Carbon emissions of Provincial Administrative Regions from the airlines in China

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Article

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Abstract This paper seeks to calculate the overall emissions of China's 413 main domestic routes in 2018, containing the Landing and Take-Off (LTO) emissions and Climb/Cruise/Descent (CCD) emissions. First, the standard calculation method of LTO emissions proposed by the International Civil Aviation Organization (ICAO) is applied to calculate the LTO emissions of 413 routes and 40 airlines. Next, the modified Fuel Percentage Method (MFPM) is used to calculate the CCD emissions of main aircraft types at various distances. Then the overall emissions are split into the Provincial Administrative Regions (PARs) on the routes to discuss the probable carbon compensations, which is the core to build an aviation carbon trading mechanism. China Southern Airlines, China Eastern Airlines, and Air China are the top three airlines in emissions. Guangdong has the most carbon emissions from airlines, but it may get the third most carbon compensation from the airlines.

Introduction

China's domestic civil aviation industry has recently ushered in rapid development[1,2]. In 2019, the total turnover of China's domestic routes was 82.95 billion ton-kilometers, an increase of 7.5% over the year 2018; Domestic routes completed 852.02 billion passenger-kilometers, a rise of 8.0% over the year 2018; Domestic air routes completed 7.86 billion ton-kilometers of cargo and mail, an increase of 4.1% over the year 2018[3]. The rapid expansion of carbon emissions accompanies the rapid development of the civil aviation industry. China's domestic airline carbon emissions increased by 95.3%, from 38.5 million tons in 2012 to 75.2 million tons in 2019 (This data is calculated based on total turnover data and unit emission data of CAAC[4]).

In addition to rapid growth, aviation emissions have other impacts[5,6]. First, it isn't easy to be transformed by vegetation because of its high emission. The aircraft cruising stage is generally more than 10,000 meters, which is too far away from the ground vegetation and cannot be transformed easily. Second, the retention time is long, and the harm of mixing with particulate matter is more than twice the harm of carbon dioxide emitted. Third, although aircraft generally fly in the stratosphere, there is still much water vapor, suspended solid particles, impurities, etc. These are easy to mix with carbon dioxide and increase harm.

Many countries and organizations have proposed market-based mechanisms to solve the aviation emission problem, such as the EU Emission Trading Scheme (EU ETS)[7] and the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) proposed by ICAO[8]. The market-based mechanism is recognized as an essential measure to solve the problem of carbon emissions. However, the EU ETS focuses on the flights in the EU, and the CORSIA only covers international flights[9]. Therefore, China also should build its carbon trading mechanism to control the fast-growing aviation emissions. As we all know, the main body of aviation carbon emissions is airlines, and aviation carbon emissions have prominent characteristics of regional transfer. For example, a flight from Beijing may emit the most emissions in Hebei rather than Beijing. Therefore, it is crucial to calculate the historical emissions of each airline to each Provincial Administrative Region (PAR).

Furthermore, the current research on carbon emissions in China's civil aviation industry uses ICAO Carbon Emissions Calculator Methodology to calculate carbon emissions. Still, they mainly focus on specific airlines and routes or the country's overall aviation carbon emissions measurement. Because its carbon emission data system of various routes and airlines is not yet complete, it also has limitations, such as incomplete aircraft coverage and incomplete applicability to routes within the specific country. For example, the ICAO Carbon Emissions Calculator Methodology can calculate the carbon emission of A320 but has not shown the difference between A320-214 and A320-232. Furthermore, China has a vast territory, and its flights are not straight, so that the same aircraft may have different emission intensities in China and other countries.

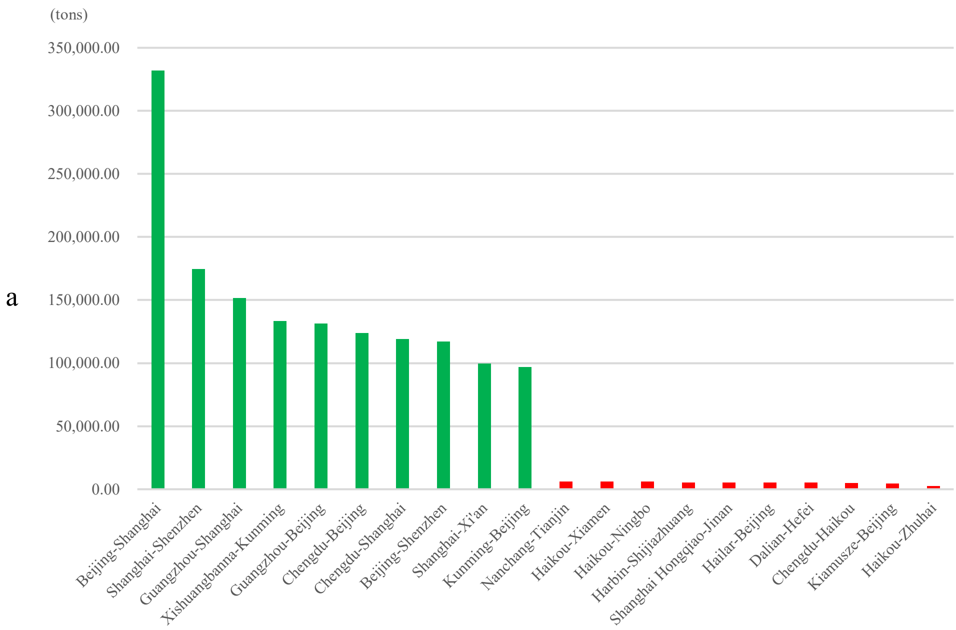
This study calculates the CCD emissions and LTO emissions of 413 routes whose daily flights are equal to or larger than 3 (containing 319 transfer routes) and 40 Chinese airlines. Then we apply the ranging function of the Baidu map[10] to split the distance of these routes into 31 Chinese PARs in 2018 and calculate the carbon emissions of each airline in each PAR on each route. First, it should be noted that the emissions of shared flights are computed on the carrier airlines. Then, the carbon emissions of each airline in each airport in the Landing and Take-Off (LTO) stage are calculated based on the proposed method of ICAO[11]. Then this study adds the emissions in the LTO stage to the split emissions to get the final emissions of the airlines to each PAR. Finally, this study calculates the airlines' compensations to the PARs to simulate the emission trading mechanism.

