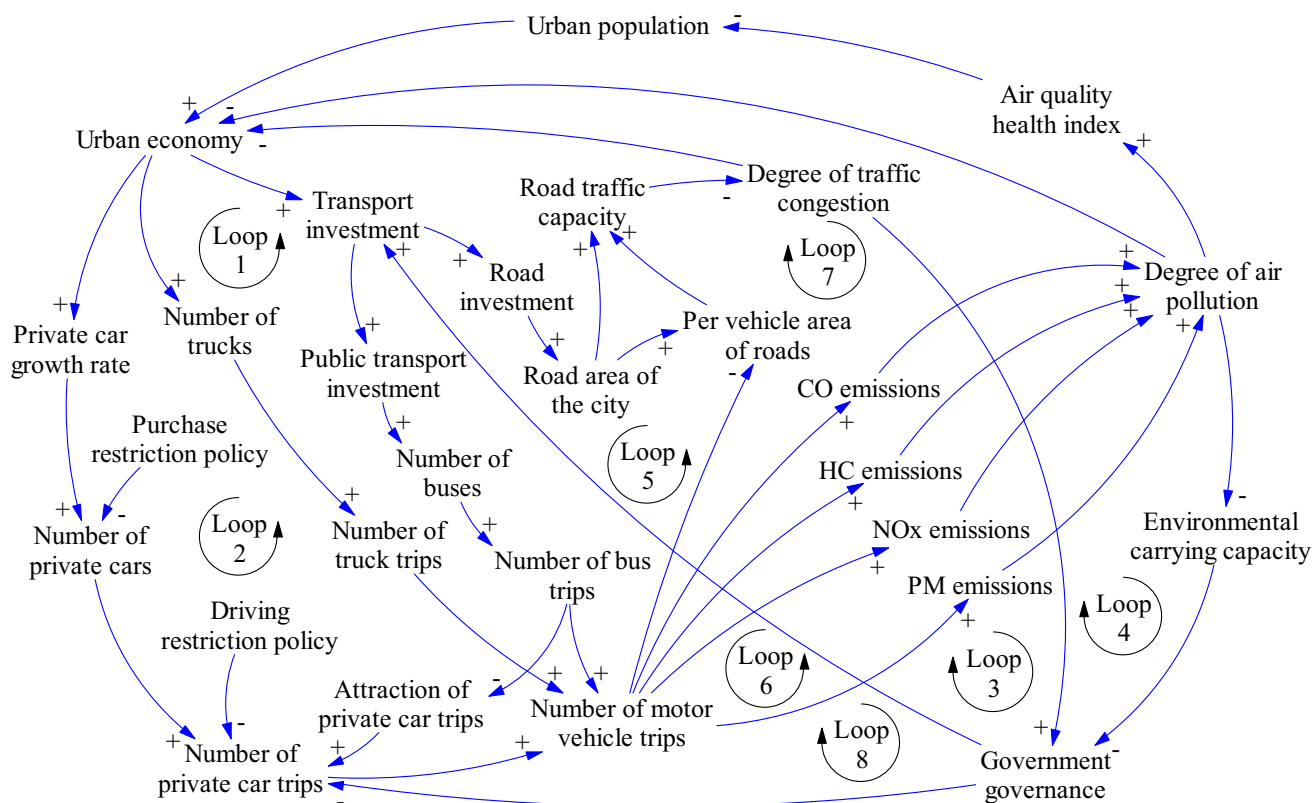
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Graphical abstract



Keywords System dynamics · Traffic-restriction policy · Air pollution · Health benefit

Abbreviations

AQHI	Air quality health index
DAP	Degree of air pollution
DTC	Degree of traffic congestion
ECC	Environmental carrying capacity
GDP	Gross domestic product
PTI	Public transport investment
PVAR	Per vehicle area of roads
RI	Road investment
RTC	Road traffic capacity
TI	Transport investment

Introduction

Problems related to urban traffic and pollution have become more serious in recent years (Zhu et al. 2019). Severe traffic congestion can impede socioeconomic development, harm the environment, and affect residents health (Tang et al. 2020). There are many types of motor vehicle exhaust pollutants, mainly including $PM_{2.5}$, NO_x , HC, CO, etc. Among

them, $PM_{2.5}$ and NO_x are important sources of “smog” pollution (Lin et al. 2019). Among various sources of air pollution, more than 40% of NO_x and $PM_{2.5}$ emissions come from road traffic (EEA 2019). In large Chinese cities such as Beijing, Shanghai, and Shenzhen, vehicles’ contribution rate to $PM_{2.5}$ concentration can range from 10 to 50% (or even higher under extreme adverse conditions) (MEE 2019). Therefore, solving traffic problems, reducing exhaust pollution, and improving urban air quality are key to sustainable urban development.

Researchers have investigated various sources of and solutions to urban air pollution. Su et al. (2020) noted that when traffic congestion occurs, vehicles travel slowly, and their rapid braking behavior results in insufficient fuel combustion and a lot of exhaust, thus increasing pollution. Adnan et al. (2016) suggested that in order to promote sustainable economy, it is necessary to switch from gasoline-based vehicles to green technology vehicles. The plug-in hybrid vehicles play a key role in the policy option to reduce environmental problems (Adnan et al. 2017). They are greener and cleaner vehicles, with fuel economy benefits

(Adnan et al. 2018). Using real-time traffic and meteorological information, Pan et al. (2016) evaluated the effects of traffic-related air pollution and found correlations between the traffic indicators of affected areas and CO concentration; specifically, CO concentration was higher during peak morning and evening hours. Chen et al. (2021) used daily data before and after the COVID-19 outbreak to analyze the effect of private vehicle-restriction policies on air pollution; they found that the policies somewhat reduced air pollution, but the effect varied according to other policies implemented during the same period as well as the economic development of a given city. Some scholars also studied driving-restriction policies and found positive effects on pollution reduction and human health (Sun and Xu 2021). Regarding pollution effects, long-term exposure has been found to hinder cognitive ability in language and math tests, thus having potentially huge health and economic costs (Zhang et al. 2018). Jia et al. (2018) established a vehicle pollutant emission-reduction management model and, based on simulation analysis, found that combining air pollution fees with subsidy policies could help reduce emissions and solve traffic problems. Such research findings can help policy makers adopt effective measures to reduce traffic-related emissions and improve air quality.

Regarding urban traffic congestion, Jia et al. (2017) established a traffic-congestion pricing model and found that reasonable congestion charges and subsidy policies could alleviate congestion and increase the supply of public transport. Zhang et al. (2019) examined the effect of driving-restriction and license plate-restriction policies on public-transport development, as well as a combination of the two; they found that such restrictions had no significant

effect on the proportion of public transport and could not fundamentally solve traffic problems. Guo et al. (2021) proposed a real-time ride-sharing framework with a dynamic timeframe and anticipation-based migration; they conducted extensive experiments on real-world datasets to demonstrate the effectiveness of the proposed framework for alleviating traffic congestion and improving travel efficiency. An overview of studies on urban air pollution and traffic congestion is shown in Table 1.

During the 2007 Olympic Games, Beijing implemented what is known as “odd–even rationing” to alleviate traffic congestion and air pollution, and good results were achieved. In the 1970s, Buenos Aires adopted odd–even traffic restrictions to reduce the number of vehicle trips by half (Sun and Xu 2021). Then, in 1989, Mexico implemented the “Hoy No Circula” restriction policy (Guerra and Millard-Ball 2017). Since then, similar measures have been adopted in many other cities, including Santiago (Yang et al. 2018), Bogota (Bonilla 2019), Medellin (Ramos et al. 2017), Milan (Sun and Xu 2021), and Sao Paulo (Zhang et al. 2020). Beijing currently has a double-tail number restriction policy in place. The double-tail number restriction means that two license plate tail numbers are restricted to travel on the road every day on weekdays. Can this policy really solve traffic and environmental problems? Is it effective in the long term? Does it trigger a paradox effect? This study conducted a detailed investigation to address these issues.

Most research on driving-restriction policies has been qualitative and lacks in-depth investigation of the dynamic characteristics of systems and the interrelationships between variables. Fulfillment of this research gap is the novelty of this work. The urban traffic–environmental system is

Table 1 An overview of urban air pollution and traffic congestion research

Research content	Method	Results	References
The effects of vehicle restriction on air pollution during COVID-19 epidemic	A multiple-period difference-in-difference(DID)	The policies effect varied according to other policies implemented during the same period as well as the economic development of a given city	Chen et al. (2021)
The effect of vehicles restriction on PM _{2.5} emission	DID model	Positive effects on pollution reduction	Sun and Xu (2021)
Health implication of improved air quality from driving restriction policy	General additive models (GAM)	Positive effects on human health	Liu et al. (2016)
The effects of driving restrictions on air quality	A theoretical model that combines an economic model	Driving restrictions might increase air pollution	Zhang et al. (2017)
Traffic congestion charges and subsidies	System dynamics	Reasonable congestion charges and subsidy policies could alleviate congestion and increase the supply of public transport	Jia et al. (2017)
The effects of car restrictions on public transport	The panel data-based policy effect evaluation method	Car restriction policies cannot solve the traffic problems at the source	Zhang et al. (2019)
The realistic ride-sharing problems	A real-time ride-sharing framework	The proposed framework is effective for improving traffic efficiency	Guo et al. (2021)

complex and is affected by external factors. It has characteristics such as nonlinearity, dynamics, and feedback. System dynamics can combine qualitative and quantitative approaches, and it can use computers to perform dynamic simulation analysis of the external environment and the internal relationships of complex systems. Grey system theory is a new method for studying uncertain systems with less data and poor information (Liu 2017). Based on known information, valuable information is extracted and introduced into the system dynamics model for simulation analysis, which can improve the accuracy and effectiveness of the model. Today, system dynamics is widely applied in research areas such as energy consumption (Liu et al. 2015), water resource management (Naderi et al. 2021), renewable energy supply chain management (Saavedra et al. 2018), green economics (Kuai et al. 2015), and circular economics (Alamerew and Brissaud 2020). Among the studies reviewed in this paper, Saavedra et al. (2018) identified the latest system dynamics contribution and trends related to the supply chain of renewable energy and emphasized on the importance of system modeling. Using system dynamics to establish a water ecological system model under different policies, Wang et al. (2014) studied the reasons for differences in water ecological carrying capacity and highlighted the limitations of environmental fee policies based on marginal benefit and cost. Xiao et al. (2016), meanwhile, used a system dynamics model to investigate energy consumption, CO₂ emission, and mitigation options in China. Compared to econometrics, this method has the advantages of strong practicability, high accuracy, and timeliness, but it cannot handle factors that are difficult to quantify in social and economic problems. It also has requirements for high accuracy and completeness of the original data, and there may also be problems such as multicollinearity and sequence correlation. In addition, this research mainly studied traffic-restriction policies. Policy variables can be exogenous or endogenous in the system dynamics model, which can be changed during the simulation operation. However, policy variables can only be exogenous variables in the econometric model. Compared with the SD method, it has certain limitations.

