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WOA–BP-based Carbon Emission and Peak Carbon Prediction for Tianjin Civil Aviation

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Abstract: As a major greenhouse gas emitter, the aviation industry faces the dual challenge of meeting the rapidly growing flight demand while reducing carbon emissions. Using Tianjin's civil aviation carbon emissions as a case study, this research compares the predictive performance of partial least squares regression (PLSR)-enhanced STIRPAT and WOA–BP models. Results indicate that the WOA–BP model achieved superior prediction accuracy, with an average absolute relative error of 1.971%. Three scenarios—low-carbon, standard, and high-carbon—were established to predict the carbon peak year for Tianjin's civil aviation. Results indicate that only the low-carbon scenario shows a peak of 928,800 tons in 2040, whereas the other two scenarios are not expected to reach the carbon peak before 2050. Thus, relevant departments should strengthen technological innovation and management coordination in the civil aviation field, rationally plan the development and emission reduction path of civil aviation, and promote the high-quality and sustainable development of Tianjin civil aviation to achieve early carbon peak.

1. Introduction

The aviation industry is one of the top ten sectors for greenhouse gas emissions globally[1]. To accurately predict carbon emissions from civil aviation, this paper will compare the effectiveness of the modified STIRPAT model [2-4]with the BP-WOA model[5-6] for forecasting civil aviation carbon emissions. Considering that carbon emissions from civil aviation fall under mobile emissions, with emission sources being very complex and difficult to measure directly, this study adopts the "top-down" accounting method proposed in the IPCC National Greenhouse Gas Inventory Guidelines (2006). Furthermore, since carbon emissions resulting from fuel consumption in aircraft are the primary source of civil aviation carbon emissions, and the fuel predominantly used in civil aviation is aviation kerosene, this paper establishes the calculation formula for civil aviation carbon emissions as: C = E Ɨ, where C represents the total carbon emissions from civil aviation, E is the amount of aviation kerosene consumed, and I is the carbon emission factor, which, according to the IPCC guidelines, is set at 3.15 kg/kg.

2. Aviation carbon emission projections

2.1. Sample Selection and Data Sources

This paper uses civil aviation in Tianjin as a case study.Relevant data for Tianjin were obtained from the China Statistical Yearbook and the Tianjin Statistical Yearbook. Subsequently, gray correlation analysis was performed. The gray correlation coefficients between passenger traffic volume, passenger turnover, GDP, tertiary industry GDP, population, and civil aviation carbon emissions in Tianjin were calculated (Table 1):

Table 1. Gray correlation between indicators and civil aviation carbon emissions in Tianjin

Indicator	Passenger traffic (10,000 persons)	Passenger traffic turnover (million person-kilometers)	GDP (billion yuan)	Tertiary GDP (billion yuan)	Population (10,000 persons)
Gray correlation	0.902	0.858	0.923	0.890	0.980

Therefore, this study chooses five indicators as reference indicators: passenger traffic, passenger turnover, GDP, tertiary GDP, and population. The data for each indicator from 2009 to 2019 were then summarized (Table 2):

Table 2. Statistical indicators for Tianjin, 2009–2019

Year	Carbon emissions (10,000 tons)	Passenger traffic (10,000 persons)	Passenger traffic turnover (million man-kilometers)	GDP (billions of yuan)	Tertiary GDP (billion yuan)	Demographic (10,000 persons)
2009	12.0118	334	4142	5709.57	2781.3	1228.16
2010	14.5899	396	5031	6830.76	3439.31	1299.29
2011	17.3043	475	5967	8112.51	4215.15	1341
2012	34.2403	1009	11807	9043.02	4761.09	1378
2013	40.6319	1186	14011	9945.44	5383.55	1410
2014	48.4648	1382	16712	10640.62	5866.30	1429
2015	54.9028	1503	18932	10879.51	6227.61	1439
2016	63.6695	1645	21955	11477.20	6940.77	1443
2017	75.7277	1863	26113	12450.56	7717.54	1410
2018	80.3851	1915	27719	13362.92	8352.32	1383
2019	86.3968	2069	29792	14055.46	8922.87	1385

2.2. Carbon Emission Prediction Using PLSR-Improved STIRPAT Model

The basic STIRPAT equation $\ln I = \ln a + b\ln P + c\ln A + d\ln T + \ln e$ is expanded to $\ln C = \ln a + b\ln K + c\ln T + d\ln G + e\ln S + f\ln P + \ln g$, where C indicates carbon emissions from civil aviation; K, T, G, S, and P represent passenger traffic, passenger turnover, GDP, tertiary GDP, and population, respectively; a denotes the model proportionality constant; b, c, d, e, and f correspond to the elasticity coefficients of K, T, G, S, and P, respectively; and g is the random error.

