



Research article

Accounting for the carbon emissions from domestic air routes in China

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ARTICLE INFO

Keywords:

CCD emissions

China

Carbon emission accounting

Fuel percentage method

ABSTRACT

This study seeks to build a database of China's 413 main routes in 2018, which contains the carbon emission intensity of the leading aircraft types, the Climb/Cruise/Descent (CCD) carbon emissions of each airline and each route, and the probable emissions when the routes are straight. First, the Modified Fuel Percentage Method (MFPM) is applied to calculate the carbon emission intensity of main aircraft types at various distances. Next, the carbon emissions and the Revenue Passenger Kilometers of 413 routes and 40 airlines are calculated. Then the carbon emissions of the actual route and straight route are analyzed. Dali-Kunming and Joy Air have the most significant emission intensity among the routes and airlines. However, the excess emissions from the non-straight routes account for about 10.15% of the actual emissions.

1. Introduction

Carbon emission has become the focus of social attention [1, 2]. The civil aviation industry, which has high efficiency, convenience, mobility, a significant driving force, and strong internationality, is strategic in the modern transportation system. With the growth of the national economy and the continuous expansion of residents' travel needs, the civil aviation transportation industry is gaining vigorous development. In contrast, aviation carbon emissions have maintained a constant growth trend. According to the International Air Transport Association (IATA), global commercial air transportation's total carbon dioxide emissions in 2019 reached 915 million tons, accounting for 2.4% of global carbon dioxide emissions. Furthermore, 85% of CO₂ Emissions come from passenger transportation, going 778 million tons [3]. At present, the demand for air passenger transportation is still maintaining strong growth. Therefore, the civil aviation industry urgently needs to balance the needs of green development and enhance the industry's competitiveness.

The United States, China, and the United Kingdom are the world's three largest aviation passenger CO₂ emission markets. However, it is predicted that China will surpass the United States to become the world's largest civil aviation transportation market by 2030. China's civil aviation transportation industry is currently in rapid development, followed by a rapid increase in aviation carbon emissions. The carbon emissions of China's domestic routes during 2012–2019 are shown in Figure 1 (This

data is calculated based on total turnover data and unit emission data of CAAC [4]).

Increasing aviation carbon emissions is the direct inducing factor of global warming, the greenhouse effect, and extreme weather (such as typhoons, high temperatures, heavy rains, mudslides, droughts, and other natural disasters), which have severely damaged the ecological environment [5, 6]. In addition, aviation pollutants stay in the atmosphere for a long time and transport distances, which have a more significant impact on human health and the quality of the atmosphere. The negative environmental externalities are becoming more and more serious, which has attracted the attention of government departments of various countries, aircraft manufacturers, airlines, airports, air traffic control, and other industries. As a result, energy conservation and emission reduction have been included in strategic development planning and specific work deployment.

Since 2012, the European Union has taken the lead in levying aviation carbon emissions taxes on all inbound airlines. Furthermore, in 2016, the 39th General Assembly of the International Civil Aviation Organization (ICAO) passed the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which aims to control the growth of international aviation greenhouse gas emissions and achieve the ideal global goal of Carbon Neutral Growth from 2020 [7]. According to the current phased responsibility distribution plan for international aviation emission reduction, the booming Chinese civil aviation industry will face considerable carbon offset pressure and aviation emission reduction

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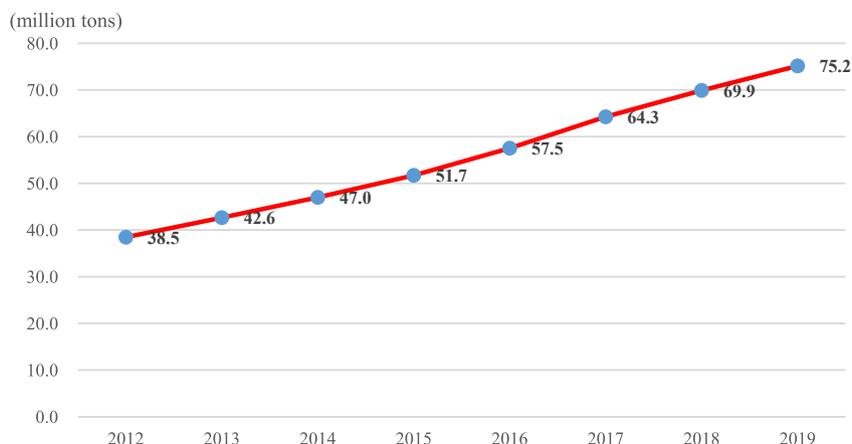


Figure 1. The carbon emissions of China's domestic routes during 2012–2019.

responsibilities. At the same time, the green development of the civil aviation industry is also of great significance to China's comprehensive implementation of the carbon-neutral vision during the “14th Five-Year Plan” period and to achieve high-quality development [8]. In this context, establishing an aviation carbon trading mechanism is the key to achieving the carbon-neutral growth of the aviation industry in China, and calculating carbon emissions of the airlines is the foundation to building a carbon trading mechanism.

The ICAO Carbon Emission Calculator [9] is a universal method for calculating aviation carbon emission. The ICAO methodology employs a distance-based approach to estimate an individual's aviation emissions using data currently available on a range of aircraft types. The ICAO Carbon Emission Calculator requires users to enter the origin and destination airport of the flight. It is then compared with the published scheduled flights to obtain the type of aircraft used to serve the two related airports and the number of departures per aircraft. Then map each plane to one of the equivalent aircraft types to calculate the trip's fuel consumption based on the great circle distance between the airports involved in the journey. The load factor and passenger-to-freight ratio obtained from the traffic and operating data collected by ICAO are then applied to obtain the proportion of total fuel usage attributable to the passengers carried. Then, the system weights the average fuel consumption of the journey based on the take-off frequency of each equivalent aircraft type. The fuel consumption is then divided by the total number of economy class equivalent passengers, giving an average fuel burn per economy class passenger. The result is then multiplied by 3.157 to obtain the amount of CO₂, which is the carbon footprint of each passenger.

However, this method has some shortcomings. First, the set distance distinction is insufficient. For example, in the ICAO Methodology [9], A320's range is from 125 km to 2,500 km, but it is much longer in China. According to the data we collected from the VariFlight [10], the flight range of A320-214 on China's domestic routes in 2018 ranged from 360 km to 3,649 km. Therefore, it is impossible to calculate according to ICAO's calculation method. Second, the specific aircraft are not distinguished. The ICAO calculation method only considers the large series but does not consider the difference between the sub-series. For example, the A320 series has many series, such as A320-100 and A320-200. According to the aircraft information of VariFlight [10], the main engine of the A320-100 series is V2500. Still, the A320-200 series' engine is CFM56-5 or V2500, which may cause these two aircraft to have a relatively significant difference in carbon emissions.