In consideration of the above, this study aimed to do the following: First, focusing on the problem of urban pollution from vehicle exhaust, taking Beijing as an example, an urban congestion mitigation and emission-reduction management model was established using system dynamics. Then, a nonlinear function that integrates system dynamics and a non-homogeneous discrete grey model (SD-NDGM) was proposed to construct an algorithm, which optimized the model. Finally, using dynamic simulation and analysis, the medium- and long-term effects of the restriction policy were explored, and policy recommendations are proposed on that basis. The contributions of this study include the following: The SD-NDGM approach was used to study the

effect of traffic-restriction policy on urban traffic and exhaust pollution, and the policy was found to be effective in the short term, but may cause negative effects (e.g., agglomeration effect, emission-reduction paradox) in the long term. The research results provide decision-making basis for the transportation and environmental protection departments.

The primary aim of this study was to help policymakers to conduct a more comprehensive assessment of policy effectiveness and present valuable insights for transportation and environmental protection departments. Detailed descriptions were as follows: (1) To explore the medium- and long-term effects of the traffic-restriction policy through dynamic simulation. (2) To evaluate whether the traffic-restriction policy really solves the traffic and environmental problems. (3) To propose recommendations for congestion mitigation and emission-reduction.

Methods

System dynamics

Jay Forrester established system dynamics in 1956 (Zhong et al. 2015). This is a method for solving nonlinear and high-order complex system problems based on feedback control theory and computer simulation technology. This method involves establishing causal loop diagrams, using stock flow diagrams, and setting equations (Wang 2009), which will give ideas about how to solve problems from the perspective of system science and inspire new ideas. The research flow chart of modeling approach is shown in Fig. 1.

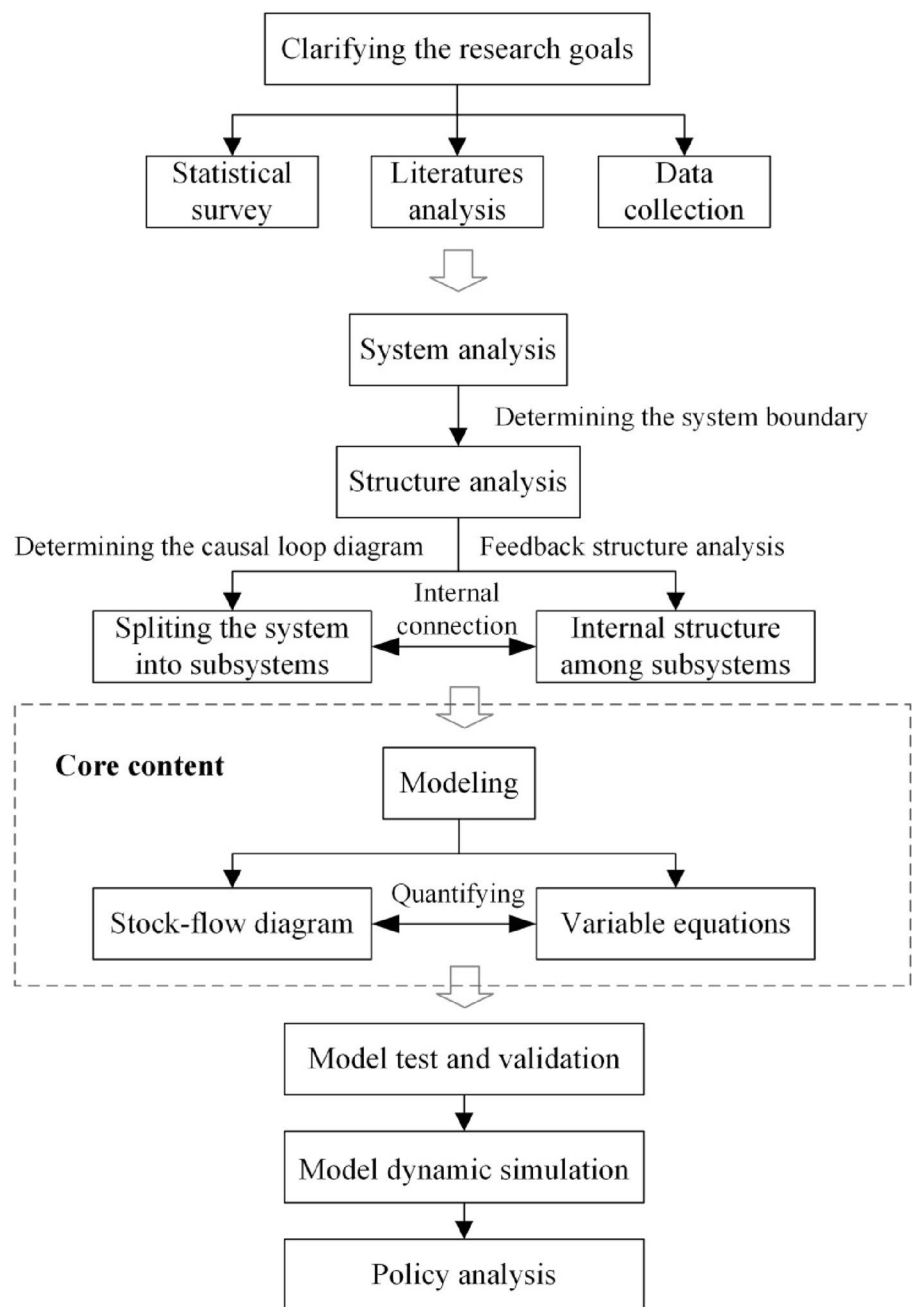
Model development

Causal loop diagram

An urban congestion mitigation and emission-reduction management model is a complex, dynamic system involving multiple elements. Based on the purposes of this study, the model was divided into five subsystems: society, economy, transportation, environment, and health. The simulation software Vensim (Wang and You 2021) was used to establish a causal loop diagram, as shown in Fig. 2. The arrows in the figure represent causal relationships between variables; “+” means a positive effect, and “-” means a negative effect. Positive feedback loops can enhance themselves through their positive loop chain while negative feedback loops have a weakening effect. The main feedback loops are as follows:

Loop1. Urban economy →⁺ Private car growth rate →⁺ Number of private cars →⁺ Number of private car trips →⁺ Number of motor vehicle trips →⁻ Per vehicle area of roads (PVAR) →⁺ Road traffic capacity (RTC) →⁻ Degree of traffic congestion (DTC) →⁻ Urban economy.

Fig. 1 A flow chart of SD modeling approach



Loop2. Urban economy \rightarrow^+ Private car growth rate \rightarrow^+ Number of private cars \rightarrow^+ Number of private car trips \rightarrow^+ Number of motor vehicle trips \rightarrow^+ PM emissions \rightarrow^+ Degree of air pollution (DAP) \rightarrow^+ Air quality health index (AQHI) \rightarrow^- Urban population \rightarrow^+ Urban economy.

Loop3. DTC \rightarrow^+ Government governance \rightarrow^- Number of private car trips \rightarrow^+ Number of motor vehicle trips \rightarrow^- PVAR \rightarrow^+ RTC \rightarrow^- DTC.

Loop4. DAP \rightarrow^- Environmental carrying capacity (ECC) \rightarrow^- Government governance \rightarrow^- Number of private car trips \rightarrow^+ Number of motor vehicle trips \rightarrow^+ PM emissions \rightarrow^+ DAP.

Loop5. DTC \rightarrow^+ Government governance \rightarrow^+ Transport investment (TI) \rightarrow^+ Public transport investment (PTI) \rightarrow^+ Number of buses \rightarrow^+ Number of bus trips \rightarrow^- Attraction of private car trips \rightarrow^+ Number of private car trips \rightarrow^+ Number of motor vehicle trips \rightarrow^- PVAR \rightarrow^+ RTC \rightarrow^- DTC.

Loop6. PM emissions \rightarrow^+ DAP \rightarrow^- ECC \rightarrow^- Government governance \rightarrow^+ TI \rightarrow^+ PTI \rightarrow^+ Number of buses \rightarrow^+ Number of bus trips \rightarrow^- Attraction of private car trips \rightarrow^+ Number of private car trips \rightarrow^+ Number of motor vehicle trips \rightarrow^+ PM emissions.