Results

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. The exact method can be found in Section "Method." 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 Supplementary Table 1 for details) show that small passenger aircraft such as CRJ900 and E190 LR equipped with high-density economy class and business class which can accommodate 86-90 passengers are more environmentally friendly on short- and medium-haul routes from 0 to 2000 kilometers.

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 2000-4000 kilometers, 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.

Carbon emissions of the LTO stage of each route. This study applies the proposed method of ICAO to calculate the emissions of the LTO stage. The emissions of each aircraft in a single LTO cycle can be found in Supplementary Table 2. The results show that the total LTO emissions of the 413 routes are 9,551,644 tons. This study applies Fig.1a to deliver the top 10 routes and bottom ten routes in LTO emissions. Fig.1b displays the top 10 airlines and bottom ten airlines in LTO emissions.



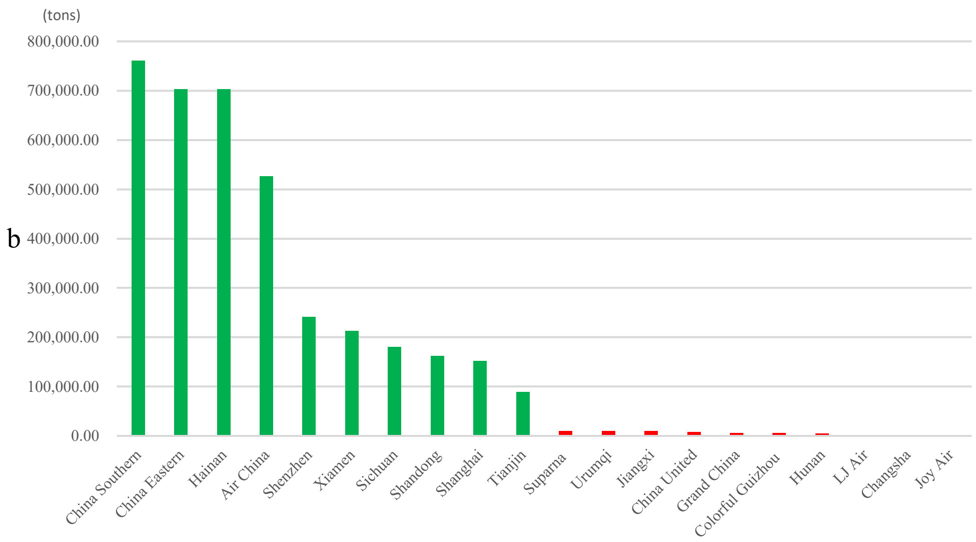


Fig. 1 LTO emissions from routes and airlines. **a** Top 10 and bottom 10 routes in LTO emissions. **b** Top 10 and bottom 10 airlines in LTO emissions

In Fig.1a and Fig.1b, the green ones are the top 10 ones and the red ones are the bottom ones. The most significant LTO emission route is Beijing-Shanghai, and the minor emission route is Haikou-Zhuhai. From the calculation method of LTO emissions, we can know that the emissions have direct relationships with the flight frequency and the aircraft type. In 2018, Beijing-Shanghai's flight frequency was 38854, which is the busiest route in China. Furthermore, the aircraft in this route contains many 747-400, 747-8I, 777-300ER, 330-343E, and 330-243E, and these five aircraft types are the top 5 in a single LTO. For example, the single LTO emissions of 747-400 are 11.193 tons, while the least one CORP MA-60 only emits 1.564 tons in a single LTO. Therefore, Beijing-Shanghai has the most significant LTO emissions. Correspondingly, the flight frequency of Haikou-Zhuhai is 2807, and its aircraft type is mainly 737-800, whose single LTO emissions are about 2.816 tons. Therefore, Haikou-Zhuhai has the most negligible LTO emissions.

The largest LTO emission airline is China Southern, and the least one is Joy Air. China Southern has 245 routes among the 413 routes, which is the most among the 40 airlines. In addition, its aircraft has many types whose single LTO emission is high, such as 777-300ER, 330-343E, and 330-243E. These two factors lead to the highest LTO emissions of China Southern. On the other hand, joy Air's route is mainly Hefei-Xi'an, and its aircraft type is CORP MA-60 (the most negligible emission in a single LTO), which has minor LTO emissions.

Overall emissions of the airlines and the emission of each airline to each PAR. The total emissions of the 413 routes are 52,295,063 tons, in which CCD emissions are 42,728,318 tons and LTO emissions are 9,566,745 tons. The routes and LTO account for about 82% and 18% of the total emissions. The CCD emissions are calculated based on the Modified Fuel Percentage Method (MFPM)[12]and the actual flying time of each flight (the data is from the variflight.com[13]) is applied to verify the results. The overall emissions of the airlines are shown in Fig.2.