Some studies have focused on estimating aviation carbon emissions. For example, Peniche Camps et al. applied the ICAO methodology to approximate the footprint for each flight to Puerto Vallarta to explore the impact of tourism on the Mexican environment [11]. Likewise, Ekici et al. estimated the HC, CO, and NO_x emissions of the five busiest airports in

Turkey during the LTO period based on the emission factors of the Turkish National Airport Authority and ICAO engine data tables [12]. Liu et al. applied the ICAO method to estimate the emissions of the routes among 208 Chinese airports, but no discussion has been done on specific aircraft and distance segments [13]. Wasiuk et al. estimated the global emissions during 2005–2011, but they have not involved particular aircraft, routes, and airlines [14].

However, there has not been a systematic study on the carbon emission calculation and database establishment of significant airlines and routes within a country, which is the basis and core for determining the overall status of the aviation industry's carbon emissions and the establishment of aviation carbon trading mechanism. Moreover, carbon emission calculation is also the prerequisite for clarifying specific emission reduction targets and scientifically formulating emission reduction plans and the key to the transition to a low-carbon economy. Therefore, establishing an aviation carbon emission database is urgent, especially for China, a major air transport country and a significant carbon emitter.

In response to the problems mentioned above, this study considers more comprehensive aircraft types and the particularity of China's domestic routes. Furthermore, through VariFlight.com [10] and Statistical Data on Civil Aviation of China [15], this study builds a database of carbon emissions and Revenue Passenger Kilometer (RPK) of China's airlines and the major routes between 413 city-pair whose daily flights are equal to or larger than 3 in 2018. The 413 city-pair includes 319 connecting routes, and the repetitive connecting routes have been deleted. This research work is significant in establishing domestic aviation carbon emission mechanisms and realizing Carbon Neutral Growth goals.

2. Results

2.1. Carbon emissions per kilometer of different aircraft types

This study calculates the carbon emissions per kilometer of 42 types of aircraft at different flight distances (see Table 1). The exact method is based on a modified method of Fuel Percentage Method (FPM) method [16]. Comparing with the ICAO Carbon Emissions Calculator Methodology, our results are calculated from the actual operations of the domestic routes in China and cover more detailed aircraft types. The results (See Data S1 for details) show that small passenger aircraft such as CRJ900 and E190 LR equipped with high-density economy class and business class that can accommodate 86–90 passengers are more environmentally friendly on short medium-haul routes from 0 to 2000 km.

On the other hand, medium-sized passenger aircraft and upgraded new passenger aircraft such as Airbus A320 series (320-214, 320-232, 320-271N) and Boeing 737 series (737 MAX 8, 737-800) show better emission reduction performance on medium and long-distance routes of

Table 1. Descriptive statistical analysis of routes.

	Min	Max	Mean	Standard Deviation
Flight frequency (times)	1875.00	38854.00	6329.03	4801.74
Flight distance (KM)	275.00	3836.00	1351.76	586.05
Passengers	300230.00	8216591.00	872010.98	835016.30
RPK (person-kilometers)	95271825.00	9906880831.00	1195651100.65	1326008034.68
Emissions per RPK (total)	.00001742	.00015815	.00009144	.00001737
Emissions per RPK (straight line)	.00001473	.00015239	.00008158	.00001684

2000–4000 km, with the characteristics of larger passenger capacity (150–200) and higher fuel efficiency. While advanced wide-body airliners on long-haul routes, such as Boeing 777, Boeing 787, Airbus 380, Airbus 330, are leading in passenger capacity. Generally, they are equipped with economy class, business class, first-class, and the aircraft fuel consumption, carbon emissions, and operation and maintenance costs are relatively high.

The aircraft types of the same series also have specific differences in carbon emission intensity, as shown in Figure 2a and Figure 2b. For

example, for the 320 series, 320-214 and 320-232 cover more route distances. Overall, 320-251N has higher carbon emission intensity under different route distances. On the other hand, 320-271N has lower carbon emission intensity at distances of 500–2500km, while 320-214 is more environmentally friendly at long route distances of more than 2500km.

For the 737 series, the 737-700 is a more environmentally friendly type at a route distance of 500–2000km, and the carbon emission intensity of the 737-800 is higher on short-haul routes (0–500km and 500–1000km). On the other hand, the carbon emission intensity of the