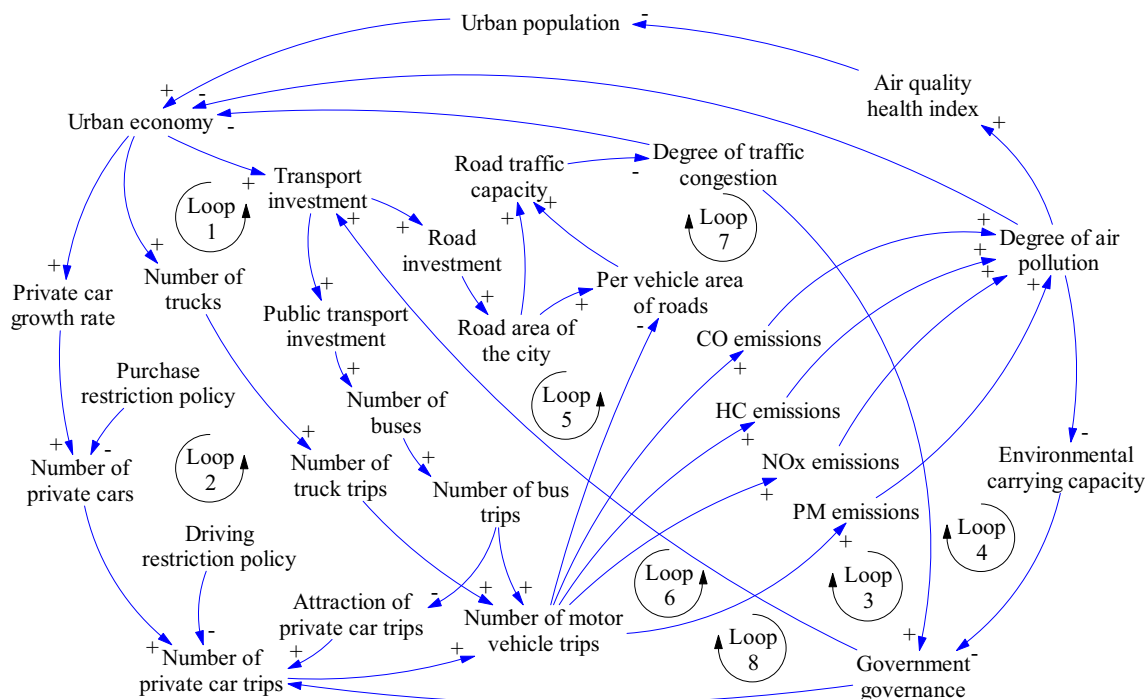


Fig. 2 Causal loop diagram of the urban congestion mitigation and emission-reduction management model

Loop7. DTC \rightarrow Government governance \rightarrow TI \rightarrow Road investment (RI) \rightarrow Road area of the city \rightarrow PVAR \rightarrow RTC \rightarrow DTC.

Loop8. PVAR \rightarrow RTC \rightarrow DTC \rightarrow Government governance \rightarrow Number of private car trips \rightarrow Number of motor vehicle trips \rightarrow PVAR.

Loops 1 and 2 are negative feedback loops. Urban economic development has improved residents living standards, causing them to buy more cars. The corresponding increase in the number of vehicle trips aggravates traffic congestion and affects the environment. Traffic congestion and air pollution in turn affect urban economic development. However, the government cannot restrict economic development to manage traffic and environmental issues. On the contrary, it must adopt appropriate policy measures to alleviate traffic congestion and improve air quality under the premise of maintaining economic development. Loops 3–8 can be analyzed likewise.

Loops 3 and 4 are also negative feedback loops based on adopting relevant policies (mainly driving-restriction policies) to alleviate DTC and improve DAP. Loops 5 and 6 show that an increase in PTI will improve the supply of public transport. Subsequently, the improved supply of public transport will reduce the attraction of private car trips, and eventually DTC and DAP will be alleviated. Loops 7 and 8 are also negative feedback loops. The former increases RI from the perspective of traffic supply to improve RTC, thereby alleviating DTC. However, Loop 8 shows that an

increase in PVAR will increase RTC, which will alleviate DTC. Ultimately, this will reduce governance to a certain extent, which in turn will increase the number of vehicle trips. An increased number of vehicle trips will lead to a smaller PVAR, which will finally intensify DTC. We can conclude, therefore, that simply increasing the road area will not fundamentally solve traffic congestion; rather, it needs to be considered in conjunction with other policies.

Stock and flow diagram

The causal loop diagram can only determine the system boundary and describe the basic structure of the feedback relationship. In a system dynamics model, variables can be divided into level variables, rate variables, auxiliary variables, and constants while causal loop diagrams cannot distinguish the differences between different variables. To this end, the model was further quantified. Based on the causal loop diagram, Vensim was used to establish a stock-flow diagram, as shown in Fig. 3. Appendix C provides descriptions of the main variables and the equations.

Model assumption

As urban traffic congestion and air pollution are affected by many variables, we made the following assumptions.

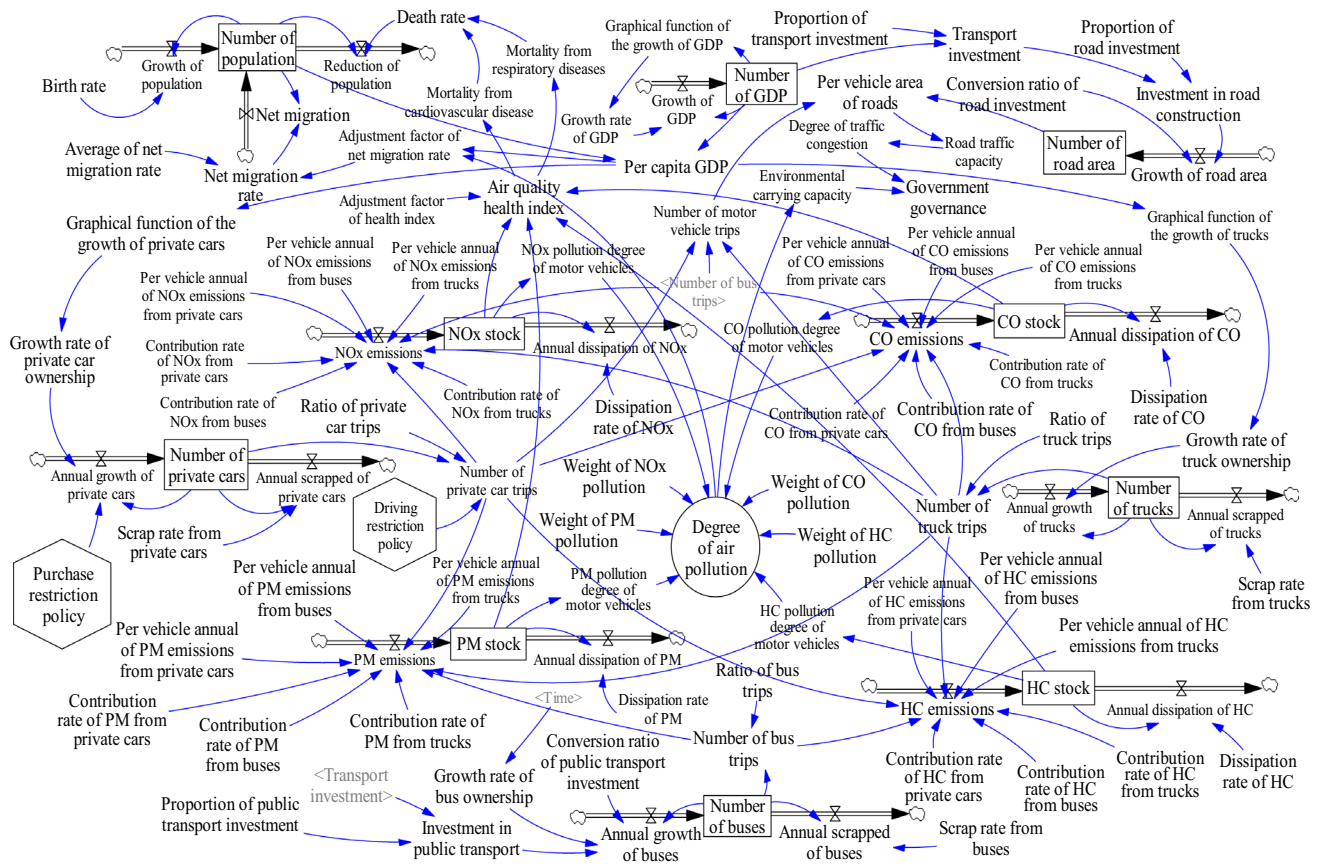


Fig. 3 Stock flow diagram of the urban congestion mitigation and emission-reduction management model

Assumption 1: In the environmental subsystem, the pollutants emitted by motor vehicles are mainly carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), and other particulate matter (PM). We selected emissions of CO, HC, NO_x, and PM as indicators to evaluate urban traffic pollution.

Assumption 2: In the social subsystem, the urban population mainly includes the permanent resident population.

Assumption 3: Regarding the driving-restriction policy, when the tail number of the restriction is *a*, about $a \times 10\%$ of vehicle trips will be reduced, except for vehicles that are not within the restriction (such as new energy vehicles, fire engines, police cars, and ambulances).

Setting: initial time = 2010; final time = 2030; time step = 1; unit of time: year.

Data sources

The data sources mainly included official website statistics, existing literature, parameter fitting and regression analysis, and indirect data based on the SD-NDGM approach.

Direct data

(1) Official website statistics

Data mainly came from the *China Statistical Yearbooks* (2011–2020), *Beijing Statistical Yearbooks* (2011–2020), *China Mobile Source Environmental Management Annual Reports* (2019–2020), *China Vehicle Environmental Management Annual Reports* (2016–2018), and *China Vehicle Emission Control Annual Reports* (2011–2015).

The following variables could be determined by calculating the data: per vehicle annual CO/HC/NO_x/PM emissions

from private cars/trucks/buses, the contribution rate of CO/HC/NO_x/PM from private cars/trucks/buses, and the initial value of the amount of road area.

Appendix B shows the detailed calculation results. Table B1 shows the partial parameters and initial values of the model.

(2) Existing literature

The following variables were determined based on the literature: dissipation rate of CO/HC/NO_x/PM (Yang et al. 2014), scrap rate of vehicles (Yang et al. 2014), ratio of vehicle trips (Zhu 2013), and air quality health index (Chen et al. 2013). Appendix C presents the specific results.

Air pollution can cause changes in physiological indicators, such as mortality. Mortality data are generally the easiest to obtain and are the end point for the most stable health effect. Therefore, AQHI was determined according to the relationship between CO, HC, NO_x, and PM emissions from vehicles and the death rate of residents. By introducing AQHI, the health effects of multiple pollutants are quantified, which can reflect the linear nonthreshold relationship between air pollution and health effects and predict the health level of residents (To et al. 2013).

