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Research Article

Evaluating Effectiveness of Low-Carbon Transition Policy Mix Based on Urban Private Car Trajectory Data

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Under the vision of achieving carbon neutrality by 2060, it is urgent to introduce appropriate carbon reduction policy for city road traffic. This paper establishes a three-layer neural network model to predict the carbon emission from private cars based on urban private car trajectory data, simulates and analyzes the carbon emission from private cars, travel cost, personal income, and government revenue under the four policy perspectives, and evaluates and compares the emission reduction effects under four policy perspectives. Next, this paper evaluates the government revenue from the perspective of carbon tax and policy mix and compares the individual consumer utility of two-commodity and three-commodity mix, as well as the total social benefits under the four policy perspectives. The results show that the policy mix has better implementation effect on carbon emission reduction, personal income, and travel cost. The implementation effect of the single carbon tax policy is better in terms of government revenue. The implementation effect of the single carbon trading policy is better in terms of social benefit. In addition, as the carbon tax rate increases, the consumer utility tends to decline. Finally, this paper puts forward specific policy implementation proposals based on the above simulation analysis.

1. Introduction

Mitigating global warming, controlling temperature rise, and finding effective low-carbon transition policies have always been the focus of people's attention. As early as 1997, the Kyoto Protocol proposed to take the market mechanism as a new path to reduce greenhouse gas emission and formed carbon emission trading with carbon dioxide as a commodity. At present, more than 30 countries in the world have introduced carbon trading, carbon tax, or policy mix to reduce carbon emission. Road transport is the fastest growing source of global carbon emission and there is an urgent need for appropriate carbon reduction policies. According to 2019 statistics from the International Energy Agency, road transport accounts for 84.1% of carbon dioxide emissions from the transport sector [1]. Road traffic is the main source of carbon emission in China, which poses a great challenge to the realization of carbon neutrality and carbon peak in China. How to reasonably reduce the carbon emission from private cars in China and introduce appropriate emission reduction policies are of great significance. Therefore, based on urban private car trajectory data, this paper evaluates the emission reduction effect of private car under carbon trading policy, carbon tax policy, and policy mix through MATLAB simulation.

At present, the research on the effectiveness of carbon tax is mainly divided into two aspects. One is that carbon tax is effective and has additional effects on carbon emission reduction. A. Baranzini found that the implementation of carbon tax can obtain hidden benefits, and its negative effects can be compensated through tax design and fiscal revenue [2]. According to Tan et al. compared with no carbon tax policy, carbon tax reduces carbon emission and corporate profits and increases social welfare to a certain extent [3]. Xie et al. concluded that the implementation of carbon tax policy can effectively reduce the carbon emission intensity of local industries, but it will cause a certain loss of GDP [4]. On the other hand, carbon tax policy is not significant and has a negative impact on carbon emission reduction. M. Bolton et al. showed that there is no clear evidence that a carbon tax will reduce carbon emissions, while other policy tools will have a role in reducing global warming [5]. O. Cass et al. proposed that the implementation of carbon tax would lead to a vicious circle in which the family would bear the cost and could not get the offset dividend. According to [6], the carbon tax policy can bring about the reduction of carbon emission, but the potential utility and negative effects are uncontrollable, so we need an adequate and appropriate carbon emission reduction plan. A large number of studies on the effectiveness of carbon trading have proved the emission reduction and economic effects of carbon trading [7–9]. As for the factors affecting the utility of carbon trading, L. S. Yang et al. proposed that the price of carbon trading would significantly affect the utility of carbon trading, and the higher the carbon price, the greater the impact of carbon trading [10]. Yu et al. proposed that the energy structure, technological innovation, and industrial structure are the three main paths that affect the effectiveness of carbon emission reduction [11]. Fang et al. believed that the initial allocation method of carbon emission rights would significantly affect the effectiveness of carbon trading [12].

At present, the effectiveness of carbon trading policy has been widely recognized. As for the comparative study on the implementation effects of carbon trading policy and carbon tax policy, most scholars believed that carbon trading policy and carbon tax policy have different application scopes and effects. Y. Hu et al. found that there is no cross-strengthening effect between carbon trading policy and carbon tax policy; the emission reduction effect of carbon tax is more significant in developing countries, and the emission reduction effect of carbon trading does not differ between developing countries and developed countries [13]. Zhao et al. found that when the amount of social emission reduction task is small, carbon trading policy is superior to carbon tax policy; when the emission reduction task is heavy, carbon tax policy is better than carbon trading policy [14]. Yu et al. found that implementing the carbon tax policy in the short term and implementing the carbon trading policy in the long term would have better emission reduction effect [15]. However, some scholars held different views. Yonah et al. believed that the implementation of carbon tax does not need complex regulation and can immediately release the carbon price signal; however, the implementation cycle of carbon trading policy is long, and the adjustment of carbon price is slow [16]. Harwatt et al. showed that personal carbon trading policy might produce greater emission reduction compared with carbon tax policy [17]. In addition, some scholars have shown that, compared with the implementation of a single carbon emission reduction policy, the low-carbon policy mix can produce better emission reduction effect. Gu et al. showed that low-carbon policy mix that combines technology transfer and R&D improvement can achieve the 2°C mitigation target [18]. Galinato simulated the policy mix of tax and subsidy and showed that the integrated policy of tax and subsidy can increase social welfare [19]. Zhao et al. compared the differences between the carbon mitigation and economic impacts of a policy mix versus a single policy and showed that the low-carbon policy mix is comprehensive in terms of both price flexibility and coverage scope [20]. The implementation of low-carbon transition policy mix can have an excellent emission reduction effect and social benefits.

