What's the Relationship Between Aircraft Taxi Speed and its Pollutant Emissions?

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***Abstract*—Aircraft taxi speed has an important effect on airport operational efficiency, fuel consumption, and pollutant emissions. In order to achieve the shortest taxi time, aircraft prefer taxiing at the fastest speed, but this does not mean that the pollutant emissions are also optimal in most cases. In the context of vigorously advocating "green civil aviation," the relationship between taxi speed and pollutant emissions (i.e., emission quantity and emission cost) needs further study to achieve the aim of lower pollutant emissions. Therefore, based on the aircraft taxi speed model and aerodynamics model, this paper establishes a multi-objective optimization model of taxi speed with consideration of pollutant emissions. Then, the light (CRJ-900), medium (A320), and heavy (A333) aircraft were selected to reveal the relationships between taxi speed, pollutant emission quantity/cost on a given route at Shanghai Hongqiao Airport. The study results show that: (1) For pollutant emission quantity, the faster average taxi speed, the less pollutant emissions of A333; while for A320 and CRJ-900, the pollutant emissions decrease first and then increase with the increase of the average taxi speed; (2) For pollutant emission cost, the faster average taxi speed, the higher pollutant emission cost of all three aircraft, which increases slowly first then rapidly; (3) The optimal taxi speed profile can be generated according to the specific demand of the airport stakeholders to seek a balance between economic benefits and environmental benefits. It also has a certain significance for the study on taxiing scheduling and planning.**

Keywords-departure aircraft, taxi speed optimization, pollutant emissions, emission cost, taxiing route, aircraft category

I. INTRODUCTION

Nowadays, air pollution caused by aircraft taxiing has aroused the attention of all sectors. The pollutants emitted by aircraft mainly include hydrocarbon (HC), carbon monoxide (CO) and nitrogen oxides (NOx), also include sulfur oxide (SOx) and particulate matter (PM). Although the current total emissions are not large, with the rapid increase in the volume of flight movements, the resulting pollutants will also increase significantly, which will seriously affect the air quality at and near the airports. Therefore, the European Union has set a goal of reducing NOx by 90% per passenger-kilometer in 2050, based on the level of pollutant emissions per passenger-kilometer in 2020 [1]. China has also actively carried out emission reduction actions and has set clear requirements for reducing emissions and developing green civil aviation. As taxiing is an essential and long-time process of aircraft surface operations and the emissions during the taxiing account for about 50% of the total emission during the landing and take-off (LTO) cycle [2]-[3], it can be seen that it is imperative to optimize the aircraft taxiing and reduce pollutant emissions.

For the study on aircraft taxiing route planning, scholars usually establish the optimization model with the minimum taxi time, reducing the taxi time by changing taxi speed. With regard to the taxi speed constraint, scholars mainly have three hypotheses: first, assuming that the taxi speed is constant, an aircraft taxis at a constant speed during the whole taxiing or taxis on the straight segment and the turning segment at a fixed value respectively; second, the taxi speed is various, and the upper limit of speed is given in advance; third, historical data is analyzed through mathematical induction to predict the optimal taxi time. To simplify the calculation, scholars usually assume that the taxi speed is constant. However, the speed variations are neglected, which may cause deviation in results from the actual operations. Therefore, in recent years, several scholars have conducted detailed researches on taxiing by dividing it into several phases such as acceleration, uniform, and deceleration phases, which is closer to the actual operations of aircraft taxiing [4]-[7].

Furthermore, aircraft taxi speed is one of the key factors affecting taxiing route planning and scheduling [8]. Several papers had discovered the effect of taxi speed on airport operational efficiency, fuel consumption, and etc. Chen (2011) studied the optimal aircraft taxiing trajectories with consideration of taxi time and fuel burn, and found that high taxi speed can reduce taxi time and improve efficiency but may cause more fuel burn because of excessive use of acceleration and deceleration [9]. On this basis, Ravizza (2013) established a taxi speed optimization model for aircraft in airport ground movement, which revealed the trade-off between taxi time and fuel consumption for the first time [10]. These studies found that generating an optimal taxiing route just based on taxi time and fuel consumption does not mean that the pollutant emission quantities and the emission costs are also optimal.