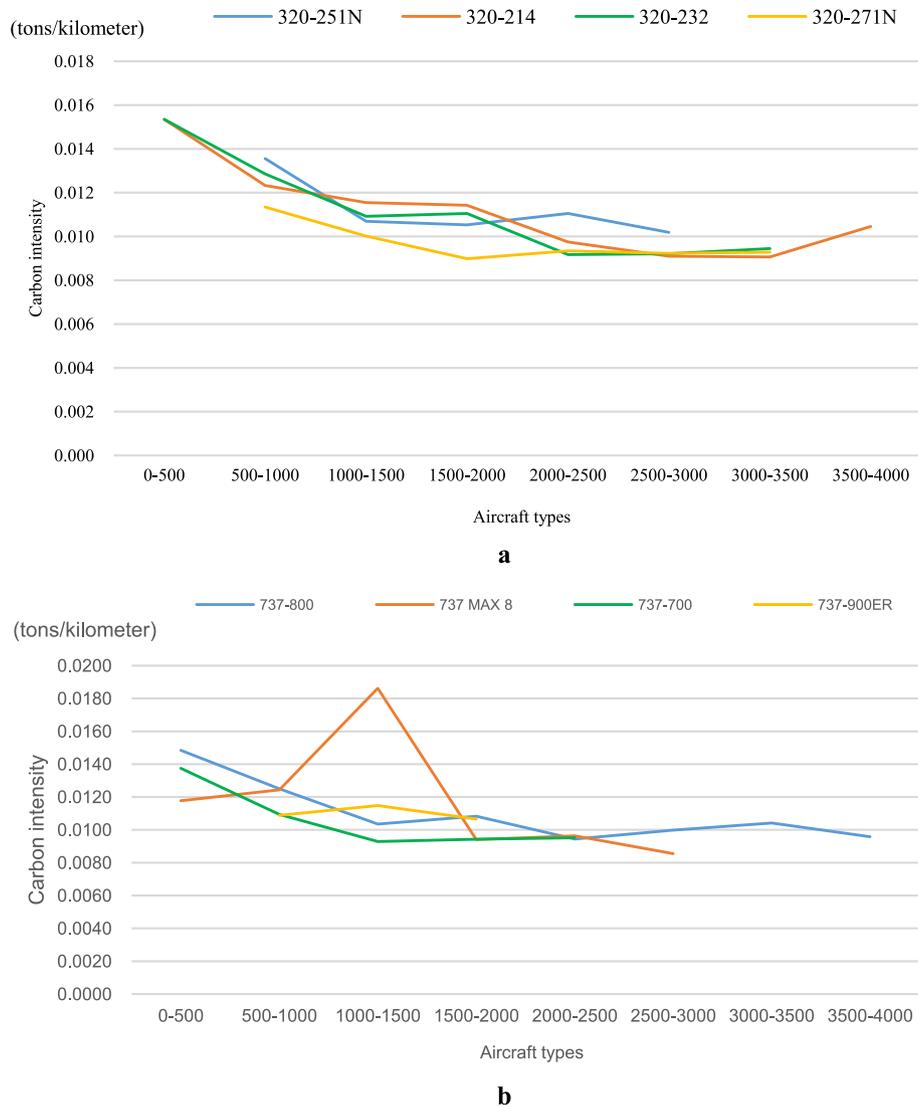


Figure 2. a: Carbon emission intensity of 320 series at different route distances. b: Carbon emission intensity of 737 series at different route distances.

737 MAX 8 at 1000–1500km is significantly higher than that of different types of the same series. Therefore, the 1000–1500km route should be equipped with more environmentally friendly types than the 737 MAX 8.

2.2. The CCD carbon emissions and RPK of various routes

Based on the carbon emissions per kilometer of different types in the first part, the carbon emissions of the 413 routes in China are estimated, as shown in Data S1. CCD emissions are defined as aircraft from an altitude of more than 3000 feet (915 m). From the descriptive statistical analysis of routes, the range and standard deviation of carbon emissions, RPK, and flight distance are extensive, indicating significant differences in operating conditions and carbon emissions among various routes.

Figure 3a and b show the top ten and bottom ten routes in carbon emissions and Revenue Passenger Kilometers (RPK). The ranking of RPK is the same as the ranking of aviation carbon emissions for most routes. In the figure, the left ordinate is carbon emissions and the right one is Revenue Passenger Kilometers.

The routes with significant carbon emissions and RPKs are concentrated in the hinterland of the three major economic belts of the Yangtze River Delta, the Pearl River Delta, and the Bohai Rim, followed by western transportation hubs such as Chongqing and Chengdu. Carbon emissions and RPKs of Guangzhou-Beijing, Beijing-Shanghai, Beijing-Shenzhen, Chengdu-Beijing, Shanghai-Shenzhen, Guangzhou-Shanghai, Chengdu-Shanghai, Beijing-Sanya, Hangzhou-Beijing, Kunming-Beijing, Chongqing-Shanghai are at the forefront of the country, far exceeding the average level, accounting for 16% of the total carbon emissions and RPKs of more than 400 routes across the country. The total carbon emission of Guangzhou-Beijing and the RPK of Beijing-Shenzhen rank first among all routes, reaching 108.98 million tons and 9.91 billion, respectively. The starting and ending cities of the routes mentioned above are Beijing, Shanghai, Guangzhou, Shenzhen, Chengdu, Kunming, Chongqing, Hangzhou, with excellent geographical location, huge air transportation market and transit demand, complete airport transit facilities, strong base airlines, stable and coordinated departmental collaboration, loose policy and legal environment, and abundant tourism resources, have become

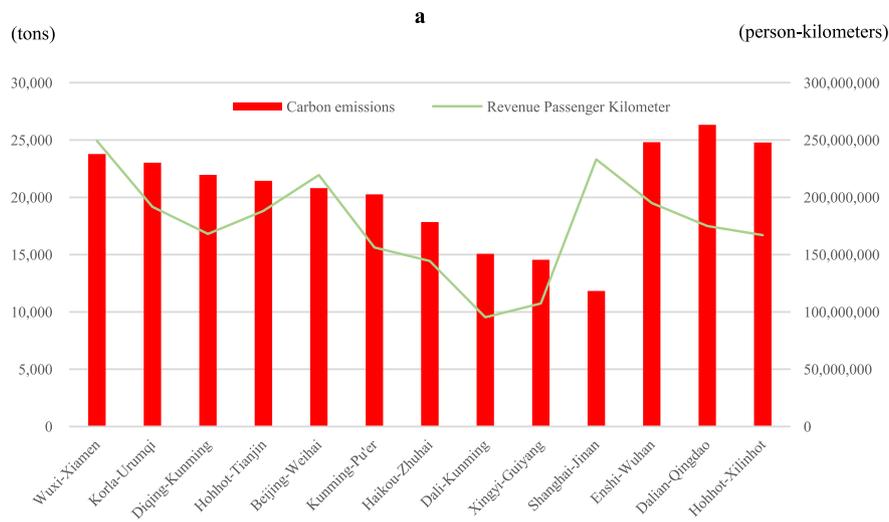
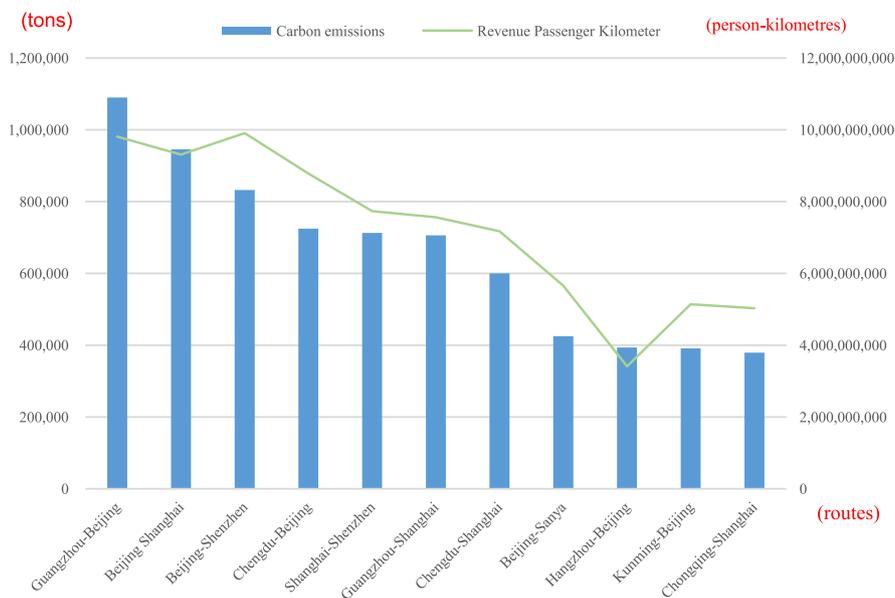


Figure 3. a: The top 10 routes in terms of carbon emissions and revenue passenger kilometer. b: The bottom 10 in terms of carbon emissions and revenue passenger kilometer.

the core airport cities of China's city-to-airline network. The diamond structure formed by these cities includes a relatively concentrated overall spatial pattern, attracting and gathering superior resources in the social economy, creating a massive flow of people, logistics, resources, technology, and information. As a result, the routes have a huge passenger and cargo throughput.