With the increasing number of carbon-emission reduction tasks, single carbon-emission reduction policy can no longer meet the existing needs, and the emission reduction effect of policy mix has become a hot topic of research. Shi et al. found that, compared with the implementation of a single emission reduction policy, the policy mix of carbon trading and carbon tax can not only achieve the emission reduction target, but also make dispersed emission sources undertake emission reduction obligations [21]. Through the empirical analysis of equilibrium model, Li et al. concluded that the policy mix could strengthen the impact on energy consumption compared with carbon trading policy and carbon tax policy [22]. Burton et al. proposed environmental policy mix that could further improve the effectiveness of carbon emission reduction [5]. Policy mix can generally balance the interests of multiple parties and has significant advantages over the implementation of a single policy. At present, there are few studies on quantitative analysis of the emission reduction effects of carbon trading, carbon tax, and policy mix. Therefore, this paper, based on the urban private car trajectory data, evaluates and compares the carbon emission reduction effects from the perspective of no policy, single carbon trading perspective, single carbon tax perspective, and policy mix perspective to provide some ideas for the implementation of carbon emission reduction policies for private cars. The remainder of this paper is organized as follows. Section 2 establishes the prediction model and the consumer utility model. Section 3 evaluates and analyzes the policy implementation effect. Section 4 compares the effectiveness of policy implementation. Section 5 puts forward conclusions and corresponding proposals.

2. Materials and Methods

2.1. Model Selection. This paper selects 10,000 urban private car trajectory datasets for regression prediction. The driving distance, driving time, and driving fuel consumption of private cars are taken as the predictive variables of regression learning [23]. In addition, carbon emission is taken as the target variable. This paper uses the set aside method to verify the dataset and cotrain the linear regression model: regression tree, support vector machine, Gaussian process regression model, tree integration, neural network, and 15 other algorithms [24]. This paper selects the final model algorithm by comparing RMSE of validation set. We find that RMSE under three-layer neural network algorithm is the smallest by comparing RMSE under ten algorithms, so this paper establishes a three-layer neural network model to predict the carbon emission of private cars. RMSE of each algorithm is shown in Table 1.

Table 1: RMSE of 15 algorithms.

Algorithm	Interactive linearity	Fine tree	Quadratic SVM	Square index GPR	Two-layer neural network
RMSE	0.00921	0.09305	1.6483	0.00921	0.00917
Algorithm	Robust linearity	Optimizable tree	Optimizable SVM	Optimizable GPR	Three-layer neural network
RMSE	0.00922	0.09304	0.15121	0.00922	0.00916
Algorithm	Step linearity	Ascension tree	Optimizable integration	Index GPR	Wide neural network
RMSE	0.00921	0.2617	0.09388	0.02748	0.00924

2.2. Three-Layer Neural Network Model. This paper takes driving mileage, driving time, and driving fuel consumption as predictive variables and carbon emission as target variables based on urban private car trajectory data. A three-layer neural network model is constructed to predict the carbon emission of private cars [25].

For the processing of the training dataset, this paper adopts the MapMinmax function to carry out the normalization. Its expression is as follows:

$$Y = \frac{(y_{\max} - y_{\min}) * (x - x_{\min})}{(x_{\max} - x_{\min})} + y_{\min}. \quad (1)$$

For three fully connected layers, the size of each layer is 10, the activation function is ReLU, and its output is as follows:

$$a_k^l = \mathrm{Relu}\left(w_k^l a_k^{l-1} + b_k^l\right), \quad (2)$$

where a_k^l is the output value of layer l, w_k^l is the k-th weight in the l-th layer, a_k^{l-1} is the k-th eigenvalue in layer l-1, and b_k^l is the deviation.

After the output of the forecast results, the root mean square error (RMSE), mean absolute error (MAE), and mean square error (MSE) are used for error evaluation to judge the accuracy. This paper calculates the actual carbon emission of private cars adopting IPCC bottom-up calculation method. Its equation is as follows:

$$S = \sum_{i=1}^{n} F_i * Q_i * E_i, \quad (3)$$

where S is the total carbon dioxide emission, F_i is the i-th energy's default value of net calorific value, Q_i is the i-th energy's default value of effective CO_2 emission factor, E_i is the i-th energy's consumption and i is the amount of energy.

2.3. Consumer Utility Model from Multiple Policy Perspectives. From the perspective of carbon trading, this paper treats fuel consumption, carbon emission, and other commodities as three kinds of commodities. According to the commodity utility function proposed by Douglas function, consumer utility depends on the degree of preference for fuel consumption, carbon emission, and other commodities. In the case of a certain income, consumer is willing to bear a limited amount of fuel consumption and carbon emission. Given a certain amount of carbon emission that the government allocates for free, consumer will have to make purchases in the carbon trading market if they exceed the free quota. From the perspective of carbon trading, the utility function and income constraints of consumer are as follows:

$$U_1(x_1, x_2, x_3) = x_1^{\alpha_1} x_2^{\beta_1} x_3^{1-\alpha_1-\beta_1}, \quad (4)$$

$$M = x_1 p_1 + (x_2 - x_0) p_2 + x_3 p_3, \quad (5)$$

where $U_1(x_1, x_2, x_3)$ is the consumer's total utility function and x_1, x_2, and x_3 represent the fuel consumption, the carbon emission, and the quantity of other commodities, respectively. α_1 and β_1 indicate the degree of consumer preference for fuel consumption and carbon emission, respectively; $1 - \alpha_1 - \beta_1$ is the degree of consumer's preference for other goods. Moreover, M is consumer income; p_1 is fuel price; p_2 is carbon price; p_3 is other commodities price; x_0 is free quota of carbon emission. From the above, it can be concluded that consumer utility maximization is an extremum problem under income constraints. The Lagrange function is constructed as follows:

$$L(x_1, x_2, x_3, \lambda) = x_1^{\alpha_1} x_2^{\beta_1} x_3^{1-\alpha_1-\beta_1} + \lambda\left[x_1 p_1 + (x_2 - x_0) p_2 + x_3 p_3 - M\right]. \quad (6)$$