After subdividing the taxiing, scholars also gave the thrust levels of different phases, which can be used to calculate the fuel consumption of each phase accurately. Nikoleris (2011) assumed the thrust levels for each taxiing phase, which are waiting (4%), acceleration (9%), turning (5%), and uniform or deceleration (7%) [5]. The study found that the fuel consumption during taxiing is mainly caused by uniform, waiting, and deceleration phases [5]. Although the International Civil Aviation Organization (ICAO) has set the thrust level of the taxiing at 7%, some scholars believe that the thrust setting given by ICAO is higher than the actual value [11], and the change in thrust level during taxiing still needs further research.

In summary, the current research has fruitful outcomes, but still has the following contents to be further studied: (1) less attention is paid to the change of speed and thrust level during taxiing, and the relationship between taxi speed and thrust needs further study; (2) current study on taxiing route planning often focuses on taxi time and fuel consumption, but seldom considers pollutant emissions. No scholars have specifically studied the relationship between taxi speed, pollutant emission quantity and emission cost.

Therefore, in light of the above discussion, especially in the context of vigorously developing “green civil aviation,” the research on aircraft taxiing should not be limited to taxi time and fuel consumption, and it is necessary to consider pollutant emissions at the same time to further optimize the taxiing route. We make the following specific contributions: first, the taxiing is subdivided into five phases according to the speed variations, and the force analysis of the aircraft is carried out to derive the relationship between the taxi speed and the thrust, so as to calculate the thrust level of each subdivided phase, which is closer to the actual operations; second, considering taxi time cost, fuel cost and pollutant emission cost, this paper establishes a multi-objective optimization model of taxi speed, and reveal the relationship between taxi speed, pollutant emission quantity and emission cost.

The remainder of this paper is structured as follows: Section II introduces aircraft taxi models and algorithm; Section III gives the data used in this paper; Section IV conducts a case simulation to reveal the relationship between taxi speed, pollutant emission quantity and emission cost; Section V draws the research conclusions and suggestions for future study of their papers.

II. METHODOLOGY

A. *Aircraft taxi speed model*

Considering the complexity of the whole surface operation, this paper focuses on the research of departure aircraft. The taxiing route usually consists of straight segments and turning segments. In this paper, the taxiing route is divided into five phases according to the taxi speed settings, which are the acceleration phase, uniform phase, deceleration phase, waiting phase, and turning phase. The total taxi time is the sum of the five phases. As shown in *Fig. 1*, 0-T_1 seconds and T_4-T_5 seconds are the acceleration phases, in which the aircraft accelerates to the maximum taxi speed of the straight segment and turning segment; the T_1-T_2 seconds is the uniform phase, in which the aircraft taxis at a constant speed on the straight segment; the T_2-T_3 seconds and T_6-T_7 seconds are the deceleration phases; the T_3-T_4 seconds is the waiting phase; the T_5-T_6 seconds is the turning phase, in which the aircraft taxis at a constant speed on the turning segment [12].

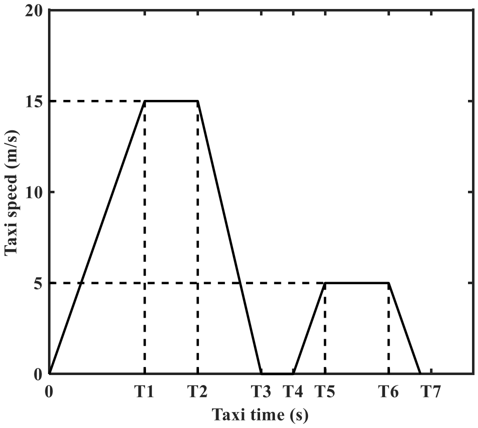


Figure 1. The taxi speed model of a certain aircraft with five phases

B. *Aircraft taxi aerodynamics model*

Based on the research results of domestic and foreign scholars [7],[13], the whole aircraft is regarded as a mass point in this paper. We assume that it is a rigid body motion, whose mass is concentrated at the particle point, and the aircraft taxis along the midline of the taxiway with the pitch angle $\beta=10^\circ$. Considering the engine thrust directly affects the fuel flow, it is necessary to conduct a force analysis, as shown in *Fig. 2*.