(3) Parameter fitting and regression analysis

The adjustment factor of net migration rate can be determined using SPSS for parameter fitting and regression analysis. Appendix C presents the specific results and other parameter equations.

Indirect data based on SD-NDGM

SD-NDGM refers to integrating system dynamics and non-homogeneous discrete grey model theory (Liu et al. 2017). The degree of air pollution is nonlinear and difficult to quantify directly; therefore, based on the amount of CO, HC, NO_x, and PM emissions from motor vehicles (2011–2019), we calculated the pollution degree of the corresponding pollutants according to the actual pollution situation. Then, referring to the weight value of each pollutant in Jia (2021), a weighted logic function was established to more accurately describe the degree of air pollution. The advantages of the SD-NDGM approach are that it can solve the problems of simulating and predicting data series with non-homogeneous exponential growth, describe the variable equations of the model with more accuracy, and improve the model validation.

In this study, the following variables were determined by graphical function: CO, HC, NO_x, PM pollution degree, air pollution degree, GDP growth rate, and the growth rate of all types of motor vehicles. When using the

graphical function, in situations where data were incomplete or the trend was not obvious, NDGM was used for prediction, and the predicted values for the simulation period were obtained with higher accuracy. Figure 4 shows the algorithm flowchart. Taking CO emissions as an example, the detailed calculation steps are shown in Appendix A.

Model test and validation

Realistic test

The main purpose of model testing is to check whether a model conforms to reality. Figure 5a shows that the more restricted the tail numbers, the lower the number of trips and the smaller the traffic burden. We also find from the figure that after adopting the odd–even license plate-restriction policy (Jain et al. 2021), the amount of private car trips was reduced by almost half. The simulation results are consistent with reality. The same is true of Fig. 5b–d.

In addition, with the gradual increase in the intensity of the policy, although the growth rate of traffic congestion and CO stock declined, their values continued to increase, indicating that the policy can alleviate traffic congestion and environmental pollution to a certain extent but cannot fundamentally achieve the governance effect.

Model validation

Definition. Assume the original sequence is listed:

$$X^{(0)} = (x^{(0)}(1), x^{(0)}(2), \dots, x^{(0)}(n)). \tag{1}$$

The corresponding simulation sequence and residual error sequence are as follows:

$$\hat{X}^{(0)} = (\hat{x}^{(0)}(1), \hat{x}^{(0)}(2), \dots, \hat{x}^{(0)}(n)) \tag{2}$$

and

$$\begin{aligned} \varepsilon^{(0)} &= (\varepsilon(1), \varepsilon(2), \dots, \varepsilon(n)) \\ &= (x^{(0)}(1) - \hat{x}^{(0)}(1), x^{(0)}(2) - \hat{x}^{(0)}(2), \dots, x^{(0)}(n) - \hat{x}^{(0)}(n)). \end{aligned} \tag{3}$$

Then, its relative error sequence is as follows:

$$\Delta = \left(\left| \frac{\varepsilon(1)}{x^{(0)}(1)} \right|, \left| \frac{\varepsilon(2)}{x^{(0)}(2)} \right|, \dots, \left| \frac{\varepsilon(n)}{x^{(0)}(n)} \right| \right) = \{\Delta_k\}_1^n. \tag{4}$$

when $k \leq n$, $\Delta_k = \left| \frac{\varepsilon(k)}{x^{(0)}(k)} \right|$ is defined as the simulated relative error of the k point, and $\Delta = \frac{1}{n} \sum_{k=1}^n \Delta_k$ is the average relative error. For a given α , when $\Delta < \alpha$ and $\Delta_n < \alpha$, the model is defined as a residual error qualified model (Liu et al. 2017). Table 2 shows the accuracy grade table.

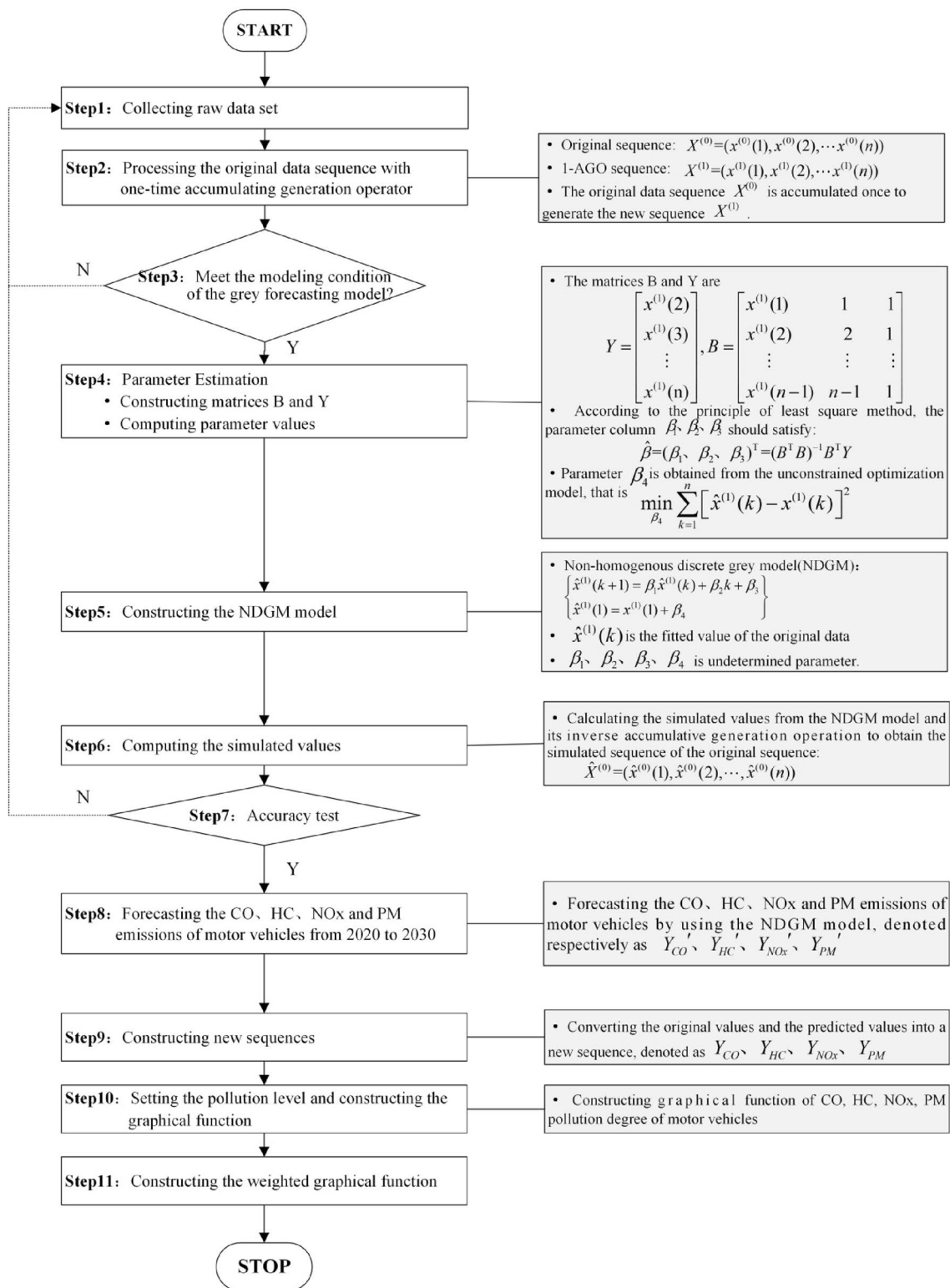


Fig. 4 An algorithm flowchart of the SD-NDGM approach

Taking some representative variables as examples (i.e., population, GDP, and private cars), the actual values and

simulated values from 2010 to 2019 were selected for the relative error test. Table 3 shows the test results.