Combining the above Douglas function and Lagrange function, the stagnation point can be obtained as follows:

$$x_1 = \frac{\alpha_1 (M + p_2 x_0)}{p_1}, \quad (7)$$

$$x_2 = \frac{\beta_1 (M + p_2 x_0)}{p_2}, \quad (8)$$

$$x_3 = \frac{(1 - \alpha_1 - \beta_1)(M + p_2 x_0)}{p_3}. \quad (9)$$

Substitute Equations (7)–(9) into (4). From the perspective of carbon trading, the utility function of consumer is as follows:

$$U_1(x_1, x_2, x_3) = \left[\frac{\alpha_1 (M + p_2 x_0)}{p_1}\right]^{\alpha_1} \left[\frac{\beta_1 (M + p_2 x_0)}{p_2}\right]^{\beta_1} \left[\frac{(1 - \alpha_1 - \beta_1)(M + p_2 x_0)}{p_3}\right]^{(1-\alpha_1-\beta_1)}. \quad (10)$$

From the perspective of carbon trading, when consumer's driving emissions exceed the free quota, the additional carbon emission trading expenses will be equivalent to the increase in fuel prices. As the cost of travel increases, consumer will look for alternatives to driving, such as taking subways and buses, and trade the saved carbon emission to benefit. According to the equation of demand price elasticity, it can be presented as follows:

$$Q(p) = Q\left(1 - \frac{\Delta P}{P}\right), \tag{11}$$

$$T_{s.y} = \left(x_2 - x_0\right) * p_2. \tag{12}$$

In the above formula, $Q(p)$ is the fuel consumption of consumer after the cost of travel increases, Q is raw fuel consumption, ΔP is price change, and P is the price of raw fuel. $T_{s.y}$ is the consumer's personal income obtained by participating in carbon trading.

From the perspective of carbon tax, this paper regards fuel consumption and other commodities as two kinds of commodities. According to the commodity utility function proposed by Douglas, consumer utility depends on the degree of preference for fuel consumption and other commodities. With a given income, there is a limit to how much consumer is willing to pay for fuel and taxes. That is, from the perspective of carbon tax, the utility function and income constraints of consumer are as follows:

$$U_2\left(x_1, x_3\right) = x_1^{\alpha_2} x_3^{1-\alpha_2}, \tag{13}$$

$$M = x_1 p_1 (1 + t) + x_3 p_3. \tag{14}$$

In model (13), α_2 represents the preference degree of consumer to fuel consumption from the perspective of carbon tax, and t represents the tax rate. By constructing Lagrange function, the utility function of consumer is as follows:

$$U_2\left(x_1, x_3\right) = \left[\frac{\alpha_2 M}{p_1 (1 + t)}\right]^{\alpha_2} \left[\frac{\left(1 - \alpha_2\right) M}{p_3}\right]^{1-\alpha_2}. \tag{15}$$

From the perspective of carbon tax, the imposition of carbon tax policy is equivalent to the rise of fuel prices and the increase of travel costs, and consumer will change the travel mode and reduce fuel consumption. In addition, tax revenue can be used to increase government revenue and promote economic development; it is as follows:

$$T_{s.s} = t * p_1 * Q, \tag{16}$$

where $T_{s.s}$ is the government revenue.

From the perspective of policy mix, the government imposes a carbon tax on consumer using fuel. In the carbon trading stage, consumer can trade or use the free carbon emission quota, and they need to buy the carbon emission beyond the free carbon emission quota. According to Douglas function and income budget function, consumer utility function and income constraint are as follows:

$$U_3\left(x_1, x_2, x_3\right) = x_1^{\alpha_3} x_2^{\beta_3} x_3^{1-\alpha_3-\beta_3}, \tag{17}$$

$$M = x_1 p_1 (1 + t) + \left(x_2 - x_0\right) p_2 + x_3 p_3. \tag{18}$$

In the above formula, α_3 and β_3 represent the consumer's preference degree for fuel consumption and carbon emission from the perspective of policy mix, respectively; $1 - \alpha_3 - \beta_3$ is consumer's preference degree for other commodities from the perspective of policy mix. The utility function of consumer is as follows:

$$U_3\left(x_1, x_2, x_3\right) = \left[\frac{\alpha_3 \left(M + p_2 x_0\right)}{p_1 (1 + t)}\right]^{\alpha_3} \left[\frac{\beta_3 \left(M + p_2 x_0\right)}{p_2}\right]^{\beta_3} \left[\frac{(1 - \alpha - \beta)\left(M + p_2 x_0\right)}{p_3}\right]^{\left(1-\alpha_3-\beta_3\right)}. \tag{19}$$

From the perspective of policy mix, fuel consumption needs to pay taxes, and individuals need to pay for their excess carbon dioxide emission. Taxes can increase government revenue, carbon trading can increase personal income, and policy mix can increase carbon emission cost and guide consumer to green travel. From the perspective of no policy, consumer utility function depends on the preference degree of fuel consumption and other commodities, and the budget for transportation is fixed. The consumer utility function and income constraint are as follows:

$$U_4\left(x_1, x_3\right) = \left[\frac{\alpha_4 M}{p_1}\right]^{\alpha_4} \left[\frac{\left(1 - \alpha_4\right) M}{p_3}\right]^{1-\alpha_4}, \tag{20}$$

$$M = x_1 p_1 + x_3 p_3. \tag{21}$$

In the above formula, α_4 represents consumer's preference degree for fuel consumption from the perspective of no policy. Carbon emission is not restricted from the perspective of no policy.

3. Results and Discussion

3.1. Analysis of Regression Effect and Fitting Effect. This paper uses the set aside method to verify dataset. As can be seen from Figure 1, this paper trains the predicted response of the regression prediction algorithm which coincides with the real response, and almost all points are located on the line. In Figure 2, the residuals of all point sets are all within plus or minus 0.05. In addition, in the regression algorithm of three-layer neural network, RMSE = 0.00916, MSE = 0.000084, MAE = 0.00781, the smaller the indicators are, the better the prediction effect of the algorithm is. Therefore, the three-layer neural network regression algorithm trained in this paper has an excellent prediction effect.