Guangzhou-Beijing, Beijing-Shanghai, Beijing-Shenzhen, Chengdu-Beijing, Shanghai-Shenzhen, Guangzhou-Shanghai, Chengdu-Shanghai, Hangzhou-Beijing, Chongqing-Shanghai connect the most critical economic development core areas and transportation in the country hub, with developed modern transportation facilities and information networks, and the close connections and collaborations between cities. Therefore, the flight frequency and RPKs of the routes mentioned above are at the forefront of the country, making them the busiest route in China and the main contributor to aviation carbon emissions. In contrast, the booming tourism industry is the main reason why the Beijing-Sanya and Kunming-Beijing routes rank high in carbon emissions. Sanya and Kunming are both tourist hotspots. In recent years, passenger throughput has continued to rise, tourism has thrived, and air transport has gradually become the primary mode of transportation for long-distance travel, accompanied by increasing aviation carbon emissions.

The total carbon emissions and RPK of the bottom ten routes of Wuxi-Xiamen, Korla-Urumqi, Diqing-Kunming, Hohhot-Tianjin, Beijing-Weihai, Kunming-Pu'er, Haikou-Zhuhai, Dali-Kunming, Xingyi-Guiyang, Shanghai-Jinan, Enshi-Wuhan, account for only 0.4% and 0.3% of the national total, roughly equivalent to the carbon emissions of Chongqing-Hangzhou and the RPK of Zhengzhou-Sanya. The main reason for the low aviation carbon emissions and RPK is the short route distance, mostly short-distance flights within or between neighboring provinces, such as Korla-Urumqi and Diqing-Kunming Kunming-Pu'er, Dali-Kunming, Xing Yi-Guiyang, Enshi-Wuhan, Hohhot-Xilinhot. For the routes of Shanghai-Jinan, Beijing-Weihai, and Wuxi-Xiamen, with the small number of flights, and the railway and road network between these areas are developed, high-speed rail and other safe and convenient ground transportation modes with low fares and high punctuality rates have shown a substitution effect and impact on civil aviation in the short- and medium-distance travel market.

The correlation coefficient between airline carbon emissions and RPK in 2018 is 0.98, indicating that RPK is one of the essential factors affecting aviation carbon emissions. To eliminate the impact of passenger traffic and transportation distance on carbon emissions and make the carbon emissions of different routes more comparable, the carbon emissions per RPK is used to analyze the differences in carbon emissions between routes. Figure 4 shows the top and bottom five routes in terms of emissions per RPK. The top five routes are labeled in red and the bottom five ones are labeled in green.

In Figure 4, the carbon emissions per RPK on Dali-Kunming, Hohhot-Xilinhot, Dalian-Qingdao, Baoshan-Kunming, and Haikou-Guilin rank the top 5, while their total carbon emissions and RPKs are at the bottom of more than 400 routes across the country. Their carbon emission intensities are 152 g/person-kilometer, 144 g/person-kilometer, 140 g/person-kilometer, 137 g/person-kilometer, and 108 g/person-kilometer. The high intensity has close relationships with the flying time and flying distance. These five routes are short-hauls whose flying distances are 275km, 501km, 358km, 373 km, and 773km. The corresponding flying times are about 37 min, 52 min, 45 min, 44 min, and 60 min. The short flight time means that the climb phase takes up a large proportion of the total time, while the relatively fuel-efficient cruise phase has a shorter time. Therefore, their carbon emission intensities are relatively high.

On the contrary, Shanghai-Urumqi and Chengdu-Sanya with higher RPKs are primarily medium and long distances. The longer the length, the more fuel consumption, and carbon emissions, but the emissions per RPK are very low. The emissions per RPK of the above two types of routes are negatively correlated with RPK, which is related to the fact that many large-scale airports relying on routes with large passenger throughput are relatively better than small and medium-sized airports in energy-saving and emission-reduction measures such as the application of new technologies and improved infrastructure, as well as the relatively high efficiency of resource utilization. For Shanghai-Zhuhai and Shanghai-Shijiazhuang, the lower carbon emissions per RPK is their carbon emissions rank far below the ranking of RPK among more than 400 routes, especially Shanghai-Zhuhai. The routes mentioned above mostly use wide-body passenger aircrafts such as A330, 737, and 747 with large



Figure 4. The top and bottom five routes in emission per RPK.

passenger capacity, and they perform well in controlling carbon emission reduction.

2.3. The carbon emissions and RPK of various airlines

This study calculates the carbon emissions and RPK of China's 40 major airlines on each route. Figure 5 shows that the airlines' carbon emissions and RPK are positively correlated, and the rankings are consistent. The units of RPK and carbon emissions are person-kilometers and tons. China Southern Airlines, China Eastern Airlines, Air China, Hainan Airlines, Shenzhen Airlines, Sichuan Airlines, Xiamen Airlines, Shandong Airlines, Shanghai Airlines, Juneyao Airlines are the top 10 airlines emissions and RPK, accounting for about 80%. Except for Sichuan Airlines, located in Chengdu, a comprehensive transportation hub in the west, the other airlines are headquartered in the hinterland of the three major economic belts of the Yangtze River Delta, the Bohai Rim, and the Pearl River Delta. These regions have accumulated significant advantages in infrastructure construction, resource allocation, attracting foreign investment, industrial chain extension, talent reserve, etc. They have good transportation accessibility, logistics accessibility, and the regional centrality of commercial resources. The top ten airlines are all state-controlled air transport companies, and most of them are full-service airlines. They operate most of China's international routes and major domestic trunk line businesses. The fleet size, passenger traffic,

and the number of flights is all at the top domestic level. Therefore, the airlines mentioned above are the backbone of China's aviation operations and the primary responsibility for aviation carbon emission reduction.

For airlines headquartered in the western region, such as Chengdu Airlines, Lucky Air, West Air, and Tibet Airlines, the main reason for their carbon emissions and RPK in the upper and middle reaches is implementing the western development strategy and the rapid development of aviation tourism. Civil aviation plays a positive role in increasing the source of passengers. Civil aviation has also become a booster for tourism development due to its convenience, speed, comfort, and considerable time and space.

The headquarters of LJ Airlines, Changsha Airlines and Joy Air are in Harbin, Changsha and Tianjin, respectively. These three airlines have fewer routes and flights, and most of them are short- and medium-distance routes and passenger traffic is limited. As a result, their aviation carbon emissions are much lower than other airlines.