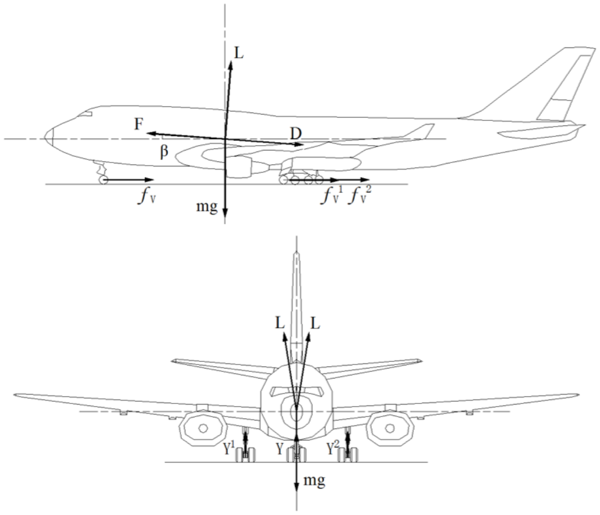


Figure 2. Force analysis of a certain aircraft

We conduct force analysis in the horizontal and vertical direction and analyze the lateral friction of three wheels, as shown in (1)-(3). In general, the aircraft takes off against the wind and taxis before the wind. Thus, the wind force usually helps reduce the thrust to arrive the specific speed. To simplify the force analysis and considering wind force does not have too much impact on the results, we do not consider wind force in this paper.

$$F\cos\beta = D\cos\beta + L\sin\beta + f_V + f_V^1 + f_V^2 + ma \qquad (1)$$

$$Y + Y^1 + Y^2 + L\cos\beta + F\sin\beta - mg = 0 \qquad (2)$$

$$f_H + f_H^1 + f_H^2 = 0 \qquad (3)$$

Where, F represents the thrust; D represents the air drag; L represents the lift force; f_V represents the longitudinal friction of the front wheel; f_V^1, f_V^2 represent the longitudinal friction of the two rear wheels; m represents the mass of the aircraft; a represents the accelerated velocity; Y represents the supporting force of the front wheel; Y^1, Y^2 represents the supporting force of the two rear wheels; g represents the acceleration of gravity; f_H represents the lateral friction of the front wheel; f_H^1, f_H^2 represent the lateral friction of the two rear wheels.

The sum of the longitudinal friction of the front and rear wheels is equal to the ground friction, so (4) is as follows:

$$f_V + f_V^1 + f_V^2 = \mu(mg - L\cos\beta - F\sin\beta) \qquad (4)$$

Where, μ represents the ground friction coefficient. Studies have shown that when the thrust level is between 5% and 7%, the ground friction coefficient of aircraft tires is usually between 0.015 and 0.02 [7], so we set it at 0.015 in this paper.

Air drag D and lift force L are expressed by (5) and (6) respectively：

$$D = \frac{1}{2}\rho V_G^2 S_a C_D \qquad (5)$$

$$L = \frac{1}{2}\rho V_G^2 S_a C_L \qquad (6)$$

Where, ρ represents the air density; V_G represents the ground speed; S_a represents the wing area; C_D, C_L represent the drag and lift force coefficient, respectively. In this paper, the influence of wind speed is not considered in the force analysis, so the ground speed of the aircraft is equivalent to the actual taxi speed of the aircraft.