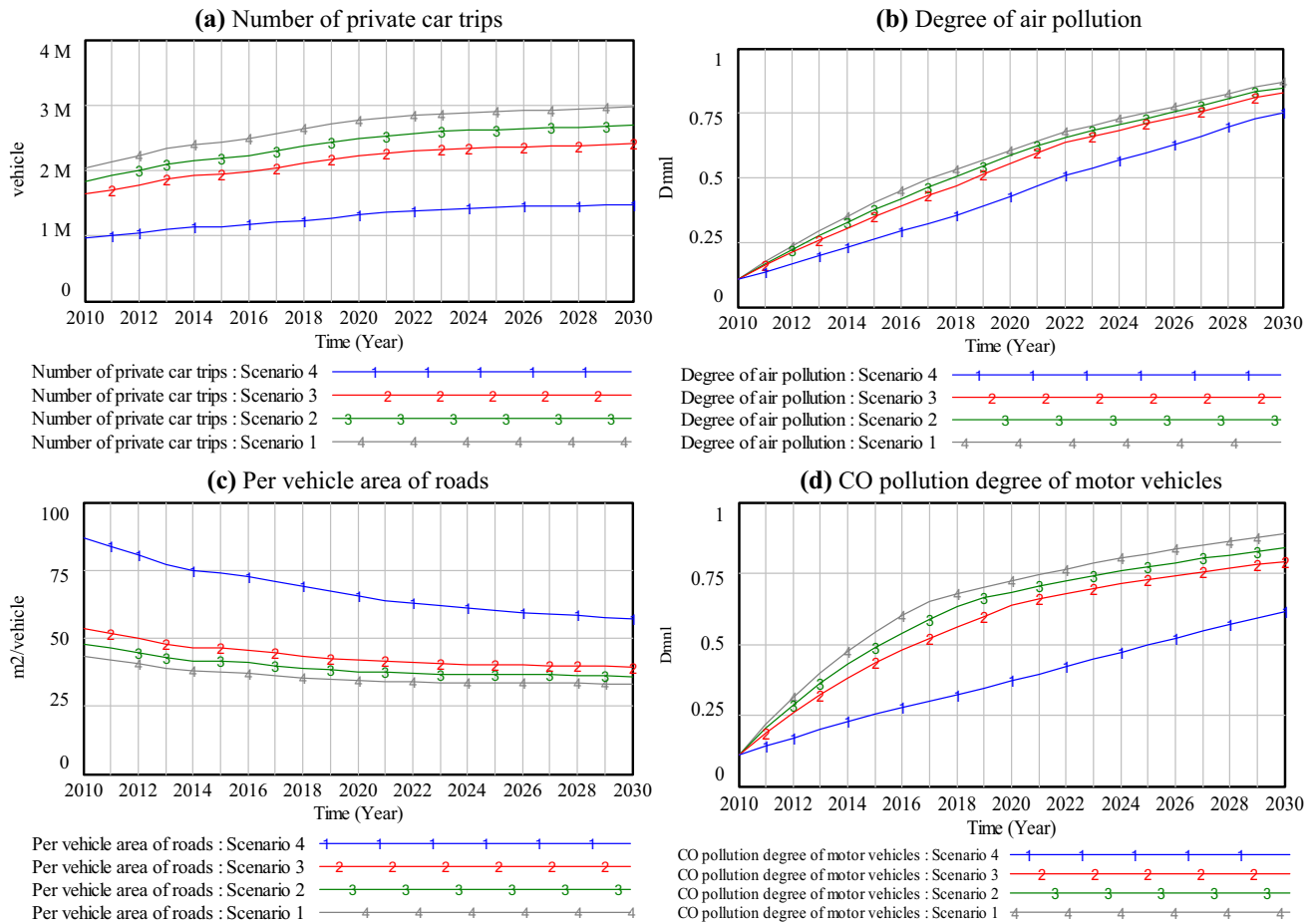


Fig. 5 Realistic test (Setting: no restriction (scenario 1); single-tail number restriction (scenario 2); double-tail number restriction (scenario 3); odd–even number restriction (scenario 4)). **a** Number of private car trips. **b** Degree of air pollution. **c** Per vehicle areas of roads. **d** CO pollution degree of motor vehicles

private car trips. **b** Degree of air pollution. **c** Per vehicle areas of roads. **d** CO pollution degree of motor vehicles

In Table 3, the average relative errors of the simulated values for population, GDP, and private cars are all less than 5%. Therefore, according to the definition and to Table 2, the accuracy belongs to grade 2, and the model has high credibility and can be used for prediction analysis.

Results

Policy effect analysis

Driving-restriction policy

Beijing began to implement a driving-restriction policy in 2007 to alleviate traffic congestion and reduce exhaust

pollution. The current traffic-restriction policy involves double-tail number restriction measures for vehicles in the area of Beijing’s Fifth Ring Road. Public electric cars, large buses, Beijing B-brand taxis, and law enforcement vehicles are not affected by the policy. Therefore, this study assumed the policy only affects private car travel. By adjusting the model parameters, the effects of the single-tail, double-tail (Su et al. 2020), and odd–even number restrictions were simulated. Figure 6 shows the results.

In Fig. 6a–d, as the policy becomes stricter, curves 1–4 show different changes. Among them, curves 1 and 2 show obvious changes while the changes in curves 3 and 4 are not obvious and show a rapid upward trend. These results indicate that the restriction policy has had a significant effect on reducing the number of vehicle trips in the short term. The more restricted the tail numbers, the fewer the trips and the smaller the traffic burden. All types of restrictions have alleviated traffic congestion in varying degrees. Table 4 shows that by 2030, with implementation of the single-tail number restriction, the number of vehicle trips in Beijing will reach

Table 2 Accuracy grade reference list

Accuracy grade	Grade 1	Grade 2	Grade 3	Grade 4
Relative error	0.01	0.05	0.10	0.20

Table 3 Model validation results

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
<i>Number of population (ten thousand people)</i>										
Actual value	1961.9	2018.6	2069.3	2114.8	2151.6	2170.5	2172.9	2170.7	2154.2	2153.6
Simulated value	1961.9	1981.7	2018.7	2053.8	2082.7	2103.8	2113.9	2124.1	2132.0	2142.8
Residual error	–	36.9	50.6	61.0	68.9	66.7	59.0	46.6	22.2	10.8
Relative error (%)	–	1.83	2.45	2.88	3.20	3.07	2.72	2.15	1.03	0.5
Average relative error (%)	1.9830									
<i>Number of GDP (100 million yuan)</i>										
Actual value	14,441.6	16,627.9	18,350.1	20,330.1	21,944.1	23,685.7	25,669.1	28,014.9	30,320.0	35,371.3
Simulated value	14,441.6	16,627.8	18,349.9	20,329.7	21,943.9	23,685.4	25,668.6	28,014.6	30,319.6	35,371.8
Residual error	–	0.1	0.2	0.4	0.2	0.3	0.5	0.3	0.4	–0.5
Relative error (%)	–	0.0006	0.0011	0.0020	0.0009	0.0013	0.0019	0.0012	0.0013	0.0014
Average relative error (%)	0.0012									
<i>Number of private cars (ten thousand vehicle)</i>										
Actual value	371.51	387.29	405.55	424.95	435.79	439.33	452.03	466.61	479.00	496.58
Simulated value	371.51	387.30	404.19	423.35	436.27	441.31	451.17	465.01	478.83	492.26
Residual error	–	–0.01	1.36	1.6	–0.48	–1.98	0.87	1.6	0.17	4.32
Relative error (%)	–	0.0026	0.3353	0.3765	0.1101	0.4507	0.1925	0.3429	0.0355	0.8700
Average relative error (%)	0.2716									

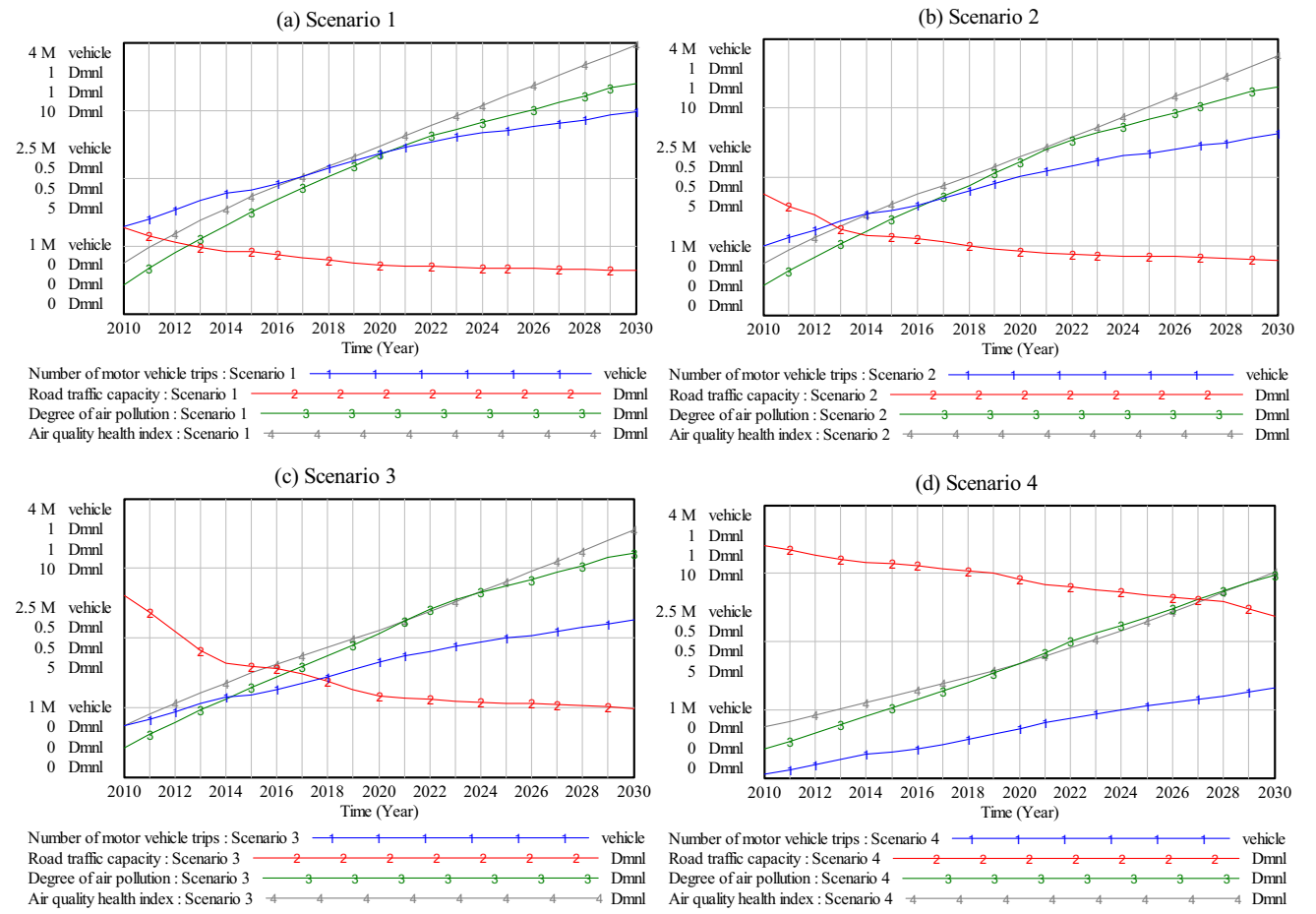


Fig. 6 Trends in the major variables under different driving-restriction policies. **a** No restriction. **b** Single-tail number restriction. **c** Double-tail number restriction. **d** Odd-even number restriction

Table 4 Simulation results for the major variables under different driving restriction policies