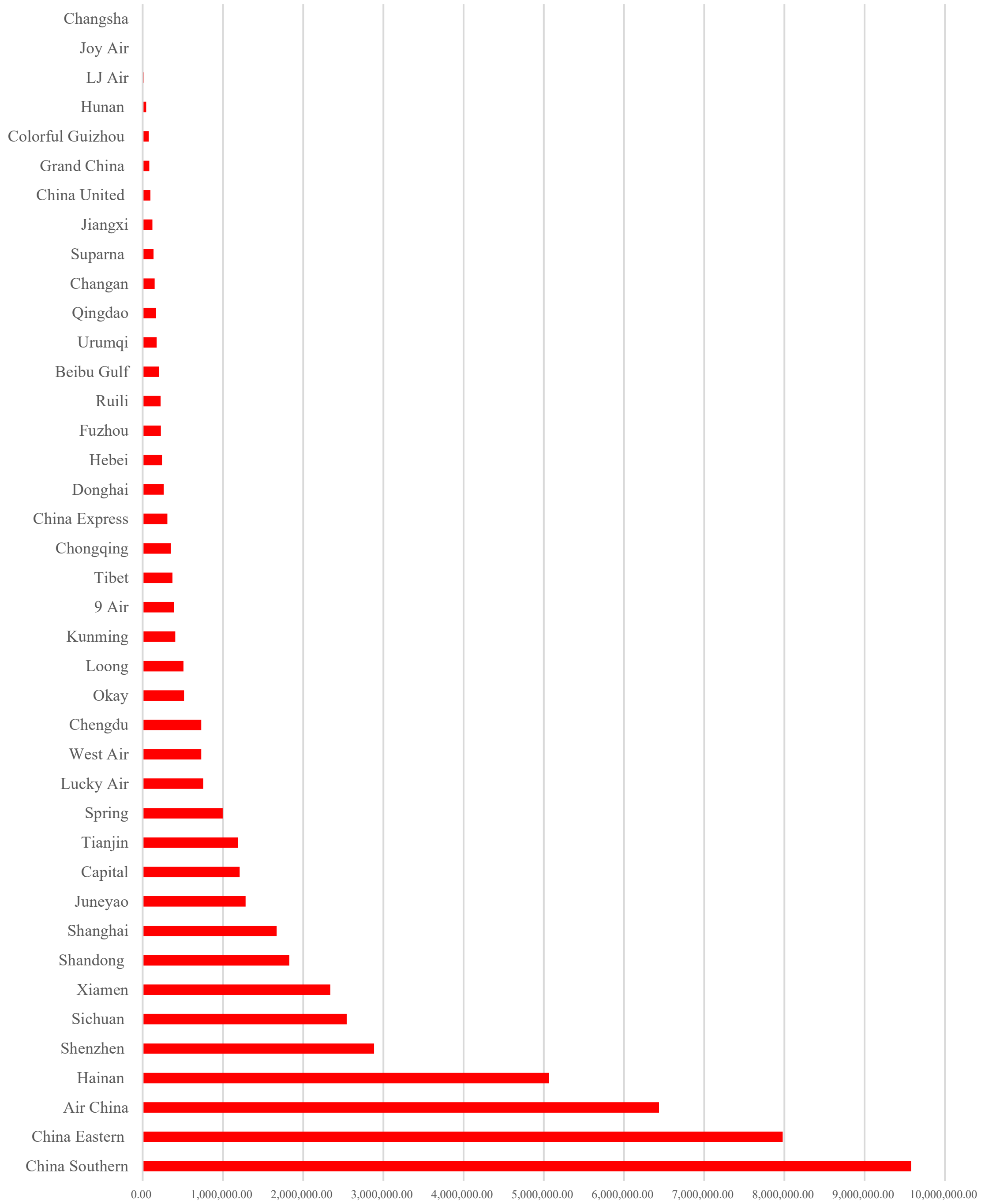


Fig. 2 Overall emissions of the 40 airlines in 2018

As shown in Fig. 2, China Southern Airlines have the most emissions among these 40 airlines, 9,578,734 tons. Meanwhile, the airline with the most negligible emissions is 8,743 tons, only 0.09% of China Southern Airlines. The other airlines with significant emissions are China Eastern Airlines (7,979,334 tons), Air China (6,435,100 tons), Hainan Airlines (5,063,289 tons), and Shenzhen Airlines (2,884,691 tons). The other airlines with small emissions are Colorful Guizhou (75,468 tons), Hunan (42,690 tons), LJ Air (11,338 tons), and Joy Air (9,978 tons). Comparing these airlines, we can see that due to the significant differences in fleet size and route resources among airlines, the emissions of domestic routes have an enormous difference.

This study applies the ranging function of the Baidu map to split the distance of 413 routes into the 31 PARs, and the overall emissions of the airlines to the PARs are shown in Fig.3. Unfortunately, the data of Taiwan, Hong Kong, and Macao is vacant.

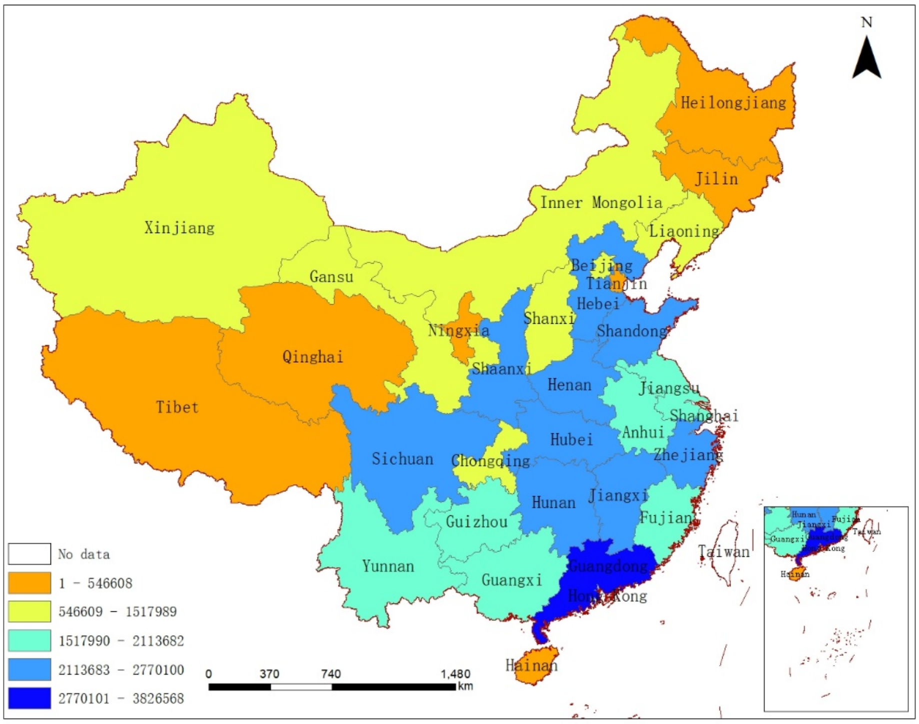


Fig. 3 Emissions of the airlines to the PARs

It should be noted that except for these PARs, about 2,144,815 tons of emissions happen at sea. About 101 routes have emissions at sea, which are larger than about 21 PARs. As shown in Fig.3, Guangdong has the most carbon emissions from airlines, approximately 3,826,568 tons, 1,056,468 tons more than the second PAR Jiangxi. This is because Guangdong has the headquarters of China Southern Airlines and has two of the busiest airports in China: Guangzhou Baiyun Airport and Shenzhen Baoan Airport. Among the 413 routes, 119 routes take off, land, or pass through Guangdong. These factors cause Guangdong to bear the most emissions.