We draw Figure 6 to show the ranks of airlines' carbon emission, RPK, and carbon emission per RPK. The results indicate a significant negative correlation between airline RPK and emissions per RPK. For example, China Southern Airline has the largest RPK, but its emission per RPK ranks 25th among these 40 airlines; Joy Air's RPK ranks 40th among these 40 airlines, but its emission per RPK ranks 1st. This result is closely related to the route layout of airlines. Joy Air is mainly engaged in short-haul routes, and the aircraft is relatively small, so its RPK is small.

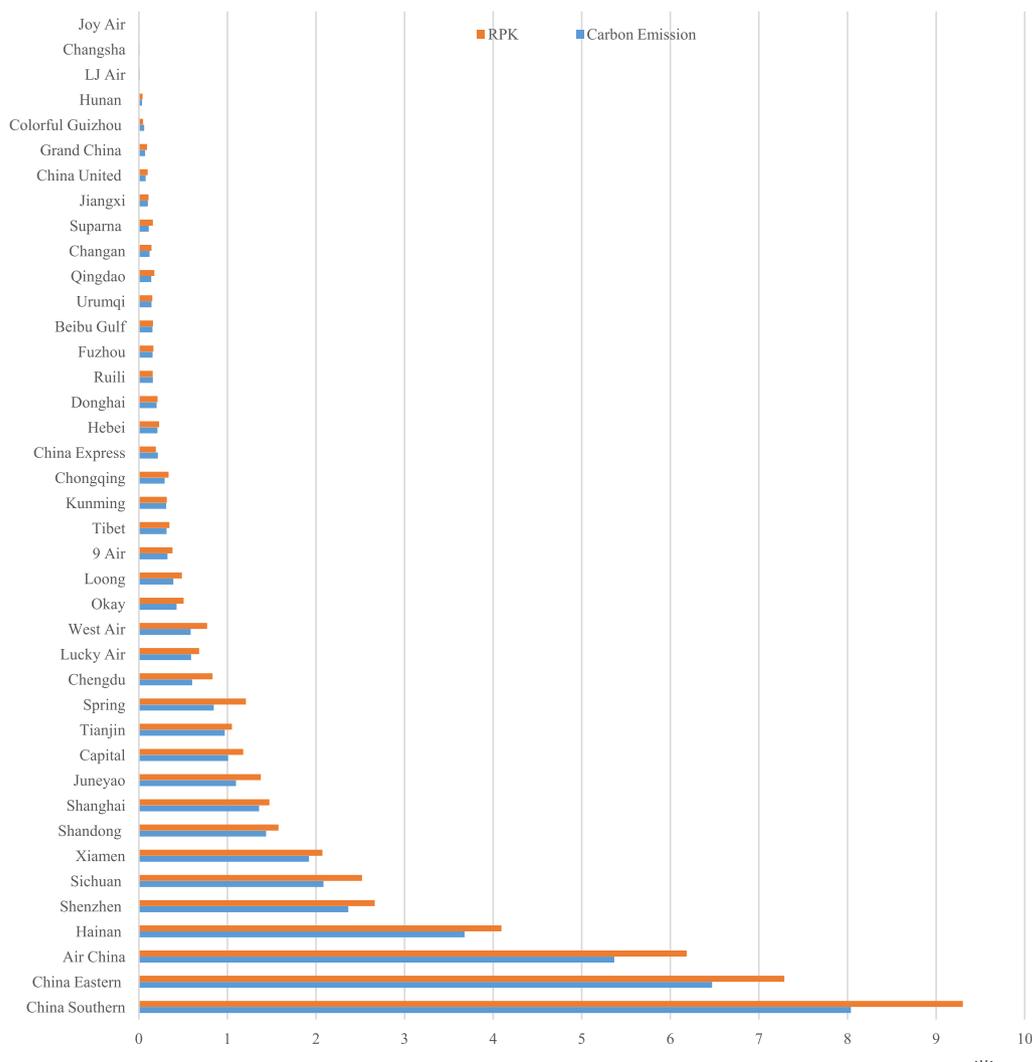


Figure 5. The carbon emission and RPK of airlines.

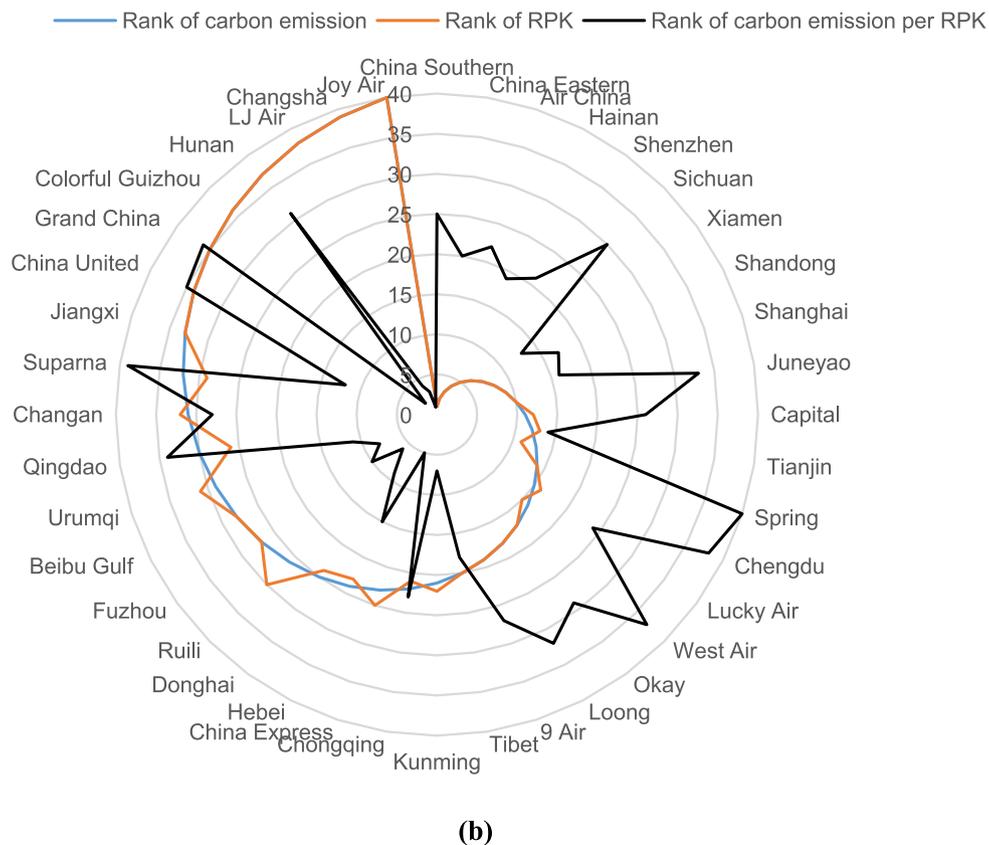
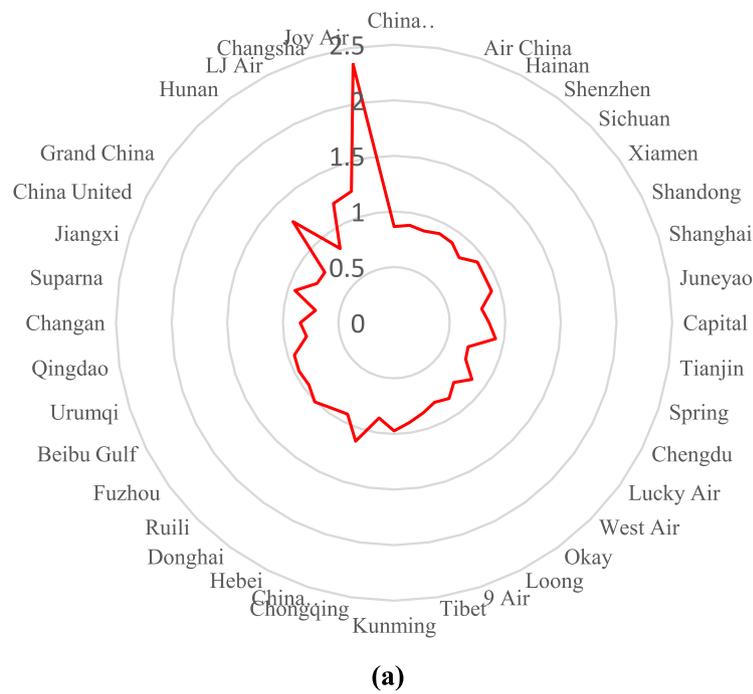