Variables	Scenarios	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Variation
Number of motor vehicle trips (Million vehicle)	No restriction	2.7724	2.8335	2.8904	2.9472	2.9887	3.0223	3.0653	3.0984	3.1372	3.1848	3.2195	–
	Single-tail number restriction	2.5048	2.5636	2.6165	2.6725	2.7204	2.7503	2.7884	2.8311	2.8636	2.9116	2.9604	–9.59%
	Double-tail number restriction	2.2349	2.2971	2.3477	2.4007	2.4506	2.4855	2.5189	2.5605	2.6001	2.6417	2.6896	–19.15%
Road traffic capacity	Odd-even number restriction	1.5428	1.6074	1.6526	1.6943	1.7411	1.7868	1.8269	1.8582	1.8921	1.9386	1.9793	–43.54%
	No restriction	0.1762	0.1721	0.1692	0.1554	0.1644	0.1640	0.1625	0.1619	0.1605	0.1575	0.1564	–
	Single-tail number restriction	0.2255	0.2203	0.2168	0.2118	0.2087	0.2085	0.2069	0.2041	0.2032	0.1991	0.1951	28.48%
Degree of air pollution	Double-tail number restriction	0.2873	0.2791	0.2744	0.2682	0.2632	0.2612	0.2597	0.2559	0.2527	0.2486	0.2435	71.06%
	Odd-even number restriction	0.7224	0.7038	0.6941	0.6845	0.6738	0.6632	0.6555	0.6505	0.6357	0.6062	0.5837	274.98%
	No restriction	0.5968	0.6342	0.6689	0.6941	0.7192	0.7440	0.7684	0.7938	0.8190	0.8478	0.8643	–
Air quality health index	Single-tail number restriction	0.5665	0.6098	0.6477	0.6723	0.6971	0.7221	0.7465	0.7712	0.7975	0.8258	0.8424	–4.40%
	Double-tail number restriction	0.5269	0.5713	0.6155	0.6477	0.6749	0.6999	0.7246	0.7493	0.7754	0.8040	0.8209	–9.10%
	Odd-even number restriction	0.4278	0.4675	0.5097	0.5412	0.5704	0.6012	0.6334	0.6661	0.6995	0.7319	0.7564	–22.68%
Air quality health index	No restriction	6.1673	6.5451	6.9221	7.2963	7.6762	8.0467	8.4063	8.7769	9.1402	9.5019	9.8775	–
	Single-tail number restriction	5.7207	6.0785	6.4401	6.7973	7.1661	7.5338	7.8882	8.2443	8.6164	8.9805	9.3566	–6.00%
	Double-tail number restriction	5.2781	5.6153	5.9615	6.3061	6.6618	7.0238	7.3785	7.7289	8.0938	8.4698	8.8493	–11.93%
Odd-even number restriction	4.1887	4.4702	4.7701	5.0809	5.3956	5.7292	6.0782	6.4334	6.7863	7.1431	7.5334	–26.75%	

2.9604 million and be reduced by 8.05% compared with no restriction being taken, with an average annual reduction rate of 9.59%. Likewise, with double-tail number restriction, the number of vehicle trips in Beijing will reach 2.6896 million and be reduced by 16.46% compared to no restriction being implemented, with an average annual reduction rate of 19.15%. Moreover, with implementation of single-tail number restriction, the number of vehicle trips in Beijing will reach 1.9793 million and be reduced by 38.52% compared with no restriction being taken, with an average annual reduction rate of 43.54%.

In addition, road traffic capacity (RTC) under the three different restriction policies increases by 28.48%, 71.06%, and 274.98% in 2030. Relatively speaking, the restriction policy on odd and even numbers shows a more obvious effect on alleviating congestion, followed by double-tail numbers and single-tail numbers. In the long run, however, RTC still declines when the traffic-restriction policy is implemented, and traffic congestion continues to rise, which indicates that the policy does not fundamentally solve the traffic congestion problem. Moreover, the driving-restriction policy is not effective for solving environmental problems, and the air

pollution and air quality health indexes still increase (i.e., the emission-reduction paradox).

Purchase-restriction policy

To ensure sustainable urban development while achieving the reasonable and orderly growth of motor vehicles, the Beijing Municipal Government implemented a measure to allocate car quotas by lottery in 2011. Based on the actual

Table 5 Simulation results for the major variables under the purchase-restriction policy (in 2030)

Variables	Number of motor vehicle trips (Million vehicle)	RTC	DAP	AQHI
No restriction	3.2195	0.1564	0.8643	9.8775
Purchase-restriction	2.8169	0.2196	0.7779	7.8555
Driving- and purchase-restriction	2.3624	0.2906	0.6559	6.3853
Variation (%)	-16.13	32.33	-15.68	-18.72

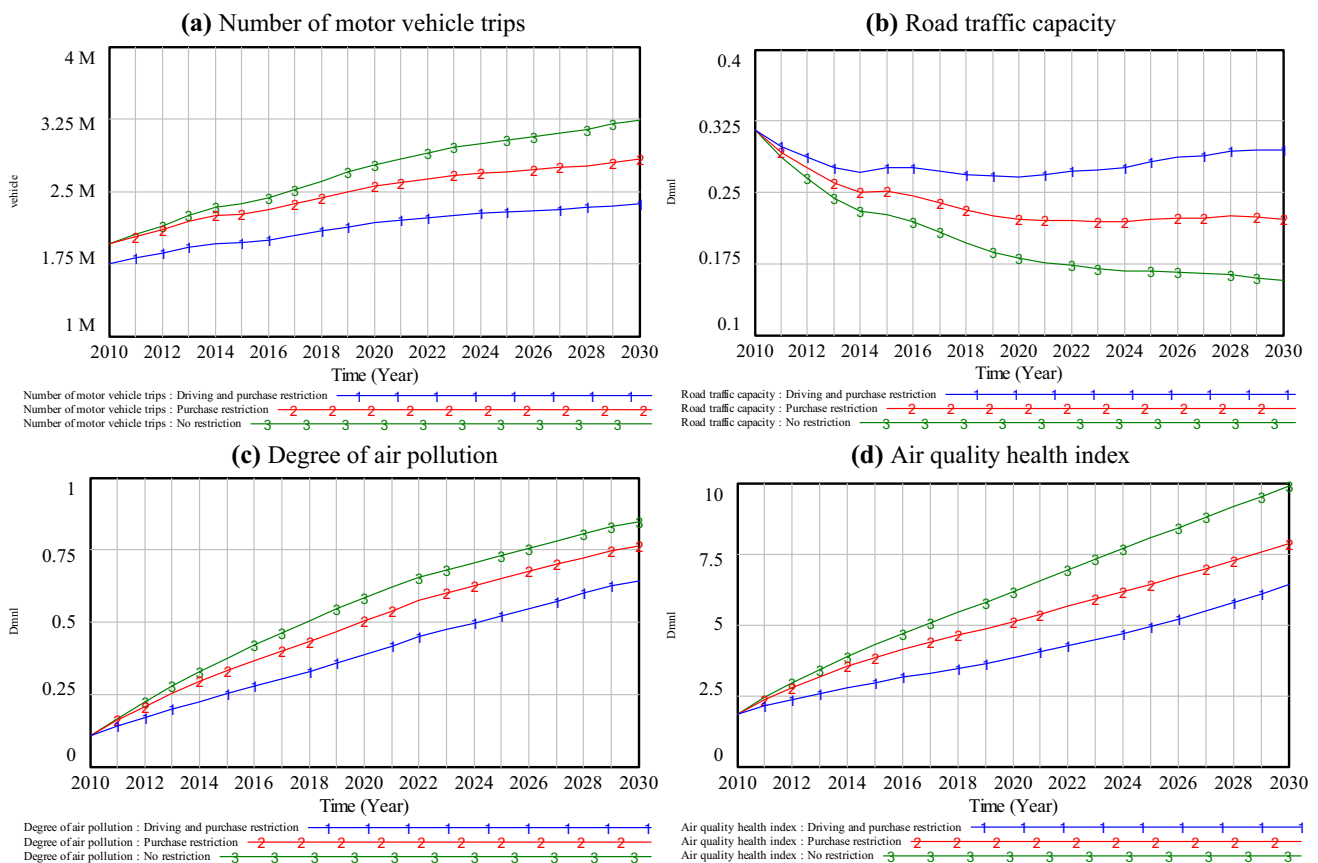


Fig. 7 Changes in the main variables under the purchase-restriction policy. **a** Number of motor vehicle trips. **b** Road traffic capacity. **c** Degree of air pollution. **d** Air quality health index

situation, this study performed a dynamic simulation of the policy. Figure 7 shows the results.

As shown in Fig. 7a and b, although the purchase-restriction policy can reduce the number of vehicle trips and relieve congestion to a certain extent, the policy effect is limited. If combined with the driving-restriction policy, RTC shows an upward trend in 2021, reflecting a rebound trend. Table 5 shows that by 2030, the number of vehicle trips under the driving- and purchase-restriction policies will reach 2.3624 million, a 16.13% reduction compared with the purchase-restriction policy alone; RTC is 0.2906, an increase of 32.33%.

Furthermore, as shown in Fig. 7c and d, the policy does not fundamentally solve the problem of air pollution. In the long run, although the growth rate of air pollution declines, the air pollution and air quality health indexes continue to rise. Thus, the policy does not significantly reduce the amount of pollutant emissions or solve the problem of vehicle pollution, and environmental carrying capacity still gradually decreases. This could be because some consumers use tactics to circumvent policy restrictions. Specifically, some consumers buy cars in other areas but drive in Beijing, resulting in an increase in pollutants, which in turn has a negative effect on air pollution governance, thus leading to the emission-reduction paradox effect.

We can conclude, therefore, that the combination of the purchase-restriction and driving-restriction policy can constrain excessive increases in the number of private cars and alleviate congestion, though the air pollution problem will not be fundamentally controlled.

Public-transport development

A fundamental way to alleviate urban traffic congestion and reduce air pollution is to develop public transport, which is cheap, convenient, and green.

In this model, keeping other variables unchanged, public-transport investment is adjusted by 1%, and the effect of policy changes on urban transportation and the environment is analyzed. Figure 8 and Table 6 present the simulation results.