The other PARs with significant carbon emissions from airlines are Jiangxi, Hunan, Shandong, and Hubei, 2,770,100 tons, 2,567,880 tons, 2,557,272 tons, and 2,526,656 tons, respectively. Jiangxi, Hunan, and Hubei are in the middle of China, and many routes must pass through these PARs. The routes taking off, landing, or passing through these three PARs are 119, 109, and 126, respectively. Many hectic routes pass through it for Jiangxi, such as Guangzhou-Shanghai, Shanghai-Shenzhen, Guangzhou-Beijing, Beijing-Shenzhen, Chongqing-Shanghai, Chengdu-Shenzhen, and Guangzhou-Hangzhou. Many routes with large passengers pass through Hubei, such as Guangzhou-Beijing, Beijing-Shenzhen, Chengdu-Shanghai, and Chongqing-Shanghai. Hunan is also on many busy routes, such as Beijing-Shenzhen and Chongqing-Shanghai. Furthermore, the Wuhan Tianhe Airport in Hubei and Changsha Huanghua Airport in Hunan are also hectic airports in China. Shandong is also the only place for many busy routes, such as Beijing-Shanghai, Guangzhou-Beijing, and Beijing-Shenzhen. Shandong's Jinan Yaoqiang Airport and Qingdao Liuting Airport are also bustling airports. These factors lead these PARs to bear the carbon emissions of many routes.

It should be noted that although Hebei is next to Beijing and Tianjin, the only two municipalities in North China, it only ranks tenth in carbon emissions. Two reasons can explain this result. First, the 102 routes only have a short part in Hebei, so the total emissions are relatively small. Second, most of China's busiest routes are concentrated in the Yangtze River Delta and Pearl River. Among the top 20 routes with the most significant flight frequency, except Chengdu-Beijing, Xishuangbanna-Kunming, and Beijing-Xi'an, the other routes are in the Yangtze River Delta and Pearl River Delta.

The least five PARs are Tianjin, Qinghai, Tibet, Heilongjiang, and Ningxia, 429,195 tons, 290,770 tons, 265,470 tons, 225,305 tons, and 205,780 tons, respectively. The number of routes taking off, landing, or passing through these five PARs is 35, 17, 3, 15, and 27, respectively. However, these five PARs are not the least five ones in route amount. The route amount of Jilin and Xinjiang is less than Tianjin and Ningxia, but the emissions they are exposed to are more significant than the latter two. Two reasons can explain it. First, Tianjin and Ningxia are too small. The area of Tianjin is 11,966 square kilometers, and that of Ningxia is 66,400 square kilometers, which causes them to cover only a tiny part of the routes. Conversely, the areas of Jilin and Xinjiang are 187,400 square kilometers and 1,660,000 square kilometers. Second, for Xinjiang, although the number of routes taking off, landing, or passing through it is 18, many routes are only in Xinjiang. For example, in Xinjiang, the flight frequency of Urumqi-Kashgar is 12022, ranking 35th among these 413 routes; Hotan-Urumqi has 7833 flights in 2018, ranking 89th; Yining-Urumqi has 7119 flights, ranking 105th among these routes.

Main routes and airlines in emissions to each PAR. We summarize the top three routes that emit to each PAR, as shown in Tab.1.

As shown in Tab.1, some PARs have undertaken many carbon emissions from the routes, but these routes do not start or end on the PAR, such as Shandong, Jiangsu, Fujian, Jiangxi, and Henan. These PARs are on China's busiest routes and cover a large part of them. For example, Shandong is on the two busiest routes, Guangzhou-Beijing and Beijing-Shanghai, account for 32.3% and 32.9% of the total distances of these two routes. Some PARs' emissions are from the routes starting or ending, such as Beijing, Shanghai, Xinjiang, Yunnan, Hainan, and Heilongjiang. Beijing and Shanghai are the most developed cities in China, so they have many routes as the starting and ending points, with many emissions. Xinjiang, Yunnan, Hainan, and Heilongjiang are on the border of China, and few routes pass through them, so their main routes with the most emissions are the ones starting or ending in them.

Regarding emitting the most significant emissions, Beijing-Shanghai's route ranks first in four PARs (Beijing, Shanghai, Jiangsu, and Tianjin), covering the most PARs among the 413 routes. As the route emitting the second-largest emissions, Beijing-Shenzhen covers Beijing and Jiangxi, Chengdu-Shanghai covers Sichuan and Hubei, Guangzhou-Shanghai covers Shanghai and Guangdong, Harbin-Shanghai covers Heilongjiang and Liaoning, and Kunming-Shanghai covers Hunan and Guizhou. As the route emitting the third-largest emissions, Guangzhou-Beijing covers Hubei and Guangdong, Guangzhou-Chengdu covers Guangxi and Guizhou, and Guangzhou-Hangzhou covers Jiangxi and Zhejiang. For China, these routes cover more provinces and have significant emissions.