Figure 6. (a): The carbon emission per RPK. (b): The ranks of airlines' carbon emission, RPK and carbon emission per RPK.

However, for the short route, the proportion of the most fuel-efficient cruise phase is small too, and the emission per kilometer is large. Therefore, there is a significant negative correlation between airline RPK and emissions per RPK.

China Southern Airlines, China Eastern Airlines, and Air China are the airlines with the most routes, reaching 245, 232, and 168 respectively,

and the three airlines operate the top ten routes in terms of carbon emissions. For example, Guangzhou-Beijing operated by China Southern Airlines, the Beijing-Shanghai operated by China Eastern Airlines, and the Guangzhou-Beijing used by Air China had emitted 537,827.33 tons, 45,3135.09 tons, and 369,882.76 tons, respectively. Their RPKs are also the largest, reflecting the leading and dominant position of the three

major airlines of China Southern, China Eastern, and Air China in China's civil aviation industry. The routes with the most negligible carbon emissions include the Xingyi-Guiyang operated by Colorful Guizhou, the Dali-Kunming route by Lucky Air, and the Kunming-Puer operated by Kunming Airlines intra-provincial or short-distance inter-provincial flights with small passenger capacity.

2.4. The carbon emission differences between actual routes and straight routes

The Nonlinear Emission Rate (NER) of the routes and the airlines (The detailed calculation method of NER is shown in the Methods section) can signify the excess carbon emissions resulting from the nonlinear routes. To get the distance, we input the longitude and latitude of the origin and destination of the route. Then we can get the straight-line distance of the route under actual conditions [17]. Therefore, it is a 3-D distance.

The results show that the total NER of the 413 routes is 10.15%, indicating that China's leading domestic routes have emitted 10.15% more carbon as the routes are not straight. If China's domestic routes are optimized, it could save about 10.15% carbon emissions in 2018. The top

10 routes and bottom routes and airlines in NER are shown in Figure 7a and b.

In Figure 7a and b, the blue ones are the top 10 ones, and the red ones are the bottom ones. Comparing Figure 7a and b, the NER differences among the routes are much more significant than those among the airlines. The largest NER among routes is from Chengdu-Xining, which is led by the aviation safety rules. In general, the routes should be set based on the law that during the whole flight path, to prevent engine failure could cause safety problems, the distance from any point to the nearest alternate airport must be less than a single flight of 60 min. The straight route from Chengdu to Xining cannot fulfill this requirement, so the aircraft must fly around Lanzhou. Correspondingly, there are many alternate airports on the straight route from Wuxi to Shenyang, so the aircraft can fly in a nearly straight route, resulting in a small NER.

The largest NER among airlines is from Changsha Airlines, whose main route is Changsha-Jieyang. The straight distance from Changsha to Jieyang is about 630 km, but the actual flight distance is 878 km, 39.3% more than the linear distance. This result is also closely related to the safety rules. On the other hand, the least NER is from LJ Air, whose main route is Hefei-Zhuhai. The straight distance from Hefei to Zhuhai is about