We substitute (4), (5), and (6) into (1), then the (7) is organized into the following form:

$$F = \frac{ma + \mu mg + \frac{1}{2}\rho V_G{}^2 S_a (C_D\cos\beta + C_L\sin\beta - C_L\cos\beta)}{\cos\beta + \mu\sin\beta)} \qquad (7)$$

When the accelerated velocity is determined, the relationship between the thrust and the speed can be further obtained. That is, the thrust is proportional to the square of the taxi speed. This formula applies only to the acceleration phase and the uniform phase.

C. *Taxi speed optimization model*

1）The optimization model with the minimum taxi time cost

According to the division of the taxiing, the total taxi time is the sum of the taxi time in five phases. Therefore, the taxi speed optimization model with the minimum taxi time cost is expressed by (8) and (9):

$$\min T = C_{\text{taxi}} \cdot \sum_{s\in R} T_s \qquad (8)$$

$$T_s = \sum\nolimits_{e=1}^{5} t_e \qquad (9)$$

Where, T represents the total taxi time cost; C_{taxi} represents the unit taxi time cost; T_s represents the taxi time of a single segment s; t_e represents the taxi time of the phase e of a single segment; e represents the taxi phase ($e = 1, 2, 3, 4, 5$), corresponding to acceleration phase, uniform phase, deceleration phase, stop waiting phase and turning phase, respectively.

2）The optimization model with the minimum fuel cost

According to (7), when the accelerated velocity is known, the relationship between thrust and speed can be obtained. The real-time thrust during taxiing can be calculated based on the real-time taxi speed. The thrust level C_T is calculated by the real-time thrust of the engine F_T and the maximum thrust of the engine $F_{\max}$, as shown in (10):

$$C_T = F_T / F_{\max} \tag{10}$$

The thrust level of the acceleration phase and the uniform phase can be obtained by the above calculations. However, the deceleration phase, the turning phase, and the waiting phase all need to consider the influence of the brakes, and it is difficult to analyze the force. Therefore, the thrust level in the deceleration phase is simplified to make it equivalent to the constant speed operation. Based on the research results of the scholars [4]-[7], the thrust level of the turning phase and the stop waiting phase are set at 7% and 3%, respectively. According to the fuel flow values under 7% and 30% thrust in the ICAO Aircraft Engine Emissions Databank, the fuel flow under other thrust levels of other phases can be obtained by linear interpolation method [5]. Therefore, the taxi speed optimization model with the minimum fuel cost is expressed by (11) and (12):

$$\min F = C_{\text{fuel}} \cdot \sum_{s \in R} F_s \tag{11}$$

$$F_s = \sum_{e=1}^{5} n_0 f_e t_e \tag{12}$$

Where, F represents the fuel cost; C_{fuel} represents the unit price of aviation fuel; F_s represents the fuel consumption on a single segment s ; n_0 represents the number of engines of the aircraft; f_e represents the fuel flow of the aircraft in the phase e .

3）The optimization model with the minimum emission cost

In this study, the pollutants emitted by aircraft during taxiing phrases include HC, CO, and NOx. The emission index numbers of these three pollutants are all derived from the ICAO Aircraft Engine Emissions Databank. The standard Log-Log curve fitting method is defined in SAE Air5715. According to the research results of DuBois and Paynter (2006), the Log-Log logarithmic fitting method can be used to calculate the emission index numbers of HC, CO, and NOx in each phase [14]-[15]. Therefore, the taxi speed optimization model with the minimum pollutant emission cost is expressed by (13) and (14):

$$\min E = \sum_{s \in R} E_s \tag{13}$$

$$E_s = \sum_{e=1}^{5} \sum_{n=1}^{3} n_0 f_e t_e I_{ne} C_n \tag{14}$$

Where, E represents the pollutant emission cost; E_S represents the emission cost on a single segment s ; n represents the type of pollutant ($n = 1, 2, 3$), corresponding to HC, CO, and NOx, respectively; I_{ne} represents the emission index number of the pollutant n in the phase e ; C_n represents the emission cost of the pollutant n .