Tab. 1 Top three routes in emission to each PAR

PARs	Routes	Emissions (tons)	Routes	Emissions (tons)	Routes	Emissions (tons)
Anhui	Chengdu-Shanghai	109,283	Chongqing-Shanghai	89,056	Shanghai-Xi'an	86,314
Beijing	Beijing-Shanghai	230,613	Beijing-Shenzhen	100,511	Chengdu-Beijing	92,265
Chongqing	Chongqing-Shenzhen	96,100	Guangzhou-Chongqing	88,740	Chongqing-Shanghai	82,086
Fujian	Guangzhou-Shanghai	274,773	Shanghai-Shenzhen	231,269	Hangzhou-Shenzhen	106,124
Gansu	Chengdu-Urumqi	110,113	Urumqi-Lanzhou	98,075	Urumqi-Xi'an	93,399
Guangdong	Shanghai-Shenzhen	237,815	Guangzhou-Shanghai	218,920	Guangzhou-Beijing	202,348
Guangxi	Guangzhou-Kunming	105,378	Chengdu-Shenzhen	100,567	Guangzhou-Chengdu	89,538
Guizhou	Chengdu-Shenzhen	89,862	Kunming-Shanghai	87,143	Guangzhou-Chengdu	84879
Hainan	Shanghai-Sanya	49,665	Beijing-Sanya	48,299	Guangzhou-Sanya	30,193
Hebei	Guangzhou-Beijing	170,563	Chengdu-Beijing	138,375	Beijing-Shenzhen	115,580
Heilongjiang	Harbin-Beijing	35,216	Harbin-Shanghai	29,791	Harbin-Qingdao	22,059
Henan	Beijing-Shenzhen	232,820	Shanghai-Xi'an	109,624	Changsha-Beijing	80,921
Hubei	Chongqing-Shanghai	173,979	Chengdu-Shanghai	171,105	Guangzhou-Beijing	144,130
Hunan	Beijing-Shenzhen	82,039	Kunming-Shanghai	76,862	Beijing-Sanya	67,721
Inner Mongolia	Beijing-Urumqi	172,370	Hohhot-Hailar	102,491	Harbin-Beijing	73,478
Jiangsu	Beijing-Shanghai	282,583	Hangzhou-Beijing	132,960	Chengdu-Shanghai	75,290
Jiangxi	Guangzhou-Beijing	265,023	Beijing-Shenzhen	189,792	Guangzhou-Hangzhou	115,911
Jilin	Harbin-Shanghai	40,434	Harbin-Beijing	39,727	Changchun-Beijing	31,702
Liaoning	Shanghai-Shenyang	64,199	Harbin-Shanghai	50,589	Beijing-Shenyang	46,458
Ningxia	Yinchuan-Xi'an	41,677	Chengdu-Yinchuan	15,836	Yinchuan-Beijing	15,796
Qinghai	Urumqi-Lanzhou	50,327	Zhengzhou-Urumqi	33,021	Chongqing-Urumqi	28,737
Shaanxi	Chengdu-Beijing	221,246	Yulin-Xi'an	117,437	Shanghai-Xi'an	89,450
Shandong	Guangzhou-Beijing	351,698	Beijing-Shanghai	304,859	Hangzhou-Beijing	122,399
Shanghai	Beijing-Shanghai	232,996	Guangzhou-Shanghai	125,188	Shanghai-Shenzhen	118,571
Shanxi	Chengdu-Beijing	196,825	Beijing-Xi'an	102,699	Chongqing-Beijing	100,728
Sichuan	Chengdu-Beijing	199,814	Chengdu-Shanghai	186,708	Chengdu-Shenzhen	122,975
Tianjin	Beijing-Shanghai	68,364	Shanghai-Tianjin	35,258	Dalian-Beijing	28,066
Tibet	Chengdu-Lhasa	151,744	Chongqing-Lhasa	60,770	Lhasa-Xi'an	52,956
Xinjiang	Lhasa-Urumqi	192,449	Hotan-Urumqi	133,186	Beijing-Urumqi	123,020
Yunnan	Xishuangbanna-Kunming	273,896	Kunming-Dehong	175,243	Kunming-Beijing	113,460
Zhejiang	Guangzhou-Shanghai	197,769	Hangzhou-Shenzhen	118,664	Guangzhou-Hangzhou	94,132

Then this study summarizes the leading airlines that emit emissions to each PAR, as shown in Tab. 2.

As shown in Tab.2, China Southern has the most significant emissions in 16 PARs, covering the most PARs among the 40 airlines. Air China has the actual emissions in 8 PARs, ranking second among the 40 airlines; China Eastern has the most significant emissions in 6 PARs, ranking third among the 40 airlines. In addition, Tibet Airlines has essential emissions in Tibet. This result is consistent with the overall emission situation. China Southern, China Eastern, and Air China are the top three airlines in terms of emissions, whose overall emissions are 9,578,734 tons, 7,979,334 tons, and 6,435,100 tons, respectively. Although the three airlines cover the most significant emissions in most PARs, they have an enormous difference. Take China Southern Airlines as an example. It emits 1,161,184 tons at its headquarters in Guangdong but emits only 45,237 tons in Heilongjiang, 3.9% of Guangdong.