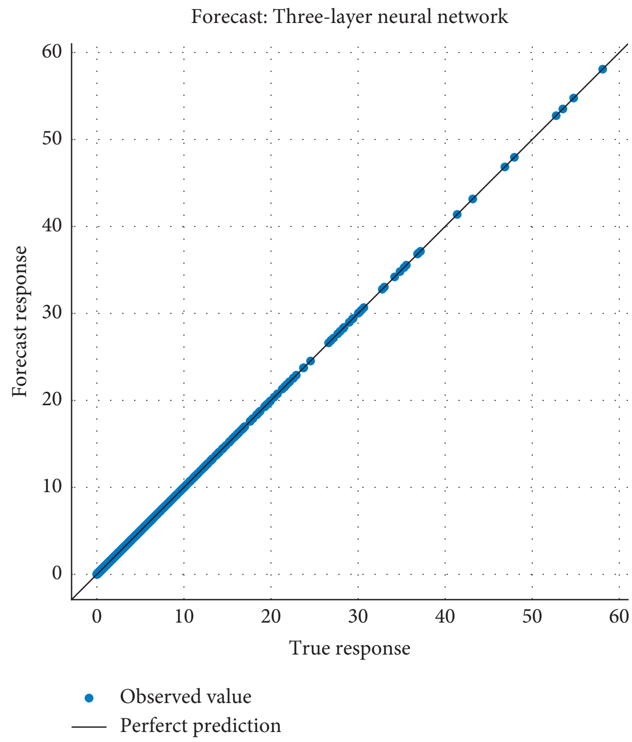

Figure 1: Verify graph with actual and predicted values.

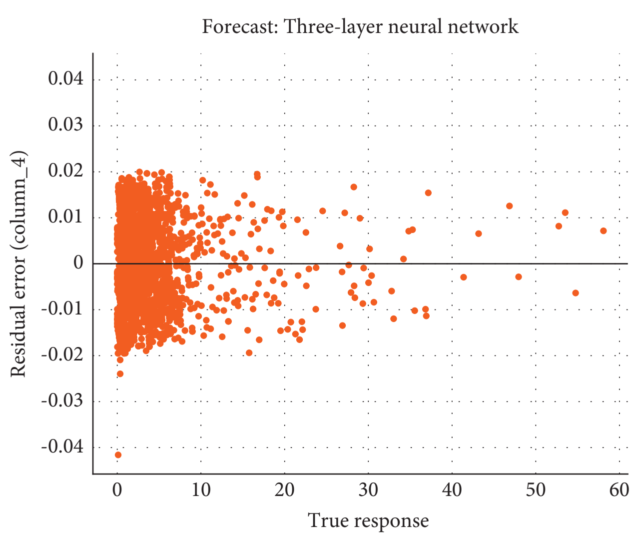

Figure 2: Residual validation graph.

The fitting effect of the three-layer neural network prediction model established in this paper is as follows. In Figure 3, training sample $R = 0.99898$; validation sample $R = 0.9993$; test sample $R = 0.99904$; all samples $R = 0.99904$. The closer R is to 1, the better the fitting effect is. The R of four sample sets is greater than 0.998; the fitting effect is excellent. In addition, as can be seen from Figure 4, the total error range of the three-layer neural network ranges from -0.03416 (the leftmost bin) to 0.04034 (the rightmost bin). This error range is divided into 20 bins, and the width of each bin is only 0.004, and the error size is less than 0.05. The prediction effect is excellent.

RMSE, MAE, and MSE of the three-layer neural network prediction model are 0.00945, 0.00802, and 0.000089, respectively; RMSE, MAE, and MSE of regression model are 0.00916, 0.00781, and 0.000084. The RMSE error is 0.00029, the MSE error is 0.000005, and the MAE error is 0.00021. The error between the two models is extremely small. Therefore, the three-layer neural network model established in this paper has a good prediction effect.