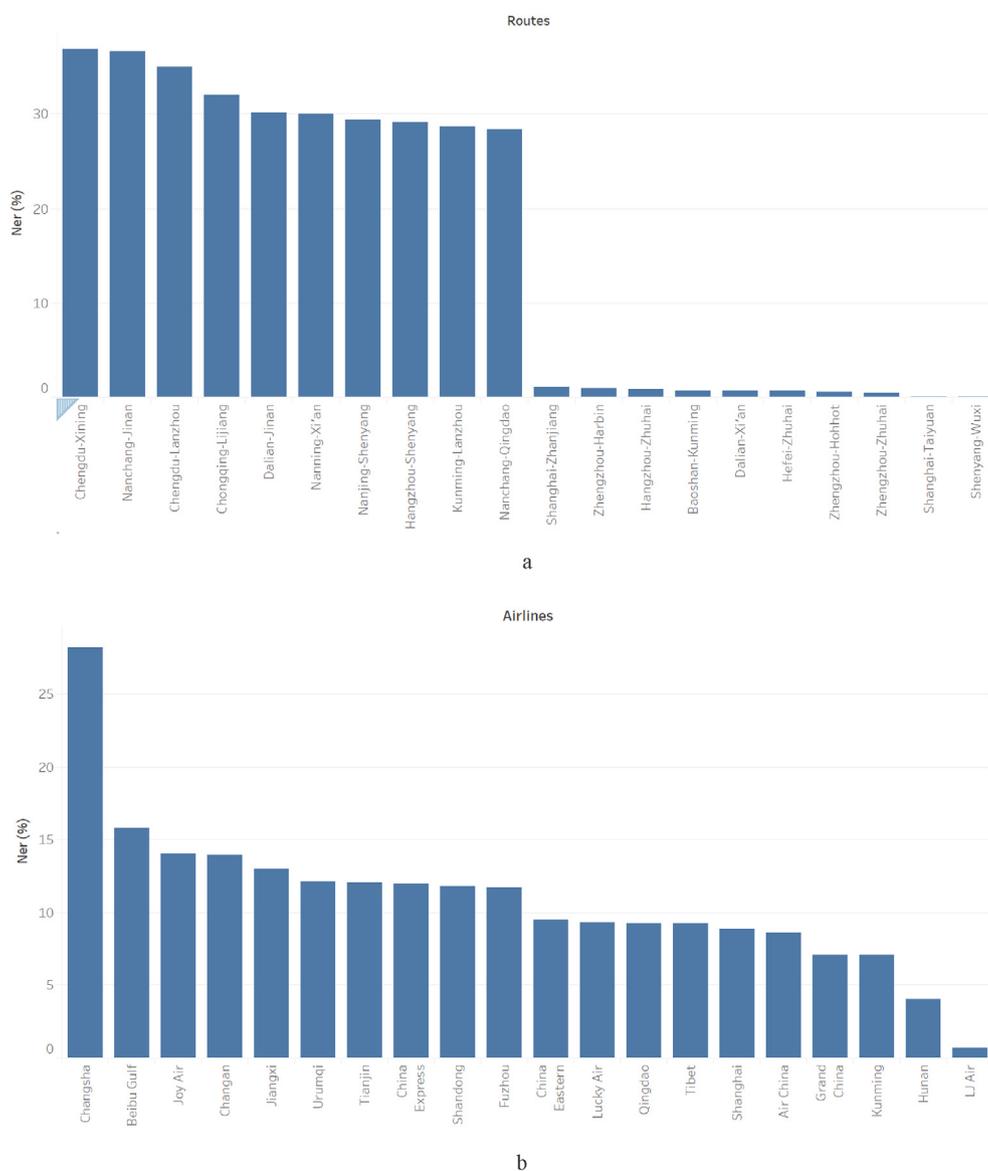


Figure 7. a: The top 10 routes and bottom routes in NER. b: The top 10 routes and bottom airlines in NER.

1122 km, and the actual flight distance is 1130 km, so LJ Air has the least NER.

3. Discussion

This study considers the more comprehensive types of China's civil aviation and the particularity of China's domestic routes. It proposes a new aviation carbon emission accounting method, a database of carbon emissions, and RPK of Chinese airlines. About 413 major routes in 2018 were established to provide a reference for energy conservation and emission reduction in China's civil aviation industry. The main research conclusions and corresponding policy recommendations are as follows:

First, the carbon emissions per kilometer of different aircraft types are additional under different flight distances. Small passenger aircraft such as CRJ900 and E190 LR are more environmentally friendly on short- and medium-haul routes from 0 to 2000 km. Medium-sized passenger planes and upgraded new passenger planes such as the Airbus A320 series and Boeing 737 Series have shown better emission reduction performance on medium and long-haul routes of 2000–4000 km. Advanced wide-body passenger aircraft such as Boeing 777, Boeing 787, Airbus 380, Airbus 330 that execute long-distance routes have relatively high fuel consumption, carbon emissions, and operation and maintenance costs.

Second, for most routes, the rank of RPKs is the same as the ranking of aviation carbon emissions. The routes with significant carbon emissions and RPK are mainly concentrated in the hinterland of the three major economic belts of the Yangtze River Delta, the Pearl River Delta, and the Bohai Rim, followed by western transportation hubs such as Chongqing and Chengdu. Short-distance routes within the province or between neighboring regions, as well as routes with developed ground transportation and fewer flights, have fewer carbon emissions and RPK. Most routes with high passenger throughput are operated by large airlines with advanced technology, complete infrastructure, and reasonable fleet planning. Thus, there is a negative correlation between emissions per RPK and RPK.

Third, most of the airlines located in the hinterland of the three major economic belts, such as China Southern Airlines, Eastern Airlines, Air China, Hainan Airlines, and Shenzhen Airlines, and Sichuan Airlines (located in Chengdu—a comprehensive transportation hub in the west), are state-holding air transport companies and full-service airlines. Most of China's international routes and major domestic mainline businesses are the backbones of China's aviation operations and the primary responsibility for aviation carbon emission reduction. The carbon emissions and RPKs of LJ Airlines, Changsha Airlines, and Joy Air are much lower than other airlines. There is a significant negative correlation between airline RPK and emissions per RPK.

Fourth, due to the aviation control restrictions and navigation technology limitations, the aircraft's actual flight path is not a straight line, and the actual flight distance is often more significant than the straight-line distance. As a result, the total Nonlinear Emission Rate (NER) in 2018 is about 10.15%. The results show that the actual carbon emissions of most airlines flying routes are more significant than the straight-line emissions. Therefore, route design and planning are essential factors influencing aviation carbon emissions.

Based on the above data calculation and analysis results, China's civil aviation sector should give full play to the role of the market mechanism, effectively promote the optimization of carbon resource allocation, comprehensively control the consumption of air transportation energy resources, reduce the emissions' impacts on the ecological environment, and realize the coordinated development of civil aviation safety, greenness service, and efficiency.

The civil aviation department should attach great importance to the use of market mechanisms to deal with aviation emissions, promote the practice and effective operation of the carbon emissions trading market in the aviation industry, establish and complete a unified carbon emission data accounting, reporting and verification system, and reasonably formulate the common but differentiated emission reduction responsibilities of the airlines, and set a reasonable total carbon emission reduction target for the

aviation industry and the allocation of specific carbon emission allowances based on the airlines' carbon emission database.

China's civil aviation sector should take responsibility for leadership in promoting the green development of civil aviation. China has built its carbon trading market on July 16, 2021 but compared with other departments. The civil aviation sector has unique advantages in balancing low-carbon development and the safety of the civil aviation industry. To achieve the Carbon-Neutral Growth of the aviation industry, it is not enough to rely on market mechanism alone. It also needs to promote biofuels and cooperate with international aviation associations (such as ICAO and IATA). The civil aviation sector's advantages can help achieve these.

Furthermore, airlines should optimize flight routes by using various flight technologies. For example, China's leading domestic routes have emitted 10.15% more carbon as the routes are not straight. This part can be reduced by upgrading flight technologies (optimizing the flight route by analyzing route, fuel, and flight height). Although some airlines have relatively small Nonlinear Emission Rates (NER), if these emissions can be reduced, it is beneficial to airlines' production operation and green development.