Tab. 2 Top three airlines in emission to each PAR

PARs	Airlines	Emissions (tons)	Airlines	Emissions (tons)	Airlines	Emissions (tons)
Anhui	China Eastern	459,089	China Southern	172,095	Hainan	165,265
Beijing	Air China	544,633	China Southern	270,595	China Eastern	254,400
Chongqing	Air China	180,912	Sichuan	156,237	China Eastern	154,201
Fujian	China Southern	412,268	Xiamen	396,471	China Eastern	256,704
Gansu	China Southern	224,101	China Eastern	170,280	Sichuan	113,116
Guangdong	China Southern	1,161,184	Shenzhen	488,282	Hainan	443,021
Guangxi	China Southern	368,632	Hainan	232,590	China Eastern	164,847
Guizhou	China Southern	269,039	China Eastern	217,597	Air China	148,436
Hainan	China Southern	149,455	Hainan	73,526	Capital	62,806
Hebei	Air China	601,882	China Southern	432,361	China Eastern	232,514
Heilongjiang	China Southern	45,237	Air China	28,801	China Eastern	26,914
Henan	China Southern	468,968	China Eastern	363,699	Air China	265,471
Hubei	China Southern	520,634	China Eastern	458,071	Air China	290,664
Hunan	China Southern	513,338	China Eastern	314,158	Hainan	263,624
Inner Mongolia	Air China	283,930	China Southern	235,538	Tianjin	114,128
Jiangsu	China Eastern	559,412	Air China	292,433	Hainan	182,303
Jiangxi	China Southern	550,104	Shenzhen	341,979	Hainan	288,690
Jilin	China Southern	112,590	Air China	50,704	China Eastern	40,778
Liaoning	China Southern	282,653	China Eastern	104,922	Air China	79,585
Ningxia	China Eastern	51,642	Air China	25,163	China Southern	24,174
Qinghai	China Southern	88,413	China Eastern	32,432	Sichuan	29,009
Shaanxi	China Eastern	470,215	China Southern	287,444	Hainan	253,175
Shandong	Air China	457,295	China Eastern	433,924	China Southern	372,240
Shanghai	China Eastern	399,061	Hainan	249,989	Shanghai	224,056
Shanxi	Air China	292,008	China Eastern	200,174	China Southern	159,932
Sichuan	Air China	447,596	Sichuan	379,556	China Eastern	364,701
Tianjin	Air China	107,691	China Eastern	60,717	Tianjin	52,296
Tibet	Tibet	78,741	Sichuan	61,005	Air China	45,101
Xinjiang	China Southern	544,892	Tianjin	113,799	Hainan	102,135
Yunnan	China Eastern	660,562	Hainan	259,782	Lucky Air	215,695
Zhejiang	China Southern	430,110	China Eastern	319,608	Air China	213,792

Regarding emitting the second and third largest emissions, China Eastern covers 11 PARs and 8 PARs, the most among the 40 airlines. Moreover, with Shanghai Hongqiao Airport and Shanghai Pudong Airport as the centers, China Eastern Airlines has established an aviation network covering Eastern, Central, and Western China, becoming the second-largest source of domestic routes.

Airlines' carbon compensation to the PARs. After splitting the emissions of each airline into each PAR, this study will discuss the airlines' carbon compensation to the PARs. According to the principle of who is responsible for discharging, the airlines emitting emissions should offer some carbon compensation to the PARs. In 2018, China carried out carbon trading pilot projects in seven provinces and cities, and the carbon trading prices of these seven pilot projects are different. According to statistics [14,15], the average costs of the seven pilot projects in 2018 are 16.35 yuan/ton in Guangdong, 19.22 yuan/ton in Hubei, 25.25 yuan/ton in Shanghai, 27.89 yuan/ton in Shenzhen, 13.70 yuan/ton in Tianjin, 4.01 yuan/ton in Chongqing, 52.72 yuan/ton in Beijing, and 23.38 yuan/ton in Fujian. This study sets the trading price of the other provinces as the average price of the seven pilots, which is 22.82 yuan/ton. Then the carbon compensations of the airlines to the PARs can be calculated. The total payments are 1,132,605 thousand yuan. The overall compensations for the PARs are shown in Fig.4.

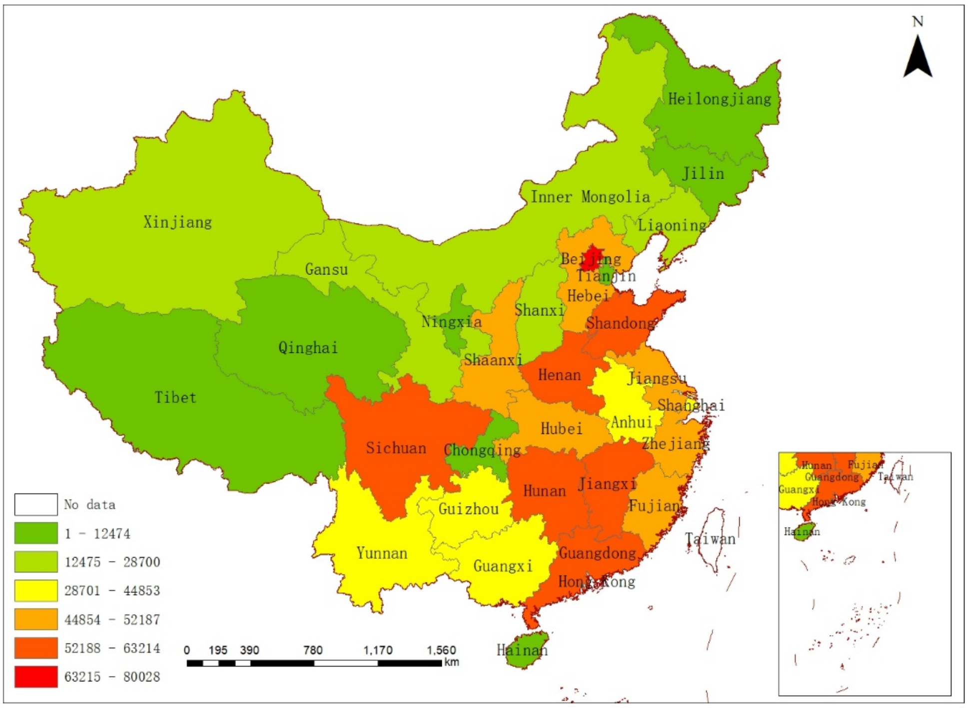


Fig. 4 Compensations to the PARs

As shown in Fig. 4, the ranking of many PARs has changed a lot compared with Fig.3. The most noticeable change is in Beijing, whose emissions rank 18th but compensations rank 1st among these 31 PARs. This change is closely related to the carbon trading price. The price of Beijing in 2018 is 52.72 yuan/ton, much higher than the other PARs, so its compensations are the most. In addition, due to the relatively low price, Hubei changes from the 5th carbon emission to the 12th compensation, and Chongqing changes from the 19th carbon emission to the 29th compensation. Guangdong bears the most emissions, but its received payment only ranks third. This result indicates that the carbon trading price has a noticeable influence on the PARs.