4）The optimization model with multi-objective

This paper considers three objectives, which are taxi time cost, fuel cost, and pollutant emission cost. Considering the different attention of stakeholders to the three objectives, the three sub-objective functions are given different weights. Therefore, the weight coefficients λ_1 and λ_2 of the sub-objective functions are introduced, which are between 0 and 1 with a step size of 0.1, and $(\lambda_1 + \lambda_2) \in [0, 1]$. By setting the weight coefficients λ_1 and λ_2 from 0 with a step size of 0.1, the multi-objective taxi speed optimization model is expressed by (15):

$$\min z = \lambda_1 T + \lambda_2 F + (1 - \lambda_1 - \lambda_2) E \tag{15}$$

D. Algorithm introduction

The above multi-objective taxi speed optimization model has 66 methods of setting the weight coefficients from 0 to 1 with a step size of 0.1, which will take a long time to achieve the simulation results. Considering that the genetic algorithm has great advantages in solving efficiency compared with a conventional precision algorithm, and scholars have improved and optimized the application of the genetic algorithm in taxiing related problems, so the optimized genetic algorithm is used to solve multi-objective optimization model in this paper. Specific steps are as follows: first, using real-number encoding, a chromosome represents a taxi speed method, the gene of the chromosome represents the maximum speed of an aircraft on a single segment, the step size is 0.5m/s; second, the initial population is generated randomly, which means multiple feasible solutions are generated, that is, multiple taxi speed methods; third, the fitness function is formed according to the objectives and weight settings; finally, through selection, crossover, mutation, re-insertion, the optimal chromosome is iteratively generated, that is, the optimal taxi speed method that meets the optimization objective(s).

III. DATA

A. Modeling of taxiways

Taking Shanghai Hongqiao International Airport (IATA: SHA) as an example, this paper pre-selects the taxiing route for a departure aircraft to study the speed change during taxiing. The route is shown in *Fig. 3*. After push-back from the gate, the departure aircraft begins to taxi in the taxiway system, which will experience acceleration, uniform, deceleration, turning, and waiting phases.

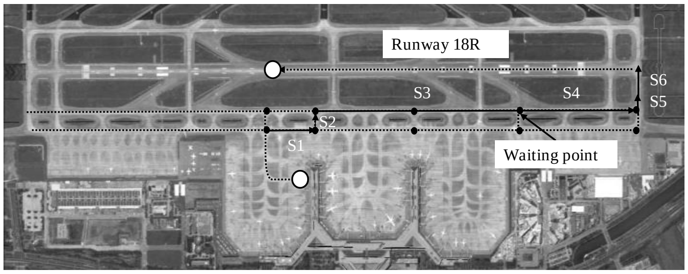


Figure 3. Taxiing route for a departure aircraft at SHA

The basic information of the departure route is shown in *Table I*. To simulate the stop waiting phase, we assume that the departure aircraft has a 10-second waiting at the waiting point as shown in *Fig. 3*, which is between S3 and S4. This is because it is an exit of a high-speed taxiway, which may occur conflicts between departure aircraft and arrival aircraft. During taxiing, the maximum taxi speeds of the straight segment and the turning segment are 15m/s and 5m/s, respectively [16]. In the acceleration phase, the accelerated velocity is generally set between 0.6 and 0.7m/s^2 [11]. Similarly, in the deceleration phase, the accelerated velocity is generally set at about 0.98m/s^2 considering passenger comfort [17]-[18]. Therefore, the accelerated velocity in the acceleration phase is set at 0.6m/s^2, and the accelerated velocity in the deceleration phase is set at 0.98m/s^2.

TABLE I. BASIC INFORMATION OF THE GIVEN DEPARTURE ROUTE

Segment	**Type**	**Length (m)**	**Initial speed V_0 (m/s)**	**Final speed V_2 (m/s)**
S1	Straight segment	220	0	5
S2	Turning segment	60*2	5	5
S3	Straight segment	1500	5	0
S4	Straight segment	1050	0	5
S5	Turning segment	60	5	5
S6	Straight segment	150	5	0

B. Specification of the typical aircraft

In this paper, A333, A320, and CRJ-900 are selected as representative aircraft of the heavy, medium, and light aircraft categories, respectively. The parameters of each aircraft are shown in *Table II*.