Figure 8a shows the effect of changes in public-transport investment on the number of private car trips. Obviously, the number of private car trips shows a downward trend with increased public-transport investment. Over time, a mere 1% change will have an effect on traffic and the environment. Table 6 shows that by 2030, when public-transport investment increases by 1%, the number of private car trips will decrease by 23.27%; when public-transport investment increases by 2%, the number of private car trips will decrease by 36.59%. Although traffic congestion and air pollution have improved at that time compared to the current

situation, they are still increasing, and the policy effect is therefore limited (see Fig. 8b and c).

However, compared with a single policy, if the driving-restriction policy is combined with public-transport development, traffic congestion, air pollution, and environmental carrying capacity will show a “rebound effect” in the later stage (see points E, F, and M in Fig. 8b–d). Traffic congestion, air pollution, and the air quality health index will be reduced by 29.13%, 52.63%, and 54.63%, respectively, and environmental carrying capacity will increase by 294.26% (see Table 6).

Therefore, while implementing the restriction policy, Beijing should also improve public-transport services and guide citizens to use public transport. In addition, with the implementation of the restriction policy, some people will switch from private cars to public transport, but the supply level of public transport might not keep up with demand. Therefore, it is necessary to improve and increase investment in public transport to support residents’ daily travel needs, thereby fundamentally solving the problems of congestion and pollution.

Sensitivity analysis

In Fig. 6b, when the single-tail number restriction policy is implemented, curves 1, 3, and 4 show an increasing trend and are at a high level while curve 2 is at a low level, showing that the policy effect is not obvious.

In Fig. 6c, it can be seen that the policy effect of the double-tail number restriction has not changed significantly compared with the single-tail number restriction, indicating that the double-tail number restriction cannot fundamentally solve traffic and environmental problems.

In Fig. 6d, it can be seen that when the odd–even number restriction policy is implemented, curve 2 increases obviously, and curve 1 decreases significantly. However, their development trends do not change, and the number of motor vehicle trips and amount of congestion continue to increase. Moreover, curves 3 and 4 show that the odd–even number restriction has no significant effect on improving air pollution. These results mean the odd–even number restriction policy can only solve traffic congestion problems in a phased or temporary manner and cannot be used in the long term. It can temporarily relieve congestion but cannot fundamentally solve the problem.

Discussion

Effects of agglomeration and synergy

Through the dynamic simulation of the driving-restriction policy, the policy was found to have a positive effect on

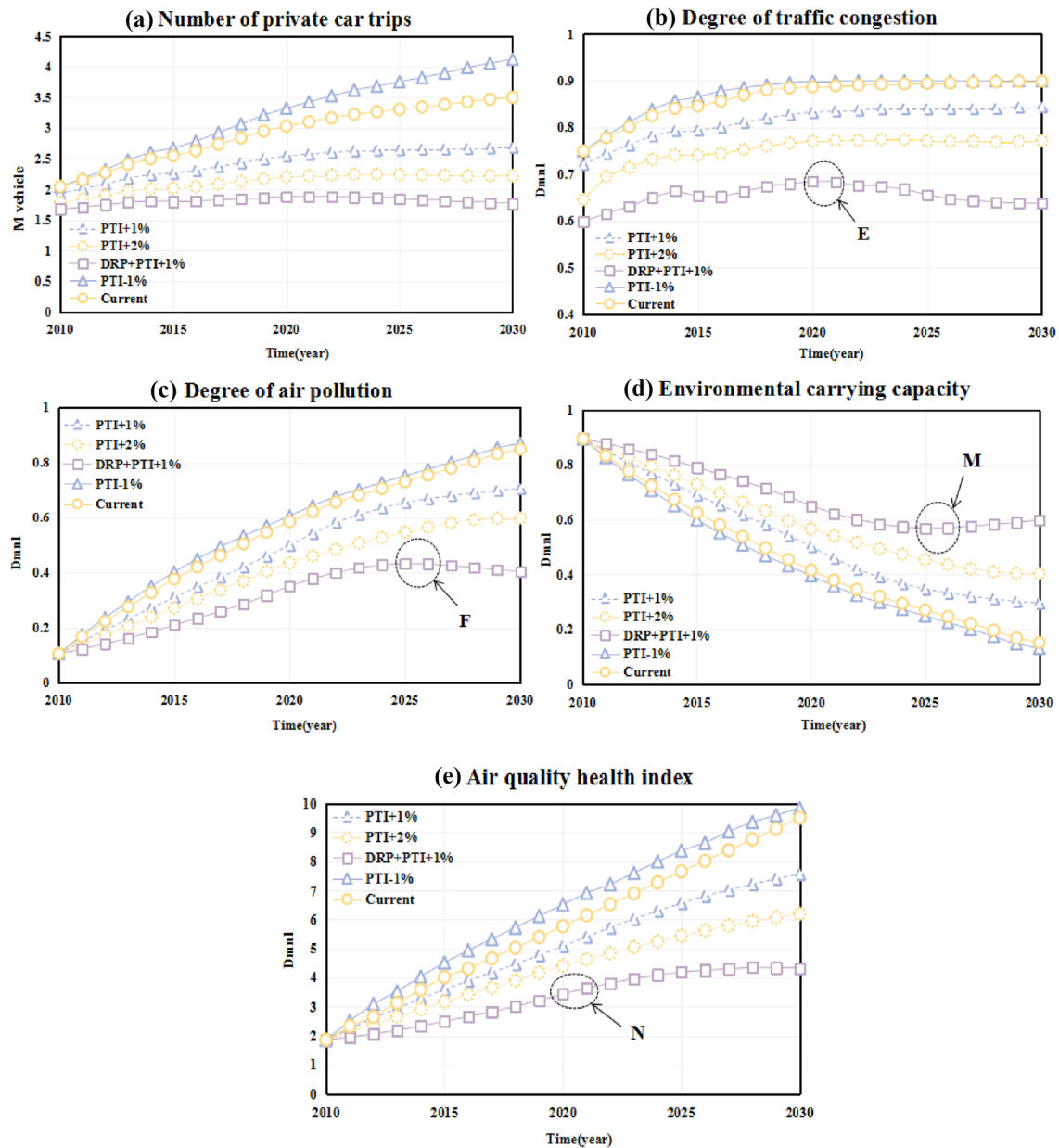


Fig. 8 Effect of the main variables under public-transport development policy. **a** Number of private car trips. **b** Degree of traffic congestion. **c** Degree of air pollution. **d** Environmental carrying capacity. **e** Air quality health index

reducing the number of vehicle trips and alleviating traffic congestion (Liu et al. 2020). With the implementation of the policy, some people will change their ways of traveling and switch from private cars to public transport (Ma et al. 2020). However, the public-transport supply might not keep up with demand in the short term, resulting in the “congestion” of public transport and an increased burden on it (agglomeration effect). This, in turn, might lead some residents to travel by car and take measures to circumvent policy, such as buying a second car. This would create a

phenomenon contrary to government intention and weaken the effectiveness of the policy. Second, the policy could cause people to travel more on unrestricted days, thus offsetting the policy effect and ultimately having an adverse effect on sustainable development.

The sensitivity analysis indicated that the odd–even number restriction policy had the most obvious effect on alleviating traffic congestion but had no significant effect on improving air pollution (see Fig. 6d). However, public-transport development combined with traffic restrictions can reduce

Table 6 Comparison of different scenarios in the development of public-transport policy (in 2030)

Variables	Number of private car trips (million vehicle)	DTC	DAP	ECC	AQHI
Current	3.4999	0.8992	0.8484	0.1517	9.5080
PTI-1%	4.1202	0.9000	0.8698	0.1302	9.8352
Variation (%)	17.72	0.09	2.52	-14.17	3.44
PTI+1%	2.6856	0.8442	0.7050	0.2950	7.5692
Variation (%)	-23.27	-6.12	-16.90	94.46	-20.39
PTI+2%	2.2192	0.7719	0.5978	0.4022	6.1890
Variation (%)	-36.59	-14.16	-29.54	165.35	-34.91
DRP+PTI+1%	1.7648	0.6373	0.4019	0.5981	4.3139
Variation (%)	-49.58	-29.13	-52.63	294.26	-54.63