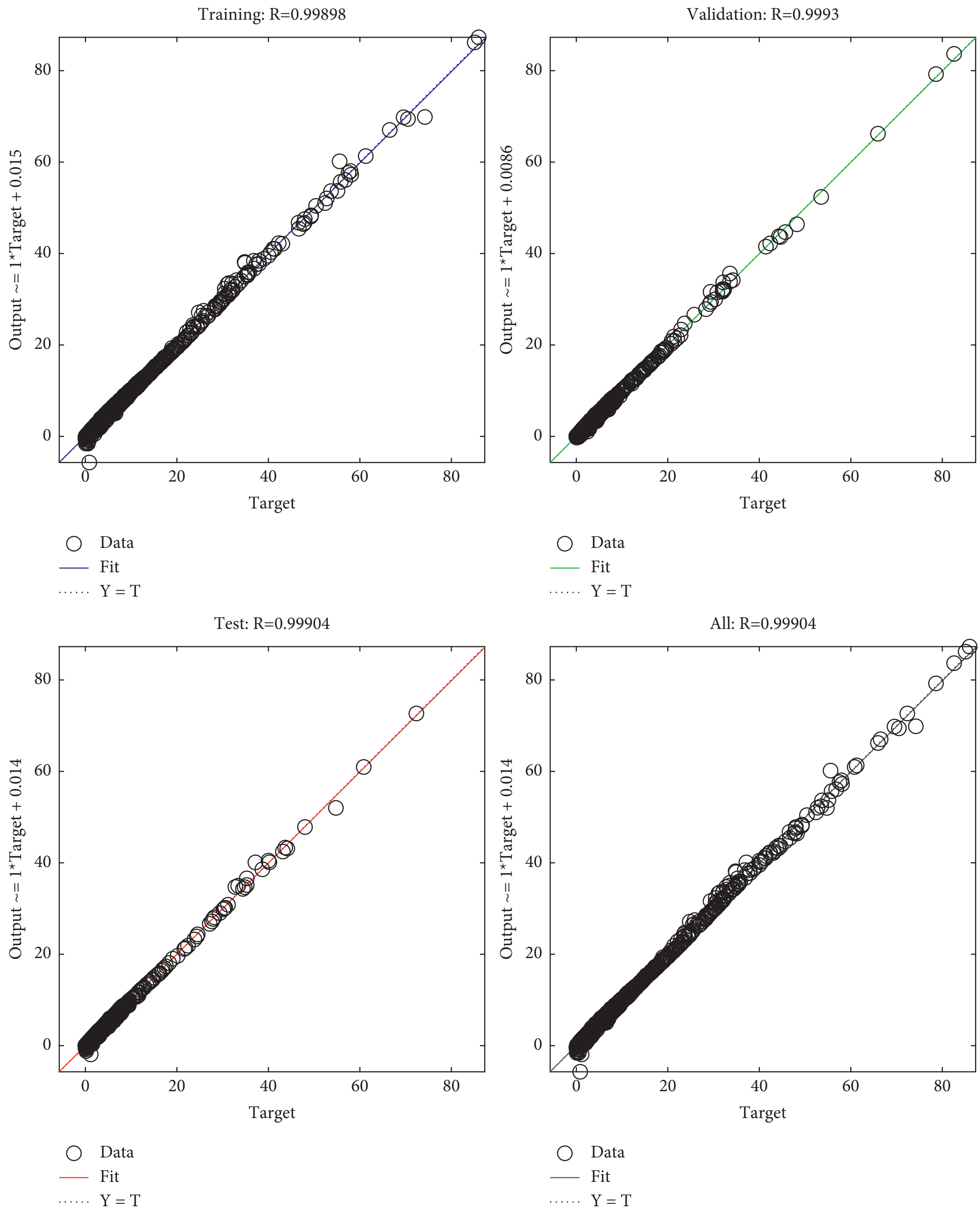

Figure 3: Regression curve of three-layer neural network.

According to the three-layer neural network model established above, this paper selects another 10,000 pieces of data that have not been trained in the model to make deep learning. After obtaining the predicted value of the carbon emission of private cars, combined with the emission reduction set by the government, the limited carbon emission will be equally distributed to urban private car consumers free of charge. After simulation calculation, the total carbon emission from 10,000 private cars is estimated to be 31187.26 kg (the emission reduction set by the government in this paper is 100%), and each private car consumer can get 3.12 kg free carbon emission.

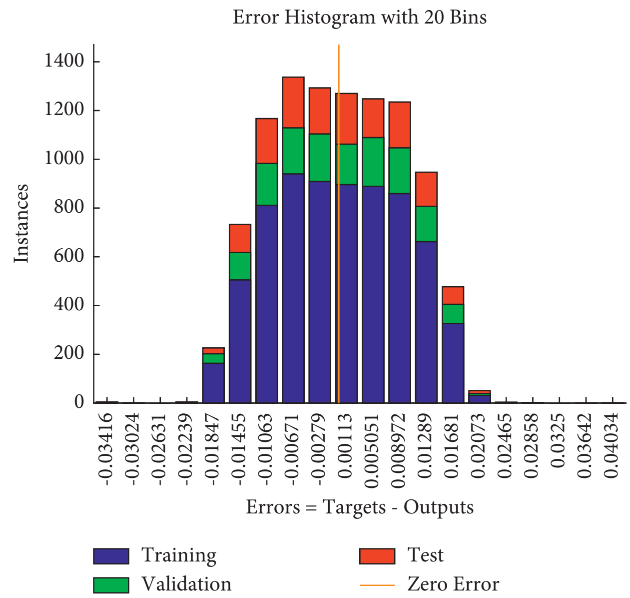

Figure 4: Error histogram of three-layer neural network.

3.2. Evaluation of Policy Implementation Effect. This paper respectively selects three groups of simulation data of excess emission, equal emission, and balance emission, evaluates and compares the carbon emission, travel costs, personal income, or government revenue of private car consumer from the perspective of carbon tax, carbon trading, and policy mix, and evaluates the effectiveness of policy implementation. Excess emission represents that the consumer's carbon emission exceeds the free quota (3.12 kg). Equal emission represents that the consumer's carbon emission is equal to the free quota. Balance emission represents that the consumer's carbon emission is less than the free quota. Government revenue refers to the carbon tax collected, which is calculated by (16). Personal income refers to the income consumers receive from carbon trading, which is calculated by (12). Travel cost refers to the cost borne by consumer to drive a car, which is calculated by (11).

As can be seen from Table 2, under the premise of excess emission, the carbon emission in the perspective of no policy is 5.07 kg, higher than the carbon emission under the other three perspectives, indicating that the implementation of emission reduction policy is effective. When the carbon tax rate is 20%, the emission reduction effect from the perspective of policy mix is the best. The government revenue from the perspective of carbon tax is the highest, and the travel cost of consumer from the perspective of policy mix is the lowest. The personal incomes under the perspectives of carbon trading and policy mix are both negative. When the carbon tax rate is 40% and 60%, the personal income from the perspective of policy mix is the best.

As can be seen from Table 3, under the premise of equal emission, consumers do not need to conduct carbon trading, and the implementation of a single carbon trading policy is ineffective at this time. The carbon emission from the perspective of no policy is 3.12 kg, which is higher than the carbon emission from the perspective of carbon tax and policy mix. The implementation of the carbon tax policy is effective. In addition, the carbon emission, travel costs, and government revenue from the perspective of carbon tax and policy mix are consistent. With the rise of the carbon tax rate, both the carbon emission and the travel costs from the perspective of carbon tax and policy mix are decreasing, the government income is increasing, and the personal income from the perspective of policy mix is increasing.

In Table 4, under the premise of the balance emission, the carbon emission from different perspectives decreases after the implementation of emission reduction policy, so the implementation of emission reduction policy is effective. When the carbon tax rate is 20%, the emission reduction effect is optimal from the perspective of policy mix. The travel cost of consumer from the perspective of policy mix is the lowest, and the personal income of consumer from the perspective of policy mix is the highest. As for the government revenue, the government revenue from the perspective of carbon tax is the highest. When the carbon tax rate is 40% and 60%, the policy implementation effect is the same as above.