In addition, the implementation of efficient operation improvement and supervision and management is an important measure to control aviation carbon emissions. On the one hand, it should be continued to optimize the fleet structure and introduce safer, more environmentally friendly, and more efficient new-generation wide-body types such as Airbus A350 and Boeing 787 to improve overall fleet performance and fuel efficiency. On the other hand, through route adjustment, temporary route construction, and management, we will continuously optimize the route structure, increase the available airspace resources, improve the efficiency of airspace use, and promote the development of aviation energy conservation and emission reduction. Furthermore, continuously improve the coordinated operation mechanism of industry entities such as airports, airlines, and air traffic control, improve the overall operational efficiency of air transport activities, promote the coordinated development of industries, and enhance the level of green development of civil aviation.

The main contribution of this paper to the literature is reflected in the following aspects.

Firstly, the CCD emissions in this paper are calculated according to the Modified Fuel Percentage Method (MFPM). Compared with the ICAO methodology, the MFPM method has significant advantages: 1. The ICAO methodology employs industry averages for the various factors contributing to the calculation of the emissions associated with the individual passenger's air travel, which cannot consider the impact of flight-specific variables on passengers' aviation emissions. The carbon emission calculation method used in this article is based on route-specific data (e. g., actual flight time) to make the calculation results more accurate. 2. Compared with the ICAO methodology, the calculation method in this paper covers more detailed aircraft types. Due to the specific differences in the carbon emission intensity of different aircraft types, this is more in line with the actual situation of China's aviation emissions. Furthermore, compared with the traditional Fuel Percentage Method, in the MFPM method, we divide the route distance into eight groups: 0–500 km, 501–1000km, 1001–1500km, 1501–2000km, 2001–2500km, 2501–3000km, 3001–3500km, and 3501–4000km. Then the carbon emissions of 42 aircraft types in these different distances were obtained to ensure that the calculation results were accurate.

Secondly, this is the first time systematically calculating the CCD carbon emissions of China's domestic routes, containing 413 routes, 40 airlines, and 42 aircraft types. It has significant reference value for improving China's domestic aviation carbon emission database, scientifically formulating emission reduction plans, and establishing aviation carbon emission mechanisms.

Thirdly, the calculation method of carbon emission intensity of aircraft types, the Climb/Cruise/Descent (CCD) carbon emissions of each airline and each route in this paper is also applicable to other regions of

the whole world and aviation pollutants other than CO₂ (such as NO_x, CO, HC), airline route distance should be divided into more groups when applied to international routes, which will provide a new train of thought for in-depth study on the aviation carbon emissions worldwide.

It should be noted that the CCD emissions are not the overall ones as this study has not considered the emissions of the altitude of fewer than 3000 feet (the emissions in the Landing and Take-Off stage (LTO)). Furthermore, this study has not considered the emissions from air cargo. Therefore, further analysis can calculate the overall emissions containing CCD, LTO, and cargo emissions. In addition, considering the significant impact of the Corona Virus Disease 2019 on the aviation industry, this article uses data in 2018 and has not been updated to the latest year.

4. Methods

4.1. Calculation the emissions of the flight $E(Q)$

$$\begin{aligned} E(Q) &= 3.157 * F(Q) = 3.157 * M_{fuel} * weight(Q) = 3.157 * (1 - M_{ff}) * weight(Q) \\ &= 3.157 * \left(1 - \prod_{i=1}^n \frac{W_i}{W_{i-1}}\right) * weight(Q) = 3.157 * \left[1 - e^{-\frac{dis * ratio_{cr}}{10 * v}}\right] * weight(Q) \\ &= 3.157 * \left[1 - e^{-\frac{dis * ratio_{cr}}{10 * v}}\right] * (aircraftbareweight + 100 * (load factor * number of seats) + 50 * seat) \end{aligned}$$

3.157 is the emission coefficient of aviation kerosene [16]. $weight(Q)$ is the total weight of the aircraft. M_{fuel} is the fuel coefficient, $M_{ff} = \prod_{i=1}^n \frac{W_i}{W_{i-1}}$ is a fuel weight proportionality coefficient, which is usually calculated by Fuel Percentage Method (FPM). The total sections of a whole flight contain 7 task sections: Engine Starting, Taxiing, Taking Off, Climbing, Cruising, Descending and Landing. W_i/W_{i-1} as the fuel weight proportionality coefficient of task section i ($i = 1, 2, \dots, 7$).

As we only consider the CCD section in this study, so we define the W_i/W_{i-1} of other sections is 1. The W_i/W_{i-1} of Climbing and Descending are 0.980 and 0.990. The equation of the CCD section to calculate W_i/W_{i-1} is $W_i/W_{i-1} = e^{-\frac{dis * c_{cr}}{10 * v * LD_{cr}}}$. dis is the cruising distance, v is the cruising speed, c_{cr} is the fuel consumption ratio when the aircraft is cruising, LD_{cr} is the lift-drag ratio when the aircraft is cruising. The value of c_{cr} and LD_{cr} has direct relationships with the aircraft type. We define $ratio_{cr} = \frac{c_{cr}}{LD_{cr}}$, and then for the cruising task section, the W_i/W_{i-1} is $W_i/W_{i-1} = e^{-\frac{dis * ratio_{cr}}{10 * v}}$.

The actual flying time of each flight is applied to check the results of $ratio_{cr}$, and get the results.

4.2. Calculation the emissions of the Nonlinear Emission Rate (NER)

The Baidu Map [17] is applied to get the straight distances between the 413 city-pairs based on the coordinates of the airports and calculate the emissions when the routes are straight. A Nonlinear Emission Rate (NER) is defined as

$$NER = \frac{(\text{Actual emissions} - \text{Straight emissions})}{\text{Actual emissions}}$$

Experimental procedures

Resource availability

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Dr. Qiang Cui (cuiqiang@seu.edu.cn) or Dr. Ye Li (happyxiaoye@yeah.net).

Materials availability

The data generated in this study have been deposited to [Data S1].

Data and code availability

The original data are collected from the VariFlight.com [10] and the Statistical Data on Civil Aviation of China [13], and we complied the data. The data on aircraft type, flying time, flying distance, transfer flight and airlines are from VariFlight.com. The data on total flight frequency and passenger turnover are from Statistical Data on Civil Aviation of China.

The overall results are shown in Data S1. The CCD emissions of the airlines and routes are shown in Table S1. The RPK of airlines and routes are shown in Table S2. The emission intensity of each aircraft is shown in Table S3.

Declarations

Author contribution statement

Qiang Cui: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Xinyi Li & Ye Li: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Funding statement

This work was supported by National Natural Science Foundation of China (71701088).

Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

Supplementary content related to this article has been published online at <https://doi.org/10.1016/j.heliyon.2022.e08716>.

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