The regression equation for carbon emissions from civil aviation calculated based on the PLSR-improved STIRPAT model is given by.

$$\ln C = -5.3340 + 0.2825\ln K + 0.3055\ln T + 0.2298\ln G + 0.2562\ln S - 0.0259\ln P$$

The predicted value of civil aviation carbon emissions for each year from 2009 to 2019 is calculated based on the regression equation. The relative error and average relative error are also determined. The results are listed in Table 3.

Table 3. Comparison of predicted and actual civil aviation carbon emissions in Tianjin (based on the PLSR-improved STIRPAT model)

Year	Actual carbon emissions (10,000 tons)	Projected carbon emissions (10,000 tons)	Relative error
2009	12.0118	11.2004	-6.76%
2010	14.5899	14.8721	1.93%
2011	17.3043	19.6889	13.78%
2012	34.2403	33.1668	-3.14%
2013	40.6319	40.4242	-0.51%
2014	48.4648	47.8096	-1.35%
2015	54.9028	52.7350	-3.95%
2016	63.6695	61.1615	-3.94%
2017	75.7277	73.8887	-2.43%
2018	80.3851	82.3378	2.43%
2019	86.3968	91.1290	5.48%

The calculation results show that the relative error ranges from -6.76% to 13.78%, and the average absolute error is 4.153%. The goodness-of-fit, calculated based on the PLSR-improved STIRPAT model, is $R^2 = 0.9932$, indicating a good fit. The comparison between the actual and predicted values is shown in Figure 1.

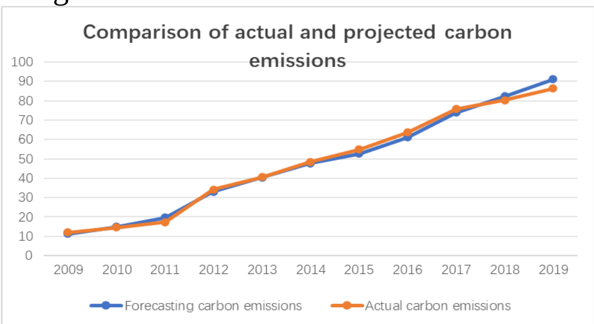

Figure 1: Comparison of predicted and actual carbon emissions from civil aviation in Tianjin (based on the PLSR-improved STIRPAT model).

2.3. Carbon emission prediction based on BP neural network and WOA–BP neural network

The BP neural network was established with the following parameters: a maximum number of 1000 iterations, an error target of 0.0001, and a learning rate of 0.01. The WOA employed the following parameters: a population size of 10 and a maximum number of 50 iterations. The data were input into both the BP neural network model and the WOA-BP neural network model, resulting in comparison charts of the actual values and predicted values for the BP neural network and the WOA-BP neural network, as shown in Figures 2, and 3.

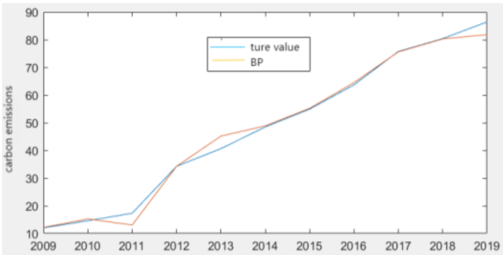

Fig. 2 Comparison of predicted and network actual carbon emissions (BP neural network)

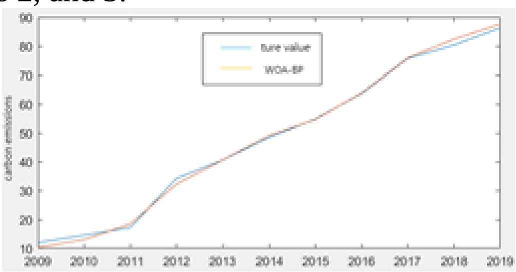

Fig. 3 Comparison of WOA–BP neural carbon emission predictions and actual values

The figure indicates that WOA–BP yields more accurate predicted values, compared with the BP neural network. The adaptation value of the WOA–BP model stabilizes after 17 iterations.

The WOA–BP model was used to predict annual civil aviation carbon emissions from 2009–2019 and calculate the relative error and average relative error. The results are presented in the Table 4. As shown in the calculations, the relative error ranges from -4.77% to 13.15%, and the average absolute relative error is 1.971%.