Overall, the carbon emission and travel cost from the perspective of policy mix are better than the other three perspectives. However, with the increase of carbon tax rate, there are differences between government revenue and personal income. Therefore, we draw Figures 5 and 6 to directly compare this difference in Section 4; besides, based on the evaluation of the policy implementation effect and the consumer utility model, this paper also compares consumer utility and social benefit under different emission reduction policies in Section 4.

Table 2: Evaluation of implementation effects of multiple policies under the premise of excess emission.

Policy category	Fuel consumption (kg)	Carbon emission (kg)	Travel cost (yuan)	Government revenue (yuan)	Personal income (yuan)
No policy	1.65	5.07	11.55	0	0
Carbon tax policy ($t = 0.2$)	1.32	4.05	11.09	1.85	0
Carbon tax policy ($t = 0.4$)	0.99	3.04	9.7	2.77	0
Carbon tax policy ($t = 0.6$)	0.66	2.03	7.39	2.77	0
Carbon tax policy ($t = 0.8$)	0.33	1.01	4.16	1.86	0
Carbon trade policy	1.58	4.85	11.49	0	-0.43
Policy mix ($t = 0.2$)	1.25	3.84	10.68	1.75	-0.81
Policy mix ($t = 0.4$)	0.92	2.82	9.02	2.58	0.08
Policy mix ($t = 0.6$)	0.59	1.81	6.61	2.48	0.33
Policy mix ($t = 0.8$)	0.26	0.8	3.28	1.46	0.58

4. Comparison of the Effectiveness of Policy Implementation

4.1. Comparison of Fuel Consumption between Emission Reduction Policy and No Policy. Whether carbon trading policy can effectively reduce emission can be judged according to the fuel consumption of consumer from two perspectives. The fuel consumption from the perspective of carbon trading is as follows:

$$x_1^1 = \frac{\alpha_1 \left(M + p_2 x_0\right)}{p_1}, \tag{22}$$

where x_1^1 is the fuel consumption from the perspective of carbon trading; the fuel consumption from the perspective of no policy is as follows:

$$x_1^4 = \frac{\alpha_4 M}{p_1}. \tag{23}$$

In the above formula, x_1^4 is the fuel consumption from the perspective of no policy. From the perspective of carbon trading, excess carbon emission will pay more transaction expenses, and consumer's preference for fuel consumption will decrease. $\alpha_1 \leq \alpha_4$, but $M + p_2 x_0 > M$; at this point, $\alpha_1 (M + p_2 x_0)$ and $\alpha_4 M$ cannot judge whether carbon trading is effective or not. When $x_1^1 < x_1^4$, the carbon trading policy is effective. Whether the carbon tax policy can effectively reduce emission also depends on the fuel consumption of consumer from two perspectives. The fuel consumption from the perspective of carbon tax is as follows:

$$x_1^2 = \frac{\alpha_2 M}{p_1 (1 + t)}, \tag{24}$$

where x_1^2 is the fuel consumption from the perspective of carbon tax. With the introduction of carbon tax, the cost of using fuel rises and the preference for fuel declines. $\alpha_2 \leq \alpha_4$, $t > 0$, $p_1 (1 + t) > p_1$, and $x_1^2 < x_1^4$. Therefore, the carbon tax policy is effective.

The fuel consumption from the perspective of policy mix is as follows:

$$x_1^3 = \frac{\alpha_3 \left(M + p_2 x_0\right)}{p_1 (1 + t)}. \tag{25}$$

Compared with consumption from the perspective of no policy, when $x_1^3 < x_1^4$, the policy mix is effective.

In all three cases, M is fixed, and if M goes to infinity, any emission reduction policy is ineffective.

4.2. Comparison of Government Revenue from the Perspective of Carbon Tax and Policy Mix. In Figure 5, the perspective of excess carbon tax and excess policy mix represent the government revenue obtained from a single carbon tax policy and policy mix under the premise of excess emission, while the perspective of balance carbon tax and balance policy mix represent the government revenue obtained from a single carbon tax policy and policy mix under the premise of balance emission. In general, government revenue from both perspectives increases first and then decreases. It can be seen from (11) and (16) that, with the increase of carbon tax rate, consumer preference and fuel consumption will decrease; thus the government will collect less tax. In addition, the government revenue from the perspective of policy mix is lower than that from the perspective of carbon tax, mainly because consumer can obtain personal income through carbon trading, which further reduces consumer preference and decreases fuel consumption. Therefore, the taxes levied by the government decrease more.

4.3. Comparison of Social Benefits from Multiple Policy Perspectives. Under the four perspectives, the personal income of consumer can be obtained as follows:

$$T = R - C, \tag{26}$$

where T is the personal income, R is the return of reducing carbon emission, and C is the cost of increasing carbon emission. Social benefits represent the sum of all personal incomes, which is nT; assuming that the price of fuel is fixed, the social benefits of consumers from four perspectives are shown in Figure 6. In the short term, when the demand for fuel consumption is low, the area of triangle ABD in the

Table 3: Evaluation of implementation effects of multiple policies under the premise of equal emission.

Policy category	Fuel consumption (kg)	Carbon emission (kg)	Travel cost (yuan)	Government revenue (yuan)	Personal income (yuan)
No policy	1.02	3.12	7.14	0	0
Carbon tax policy ($t = 0.2$)	0.82	2.52	6.89	1.15	0
Carbon tax policy ($t = 0.4$)	0.61	1.87	5.98	1.71	0
Carbon tax policy ($t = 0.6$)	0.41	1.26	4.59	1.72	0
Carbon tax policy ($t = 0.8$)	0.20	0.62	0.61	1.72	0
Carbon trade policy	1.02	3.12	7.14	0	0
Policy mix ($t = 0.2$)	0.82	2.52	6.89	1.15	0.27
Policy mix ($t = 0.4$)	0.61	1.87	5.98	1.71	0.31
Policy mix ($t = 0.6$)	0.41	1.26	4.59	1.72	0.47
Policy mix ($t = 0.8$)	0.2	0.62	0.61	1.12	0.58

Table 4: Evaluation of implementation effects of multiple policies under the premise of balance emission.