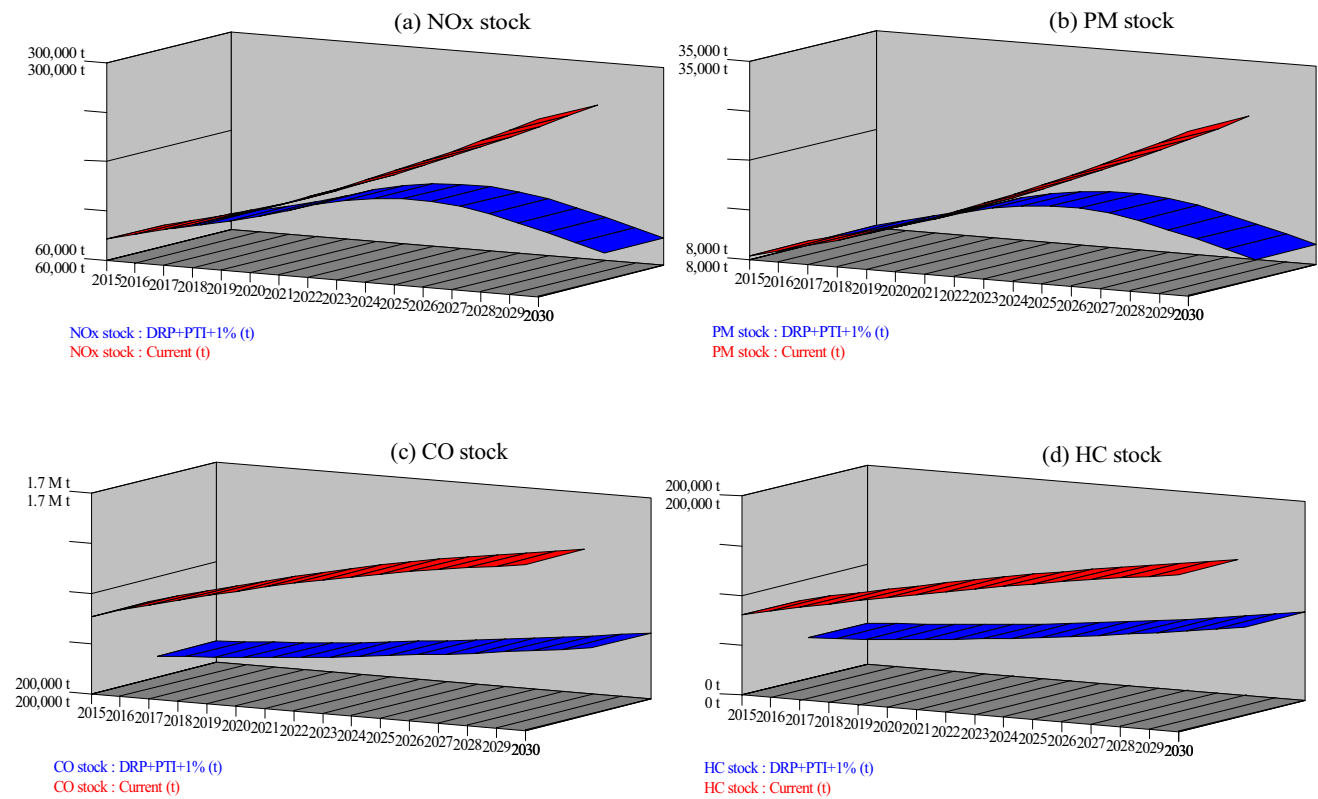


Fig. 9 Synergistic effects of the combined policy. **a** NO_x stock. **b** PM stock. **c** CO stock. **d** HC stock

Table 7 Effects on NO_x, PM, CO, and HC stock under a combined policy

Variables	Scenarios	2015	2016	...	2029	2030
CO stock	Current	778,154	841,491	...	1,410,250	1,441,260
	DRP+PTI+1%	358,257	372,205	...	663,334	691,553
HC stock	Current	80,595	87,058.4	...	153,479	157,779
	DRP+PTI+1%	40,924.1	42,735.1	...	83,937.5	88,240.7
NO _x stock	Current	85,799.8	94,370.3	...	258,434	274,922
	DRP+PTI+1%	78,502.8	86,375.3	...	102,878	92,952.6
PM stock	Current	8554.17	9549.33	...	28,500.2	30,423
	DRP+PTI+1%	8391.27	9386.43	...	11,803	10,675.1

emissions (synergistic effect). This study assumed that CO, HC, NO_x, and PM emitted by vehicles are indicative pollutants that affect air quality. The detailed analysis is as follows:

In Fig. 9a–d, the stock of NO_x, PM, CO, and HC is reduced in varying degrees compared with the current scenario. Specifically, with time, NO_x and PM stock first rise and then slowly descend after 2026. Changes in the curves are not obvious in the early stage, and there is a lagging effect. Although the stocks of CO and HC are increasing, the growth rate slows down and is controlled to a certain extent.

In addition, Table 7 shows that under the scenario of implementing the driving-restriction policy and developing public transport, the stock of CO, HC, NO_x, and PM decreases by 52.02%, 44.07%, 66.19%, and 64.91%, respectively, by 2030.

Therefore, combining public-transport development with driving-restriction policy can effectively reduce vehicle emissions and achieve emission-reduction targets.

Health benefits

Reducing air pollution is important for improving public health. Vehicle exhaust emissions reduce air quality and harm human health. In 2019, the respiratory-related mortality rate among Beijing residents reached 0.656%, ranking fourth among all mortality causes (9.4%). Some have suggested that the driving-restriction policy can significantly reduce harmful pollutants by reducing vehicle trips and thus provide benefits for health (Liu et al. 2016). However, this is not the case in the long run (Fig. 5b and d).

Air pollution adversely affects human health and is estimated to be responsible for some of the annual premature mortality in the United States (Dedoussi et al. 2020). Considering the direct relationship between air pollution and human health, this study introduced AQHI. It is associated with four types of pollutants emitted by vehicles and affects the death rate of residents. The larger the AQHI, the more serious the air pollution, and the greater the adverse effect on residents' health.

In Fig. 6a–d, curve 3 continues to rise, which indicates that pollutant emissions keep increasing, and the emission rate does not slow down. AQHI and DAP continue to increase, and the same is true in Fig. 7c and d. In other words, neither the driving-restriction policy nor the purchase-restriction policy can effectively control the negative effects of vehicle emissions. Air quality will continue to decline and endanger residents' health. Therefore, an effective solution is needed. When the driving restriction is implemented and public-transport investment is increased, DTC and DAP will show rebound effects in 2020 and 2025, respectively (see points E and F in Fig. 8b and c), and AQHI will show an “inflection point” in 2020 (see point N

Table 8 Simulation results of air quality health index

Time	AQHI	Variation (%)	Time	AQHI	Variation (%)
2010	1.8555	–	2021	3.6325	0.0582
2011	1.9461	0.0488	2022	3.8103	0.0490
2012	2.0556	0.0563	2023	3.9648	0.0405
2013	2.1836	0.0623	2024	4.0900	0.0316
2014	2.3275	0.0659	2025	4.1834	0.0228
2015	2.4900	0.0698	2026	4.2519	0.0164
2016	2.6548	0.0662	2027	4.2955	0.0103
2017	2.8208	0.0625	2028	4.3459	0.0117
2018	3.0019	0.0642	2029	4.3369	–0.0021
2019	3.2086	0.0689	2030	4.3139	–0.0053
2020	3.4327	0.0699	–	–	–

in Fig. 8e) and a downward trend in 2029 (see Fig. 8e and Table 8). Compared with the current situation, DAP and AQHI will decrease by 52.63% and 54.63% in 2030, respectively. Therefore, increasing investment in public transport while implementing the restriction policy could alleviate traffic congestion, improve air quality, and reduce negative effects on residents' health.

Conclusions and policy recommendations

This study used SD-NDGM to establish an urban congestion mitigation and emission-reduction management model. Based on dynamic simulation analyses of the effects of traffic policies from a medium- and long-term perspective, the following conclusions can be presented.

First, this study's SD-NDGM-based algorithm solves the problem of simulating and predicting data series with non-homogeneous exponential growth. It can more accurately describe the variable equations of the model and improve the model's accuracy and effectiveness.

Second, the driving-restriction policy has a time effect. In the short term, it has a significant effect on reducing the number of vehicle trips. However, it may have negative effects in the long term (agglomeration effect and emission-reduction paradox), and it does not fundamentally solve traffic and environmental problems. It can only be used as a phased policy, not as a long-term measure. The reasons may be as follows: Residents have responded positively to the policy in the short term. However, with the implementation of the policy, the work and life of some residents may be affected, and the mandatory restrictions of the policy may encourage residents to take countermeasures to circumvent the policy, thereby increasing the external costs of the society, such as buying a second car and increasing the number of trips on unrestricted days,

which will weaken the effectiveness of the policy. The agglomeration effect is reflected in the phenomenon such that with the implementation of the policy, some people will change their ways of travelling and switch from private cars to public transportation. However, the public-transport supply may not be able to meet the demand in the short term, resulting in “congestion” and increased burden on the public transport system.

Third, the purchase-restriction policy alone has a limited effect on solving traffic problems. If it is combined with the driving-restriction policy, it can constrain excessive increases in private cars and alleviate traffic congestion. Moreover, although road-traffic capacity shows an upward trend in 2021, in the long run, the policy will fail to fundamentally solve the problem of air pollution.

Finally, it is not advisable to rely only on driving-restriction policy. It is necessary to flexibly adjust the policy and combine it with other measures. Because driving-restriction policy may increase the burden on public transport, the public-transport supply needs improvement. DTC and DAP show a rebound effect, and AQHI has a “turning point.” In particular, traffic congestion, air pollution, and the air quality health index will be reduced by 29.13%, 52.63%, and 54.63%, respectively, and environmental carrying capacity will increase by 294.26%, providing certain environmental, social, and health benefits. Although the effect of the policy will be somewhat delayed, the result will be more stable.

Based on the above conclusions, the following policy recommendations are proposed.

First, the driving-restriction policy can only be used as a short-term measure and cannot fundamentally solve the traffic problem. Traffic governance is a complex, long-term process, requiring a comprehensive, scientific, and systematic policy system. When implementing such policy, it is necessary to fully consider the development background of regions and make flexible adjustments. In the long run, Beijing needs more comprehensive and feasible policy tools, such as traffic congestion charges, fuel taxes, and new energy vehicles. Some have also suggested that market-based measures should be used to control congestion. Price levers can be used in various stages in the use of vehicles to adjust the relationship between supply and demand and reduce the intervention of nonmarket mechanisms.

Second, to avoid the agglomeration effect while increasing investment in public transport, short-distance travel using shared bicycles could be encouraged. It is also necessary to increase the governance of shared bicycles to deal with parking problems while supporting residents’ travel needs to solve traffic and pollution problems at the root.

Finally, improving residents’ acceptance of policies is key to managing traffic problems. While prioritizing public transport and encouraging green travel, it is also necessary to improve urban road planning, increase public-transport

infrastructure, and improve convenience; this can help encourage residents take the initiative to use public transport. Furthermore, restrictions on the use of private cars may cause residents to take countermeasures to circumvent policies, thereby increasing external costs to society.

The findings of this study can help readers to further understand the urban traffic-restriction policy, provide detailed information for assessing the social impact of the policy, and also help policymakers to conduct a more comprehensive assessment of policy effectiveness. The research results provide references for the government to formulate more efficient and reasonable congestion mitigation and emission-reduction policies and can also provide decision-making basis for the transportation and environmental protection departments. However, the model has some limitations: Due to limited data, research on the effect of policies on the health benefits of residents is not sufficiently thorough. In the future, we will conduct in-depth research on the health benefits of policies and increase our efforts to obtain relevant real-time data for further verification.

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Data availability All the data generated or analyzed during this study are included in this published article.

Declarations

Competing interests The author has no conflicts of interest to declare.

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