Table 4. Comparison of predicted and actual civil aviation values carbon emissions in Tianjin (using the WOA–BP model)

Year	Actual carbon emissions (10,000 tons)	Projected carbon emissions (10,000 tons)	Relative Error Error
2009	12.0118	11.9863	-0.21%
2010	14.5899	14.5589	-0.21%
2011	17.3043	19.5803	13.15%
2012	34.2403	32.6079	-4.77%
2013	40.6319	40.5563	-0.19%
2014	48.4648	48.4602	-0.01%
2015	54.9028	54.0981	-1.47%
2016	63.6695	63.6615	-0.01%
2017	75.7277	75.7648	0.05%
2018	80.3851	81.6097	1.52%
2019	86.3968	86.4742	0.09%

2.4. Prediction of Tianjin civil aviation carbon emissions and carbon peak (based on WOA–BP)

The preceding analysis demonstrates the superior predictive performance of the WOA–BP model relative to the PLR-improved STIRPAT model. Thus, the WOA–BP model is adopted to predict future civil aviation carbon emissions in Tianjin. Scenarios for civil aviation carbon emissions in Tianjin are created based on the indicators specified in the *Outline of the 14th Five-Year Plan for the Development of the National Economy and Society of Tianjin and the Visionary Goals for 2035*. The projected time period of civil aviation carbon emissions is divided into three time periods: 2020–2030, 2030–2040, and 2040–2050. Three scenarios are set: low-carbon scenario, standard scenario, and high-carbon scenario. The specific parameter settings are listed in Table 5 (growth rate/%).

Table 5. Parameter settings for three scenarios

Scenario	Timing	Passenger traffic	Passenger traffic turnover	GDP	Tertiary GDP	Demographic data
Low carbon	2020–2030	0.02	0.02	0.035	0.02	0.001
	2030–2040	0.01	0.005	0.025	0.01	-0.001
	2040–2050	-0.02	-0.025	0.02	0.005	-0.002
Standard	2020–2030	0.03	0.03	0.05	0.03	0.0015
	2030–2040	0.01	0.02	0.045	0.02	0.005
	2040–2050	-0.01	0.01	0.04	0.01	-0.001
High carbon	2020–2030	0.04	0.045	0.065	0.045	0.003
	2030–2040	0.03	0.035	0.055	0.035	0.002
	2040–2050	0.02	0.03	0.045	0.025	0.0015

The set parameters are input into the WOA–BP model, and the prediction curves for civil aviation carbon emissions in Tianjin under the three scenarios are shown in Figure 4.

The prediction curve shows that Tianjin civil aviation carbon emissions peak at 92.88 Mt in 2040 (low carbon scenario). Emissions do not peak by 2020 under standard and high-carbon scenarios.

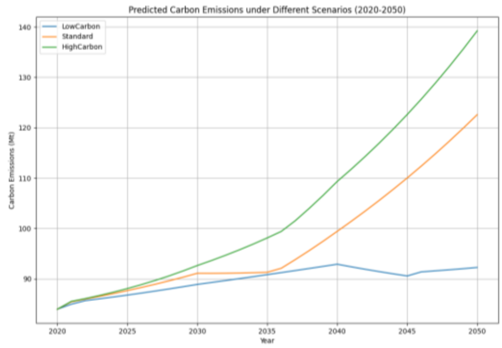

Fig. 4 Carbon Emission Forecast Curve for Tianjin Civil Aviation under Three Scenarios (2020–2050)

3. Conclusions

This study compared the predictive accuracy of the PLSR-improved STIRPAT model and the WOA–BP model for civil aviation carbon emissions in Tianjin. The results demonstrate the superior accuracy of the WOA–BP compared with the STIRPAT model.

Based on the WOA–BP neural network model, this study predicted civil aviation carbon emissions in Tianjin under various scenarios. The results indicate that emissions can peak in 2040 under the low-carbon scenario. However, this timeline is later than the national commitment to peak emissions by 2030, as pledged at the 75th United Nations General Assembly. Thus, the civil aviation sector in Tianjin is under significant pressure to reduce emissions. Therefore, relevant government departments should introduce appropriate green civil aviation policies to promote high-quality and sustainable development. These policies will facilitate reaching peak civil aviation carbon emissions in Tianjin.

Annual increases in the number of civil aviation passengers, passenger turnover, and GDP of the tertiary industry are associated with an increase in aviation fuel consumption. Civil aviation carbon emissions primarily result from the combustion of aviation fuel; thus, relevant departments must coordinate the development of civil aviation with emissions reduction to ensure control over the growth of passenger count, passenger turnover, and tertiary industry GDP, prioritizing planned and high-quality civil aviation development over hasty expansion.

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