Policy category	Fuel consumption (kg)	Carbon emission (kg)	Travel cost (yuan)	Government revenue (yuan)	Personal income (yuan)
No policy	0.42	1.29	2.94	0	0
Carbon tax policy ($t = 0.2$)	0.34	1.04	2.86	0.48	0
Carbon tax policy ($t = 0.4$)	0.25	0.77	2.45	0.70	0
Carbon tax policy ($t = 0.6$)	0.17	0.52	1.90	0.71	0
Carbon tax policy ($t = 0.8$)	0.08	0.25	1.00	0.45	0
Carbon trade policy	0.35	1.07	2.45	0	0.51
Policy mix ($t = 0.2$)	0.27	0.83	2.27	0.38	0.57
Policy mix ($t = 0.4$)	0.19	0.58	1.86	0.53	0.63
Policy mix ($t = 0.6$)	0.1	0.31	1.12	0.42	0.7
Policy mix ($t = 0.8$)	0.02	0.06	0.25	0.11	0.77

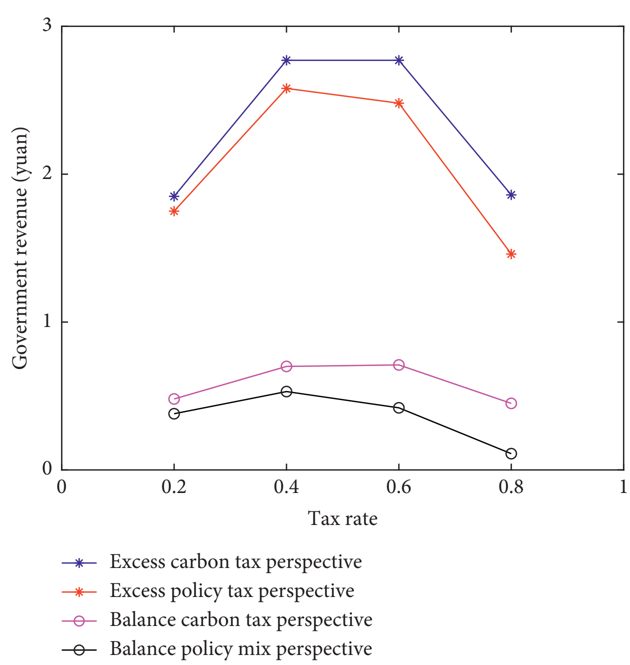

Figure 5: Comparison of government revenue.

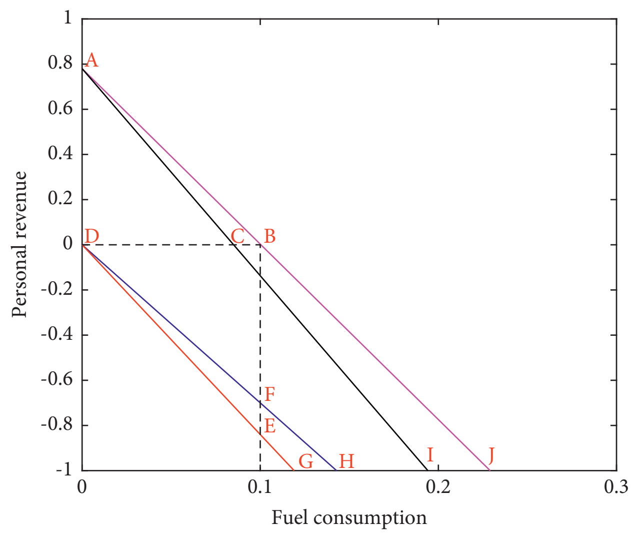

Figure 6: Social benefits from four perspectives.

figure above is the total social benefits from the perspective of carbon trading, and the area of triangle ACD is the total social benefits from the perspective of policy mix. The area of triangle BDF is the negative total social benefits from the perspective of no policy, while the area of triangle BDE is the negative total social benefits from the perspective of carbon tax. $S_{\Delta AB\,D} > S_{\Delta AC\,D} > S_{\Delta B\,DF} > S_{\Delta B\,DE}$; the social benefits from the perspective of carbon trading are higher than those from other perspectives. Therefore, in the short term, when the emission reduction task is certain, carbon trading can obtain greater social benefits. When the demand for fuel consumption is high, the social benefits under the four perspectives are $S_{\Delta AOJ}$, $S_{\Delta AOI}$, $S_{\Delta AOH}$, and $S_{\Delta AOG}$, respectively. The total social benefits under the perspective of carbon tax are higher than those under other perspectives. Therefore, when the long-term carbon emission reduction task is heavy, carbon tax policy can be adopted to improve social benefits.

4.4. Comparison of Consumer Utility from Multiple Policy Perspectives. The four perspectives of consumer utility are (10), (13), (17), and (20). This paper assumes that consumer has a consistent preference for each commodity; that is, $\alpha_1 = \alpha_2 = \alpha_3 = \alpha_4$ and $\beta_1 = \beta_2 = \beta_3 = \beta_4$. Fuel consumption, carbon emissions, and other commodities are regarded as three kinds of commodities. The consumer utility of carbon tax policy and no policy is compared between two-commodity mix (fuel consumption and other commodities). It is as follows:

$$U_4^2 = \frac{U_2(x_1, x_3) = [\alpha_2 M/p_1(1+t)]^{\alpha_2}[(1-\alpha_2)M/p_3]^{1-\alpha_2}}{U_4(x_1, x_3) = [\alpha_4 M/p_1]^{\alpha_4}[(1-\alpha_4)M/p_3]^{1-\alpha_4}}, \quad (27)$$

where U_4^2 is the ratio of consumer utility under carbon tax policy to no policy. The consumer utility of carbon trade policy and policy mix is compared between three-commodity mix (fuel consumption, carbon emission, and other commodities), and it is as follows:

$$U_3^1 = \frac{U_1(x_1, x_2, x_3) = [\alpha_1(M+p_2x_0)/p_1]^{\alpha_1}[\beta_1(M+p_2x_0)/p_2]^{\beta_1}[(1-\alpha_1-\beta_1)(M+p_2x_0)/p_3]^{(1-\alpha_1-\beta_1)}}{U_3(x_1, x_2, x_3) = [\alpha_3(M+p_2x_0)/p_1(1+t)]^{\alpha_3}[\beta(M+p_2x_0)/p_2]^{\beta_3}[(1-\alpha-\beta)(M+p_2x_0)/p_3]^{(1-\alpha_3-\beta_3)}}, \quad (28)$$

where U_3^1 is the ratio of consumer utility under carbon trading policy to policy mix. In the process of policy implementation, the carbon tax rate can be adjusted continuously, as shown in Figure 7.