The overall compensations that the airlines need to pay are shown in Fig.5.

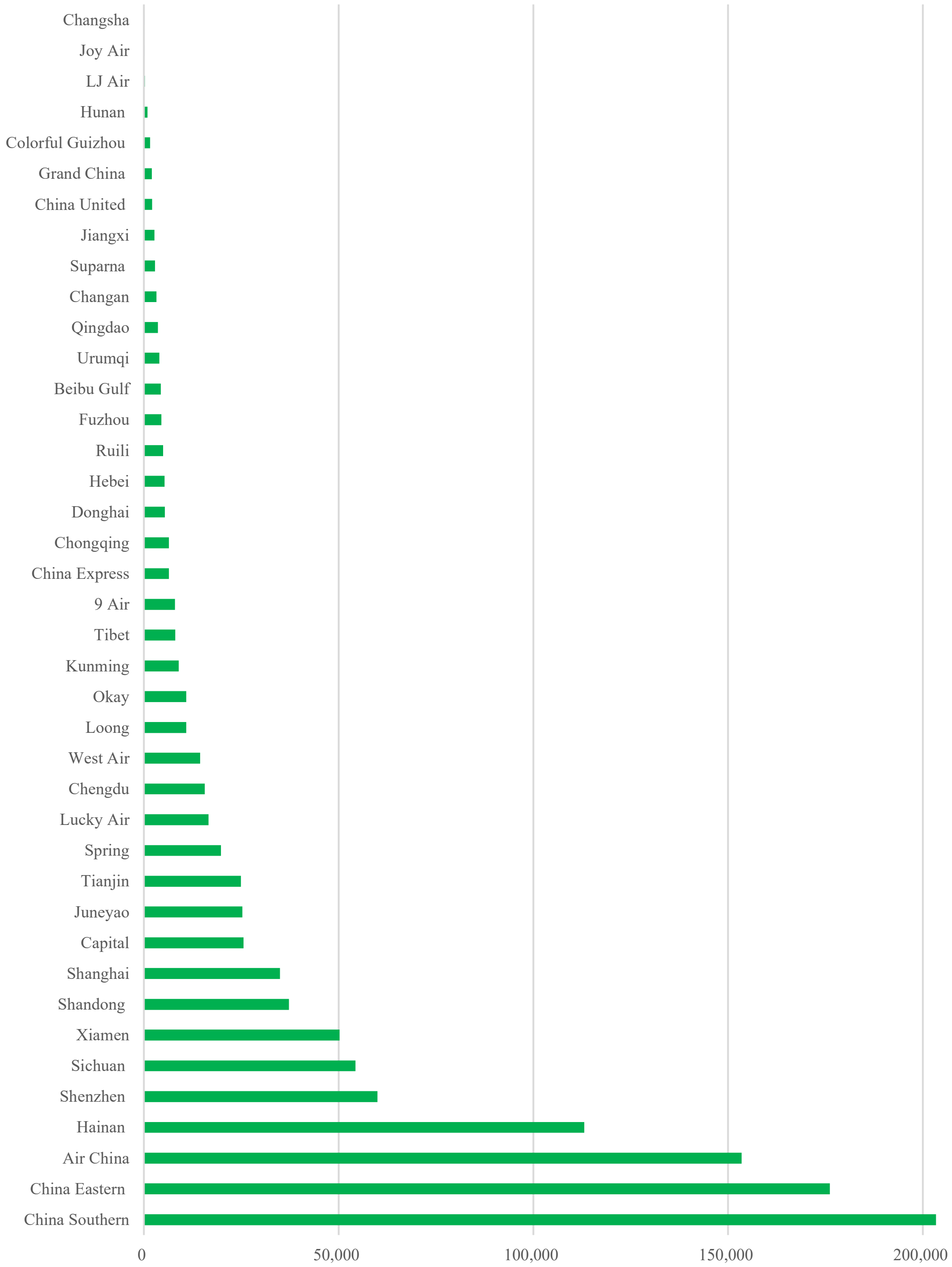


Fig. 5 Overall compensations of the airlines

Comparing Fig. 2 and Fig. 5, we can find that the order of several pairs of airlines has exchanged, such as Capital and Juneyao, Chengdu and West Air, Loong and Okay, Tibet and 9 Air, China Express and Chongqing, and Ruili and Fuzhou. In Fig. 2, Capital, Chengdu, Loong, Tibet, China Express, and Ruili rank 11th, 16th, 18th, 21st, 23rd, and 27th. However, they rank 10th, 15th, 17th, 20th, 22nd, and 26th in Fig. 5. This result indicates that the carbon trading price has a certain impact on various airlines. As the carbon trading price of different regions is different, the airlines whose routes pass through the regions with high prices may need to bear more compensation.

Discussion

This study focuses on calculating the overall emissions of the airlines to the Provincial Administrative Regions (PARs) and discussing the compensations that the airlines should pay to the PARs according to the principle of who is responsible for discharging. The overall emissions contain the CCD emissions and LTO emissions of 413 routes and 40 airlines in 2018, and the overall emissions are split into 30 PARs. Therefore, this research can provide a reference for China to build a domestic aviation carbon trading mechanism. The main conclusions and 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 kilometers. 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 kilometers. 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, the LTO emissions have direct relationships with flight frequency and aircraft type. For example, some aircraft, such as 747-400, 747-8I, 777-300ER, 330-343E, and 330-243E, have more emissions in a single LTO. Although these aircraft have better performance in medium and long-haul routes due to their extensive range and large passenger capacity, their significant emissions in a single LTO are not friendly to the local environment. On the other hand, although Some aircraft are only suitable for short-distance routes, such as E195LR, E190 LR, CRJ900, and CORP MA-60, they have fewer single emissions and fewer impacts on the environment of the airport.