As can be seen from Figure 7, when consumer has the same preference α, the ratio of consumer utility of the two-commodity mix decreases with the increase of tax rate. After the implementation of the carbon tax policy, the consumer utility will continue to decrease compared with that without the implementation of the emission reduction policy. Therefore, the implementation of the carbon tax policy will lead to the decline of the consumer utility. In the three-commodity mix, consumer has the same preference α and, with the increase of tax rate, the ratio of consumer utility of the three-commodity mix increases; that is, compared with the implementation of a single carbon trading policy, the

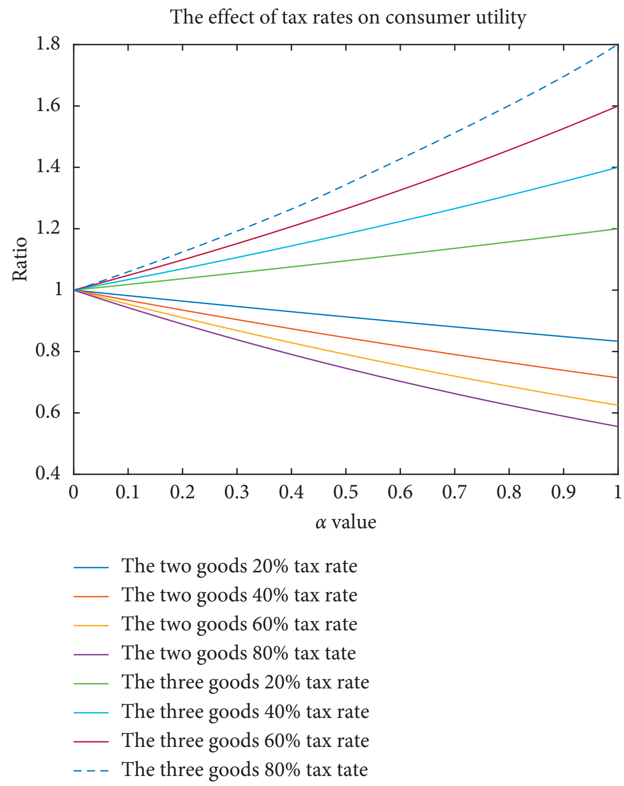

Figure 7: The comparison of consumer utility.

implementation of policy mix will lead to the decline of consumer utility. In addition, when the tax rate is fixed, the implementation of carbon tax policy will lead to the decline of consumer utility with the increase of consumer preference α, regardless of the mix of two commodities or three commodities.

5. Conclusions

By comparing the effectiveness of the implementation of four policies, this paper concludes that the implementation of carbon tax policy is effective, and the implementation of effective carbon trading policy and policy mix needs certain conditions. This paper, through the evaluation of consumer's personal income, travel cost, carbon emission, and government revenue, concludes that the carbon emission and travel cost from the perspective of policy mix are better than the other three perspectives. Moreover, the government revenue from the perspective of carbon tax is the highest, but there are some differences between government revenue and personal income with the rise of carbon tax rate. By comparing the difference of government revenue between single carbon tax policy and policy mix, this paper concludes that the reason for the difference of government revenue is that the increase of carbon tax leads to the decrease of consumer's preference for fuel consumption. By comparing the consumer's individual utility from multiple policy perspectives, this paper concludes that the implementation of carbon tax policy will lead to the decline of consumer utility. By comparing social benefits from multiple policy perspectives, this paper concludes that the carbon trading policy is better in the short term, while the carbon tax policy is better in the long term.

Compared with previous studies [14, 26], this paper introduces emission reduction policies such as carbon trading, carbon tax, and policy mix into the carbon emission of private cars and quantitatively evaluates the emission reduction effects, personal utility, and social benefit from four policy perspectives, so as to provide guidelines on carbon emission reduction from urban private cars.

In line with the vision of achieving carbon neutrality by 2060, road transport emission reduction policies need to be implemented. Based on the evaluation and comparison of emission reduction from four policy perspectives proposed in this paper, the relevant policy proposals can start from the following aspects. (1) Different emission reduction measures should be taken according to the actual situation of different regions and industries. Carbon tax policy, carbon trading policy, and policy mix have different emission reduction effects and social benefits. Areas with high carbon emissions should adopt the optimal policy mix to limit carbon emissions and improve social benefits. (2) It is better to implement the carbon trading policy in the short term and the carbon tax policy in the long term and rationally shift to the policy mix to obtain benefits that are more comprehensive. Carbon trading has low social cost and strong flexibility, which is conducive to reducing the loss of social benefits in the short term. The social cost of carbon tax is high, but it is easy to implement. After a certain amount of short-term tasks is completed, carbon tax policy can be introduced. (3) Carbon tax policy can be combined with the subsidy mechanism. The adoption of carbon tax policy will reduce consumer utility. Government can combine the carbon tax policy with the subsidy mechanism and use the revenue to invest in new energy technology R&D and emission reduction projects to make up for the drawbacks of carbon tax policy.

Data Availability

The data used to support the findings of this study have not been made available because of the confidentiality agreements with research collaborators. The data form part of an ongoing commercial program and study.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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