Third, China Southern Airlines, China Eastern Airlines, and Air China are the top three airlines in emissions, while LJ Air, Joy Air, and Changsha Airlines are the bottom three. Due to the significant differences in fleet size and route resources among airlines, emissions are enormous. Therefore, in the aspect of carbon compensations that need to be paid, the top airlines in emissions are also at the top, and the lower airlines in emissions are also ranked lower. However, the order of several pairs of airlines has been exchanged, which indicates that the carbon trading price has a particular impact on the airlines.

Fourth, Guangdong has the most carbon emissions from airlines, but it may get the third carbon compensation from the airlines. Two reasons lead to the significant emissions in Guangdong: the headquarters of China Southern Airlines and the large number of routes taking-off and landing it. Furthermore, the PARs with the most negligible emissions are not those with the minor routes. Due to the relatively low price, Hubei and Chongqing have a noticeable change in the ranking among these 31 PARs, which shows that the carbon trading price has an apparent influence on the PARs.

Finally, because some PARs are on China's busiest routes and cover a large part of them, although the routes do not start or end on them, they have undertaken many carbon emissions from these routes. For example, Beijing-Shanghai's route ranks first in emissions in four PARs, and China Southern has the most significant emissions in 16 PARs. As a result, different routes and airlines have distinctly different impacts on the PARs.

It should be noted that the overall emissions are calculated through the standard LTO stage.

The carbon emissions due to delays are not considered. In this paper, the traditional method is adopted to split various routes into various PARs, and the aircraft transfer caused by temporary weather is not considered. Furthermore, this study has not evaluated the emissions from air cargo. Therefore, further investigation can calculate the emissions caused by delay, aircraft transfer, and air cargo.

Methods

ICAO standard method to calculate LTO emissions

The take-Off and Landing stage (LTO) refer to the aircraft's whole process during takeoff and landing. This stage defined by ICAO includes four states, including approaching, taxiing, taking-off, and climbing, which defines climbing as the boundary layer from the end of aircraft takeoff to the aircraft's flight out of the atmosphere. Therefore, this paper uses the standard LTO cycle definition specified by ICAO to calculate the fuel consumption, including all activities at an altitude below 3000 feet (915m) near the airport. Therefore, this stage is not directly related to the route. In addition, the climbing process requires higher fuel consumption than the cruise phase at a constant altitude. Thus, the Climb, Cruise, and Descent cycle (CCD) are defined as all activities that occur at the height of 3000 feet (915 meters). Thus, fuel use accounts for most of the whole voyage and is directly related to the flight distance.

The calculation formula of carbon emissions in LTO stage is:

$$E_{LTO} = 3.157 * \sum_{m} P_a \times N_a \times C_m \times t_m \times F_{am} \tag{1}$$

E_{LTO} is the emissions in the LTO stage; P_a is the standard thrust of the engine of aircraft type a (unit: kg); N_a is the number of engines of aircraft type a; C_m is the thrust setting of stage m; t_m is the working time of phase m, F_{am} is the fuel consumption rate. 3.157 is the emission coefficient of fuel. The value range of m is 1, 2, 3, and 4, respectively corresponding to the four stages of takeoff and landing in the aircraft flight process: takeoff, climb, approach and taxiing. According to the standard LTO cycles defined by ICAO, when the aircraft is taking off, its engines are at 100% thrust and working time is 0.7 minutes; when the aircraft is climbing, its engines are at 85% thrust and working time is 2.2 minutes; when the aircraft is approaching, its engines are at 30% thrust and working time is 4 minutes; when the aircraft is taxiing, its engines are at 7% thrust and working time is 26 minutes. Therefore, in a standard LTO cycle, the total working time is 32.9 minutes.

The fuel consumption rate is calculated as:

$$F_{am} = \frac{1}{A} \sum_{j} K_j \, F_{jmi} \tag{2}$$

A is the total number of airlines with aircraft type a; j is the type of engine of the aircraft; K_j is the number of aircraft type a equipped with engine type j; F_{jmi} is the fuel consumption rate of engine type j under the m setting. The data is from the ICAO Aircraft Engine Emissions Databank [11]. This formula is based on the weighted average of all possible engine types of the domestic routes in China. The LTO emission of each aircraft can be found in Supplementary Table 2.

Modified Fuel Percentage Method (MFPM)

The CCD emissions of the flight $E(Q)$ can be calculated by

$$E(Q) = 3.157 * F(Q) = 3.157 * M_{fuel} * weight(Q) = 3.157 * \left(1 - M_{ff}\right) * weight(Q)$$

$$=3.157 * \left(1 - \prod_{i=1}^{n} \frac{W_i}{W_{i-1}}\right) * weight(Q) = 3.157 * \left[1 - e^{-\frac{dis*ratio_{cr}}{10*v}}\right] * weight(Q)$$

$$=3.157 * \left[1 - e^{-\frac{dis*ratio_{cr}}{10*v}}\right] * (aircraftbareweight + 100 * (load\ factor * number\ of\ seats) + 50 * seat) \qquad (3)$$

3.157 is the emission coefficient of aviation kerosene[12]. $weight(Q)$ 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 seven 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 $i\ (i = 1,2, \ldots ,7)$.

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 $ratio_{cr} = \frac{c_{cr}}{LDc_{cr}}$, 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 in Supplementary Table 1.

Data sources. The original data are collected from the VariFlight.com[13] and the Statistical Data on Civil Aviation of China[16], 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 data on the engines of each aircraft and the data on the engines are from ICAO Aircraft Engine Emissions Databank[11].

Data availability. The emission intensity of each aircraft is shown in Supplementary Table 1. The emissions of each aircraft in a single LTO cycle can be found in Supplementary Table 2. The original daily flight data is shown in Supplementary Table 3 (We found that there was little difference in weekly flight information, so we collected data in weekly units, but for the convenience of display, the table shows the daily flight information). The split distances of each province on the routes can be found in Supplementary Table 4. The overall emissions of the routes are shown in Supplementary Table 5. The overall emissions of the airline are shown in Supplementary Table 6 (There are 40 airlines in total. To facilitate the display, this paper takes Air China as an example).

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Competing interests: The authors declare no competing financial interests.

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- SupplementaryTables.xlsx