TABLE II. SPECIFICATIONS OF THE TYPICAL AIRCRAFT

Weight category	**Heavy**	**Medium**	**Light**
Typical aircraft type	A333	A320	CRJ-900
Maximum take-off weight (kg)	242000	78000	36500
Maximum thrust (kN)	574	222.4	64.499
Fuel flow at 7% maximum thrust (kg/s)	0.228	0.101	0.064
Fuel flow at 30% maximum thrust (kg/s)	0.724	0.291	0.179
Wing area (m^2)	362	122.4	79.3
Drag force coefficient	0.02	0.02	0.019
Lift force coefficient	0.19	0.18	0.13
Engine Type	CF6-80E1A2	CMF56-5-A1	CF34-8C5
Number of engines	2	2	2
Seats	270-440	123-180	90

C. Flight taxi cost data

Based on the research results of domestic and foreign scholars [19]-[20], the unit taxi time cost of the three aircraft and the unit emission costs of the three pollutants in 2018 in China are calculated, as shown in *Table III*.

TABLE III. SUMMARY TABLE OF FLIGHT TAXI COST

Category		**Cost value**
Unit taxi time cost (RMB/s)	A333	4.60
	A320	2.20
	CRJ-900	1.03
Unit emission cost (RMB/kg)	HC	50.50
	CO	1.12
	NO_x	113.46

IV. RESULTS AND DISCUSSIONS

By assigning different weights to the three objectives, the Pareto optimal solutions of the three aircraft, namely the optimal taxi speed methods under 66 different weight settings, are obtained. At the same time, we obtain the pollutant emission quantities and pollutant emission costs corresponding to various optimal taxi speed methods. The number of optimal solutions shown in the results is less than the number of weight combinations because the step size of the taxi speed is set at 0.5m/s, and under some different weight settings, the same speed optimization result occurs.

A. Relationship between taxi speed and emission quantity

We draw the diagram of the relationship between the average taxi speed and the total pollutant emission quantities of A333, A320, and CRJ-900, and the lowest point of the emission quantity is circled as shown in *Fig. 4*, respectively.

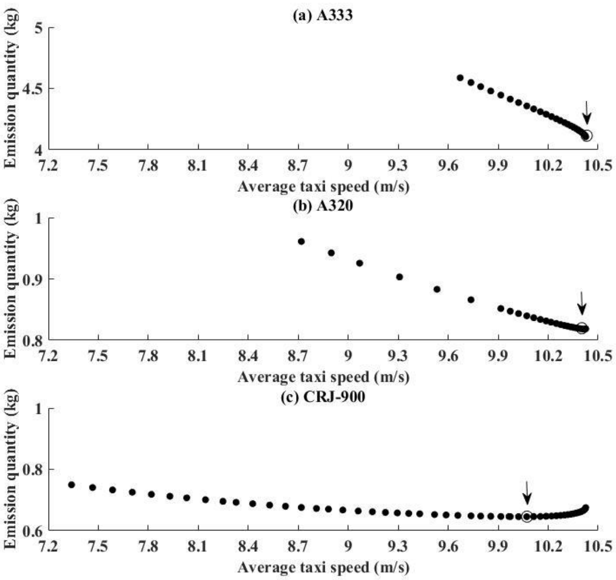


Figure 4. The diagram of the relationship between the average taxi speed and the emission quantity of typical aircraft

It can be seen from *Fig. 4(a)* that as the average taxi speed increases, the pollutant emission quantity of A333 decreases almost linearly, which is related to the emission characteristics of the three pollutants. According to the emission index numbers of the three pollutants given by the ICAO engine emission database under different thrust settings, we draw the diagram of the pollutant emission characteristics A333 (equipped with CF6-80E1A2 engine). As shown in *Fig. 5*, the greater the fuel flow during the taxiing, the smaller the total emission index number of the three pollutants.

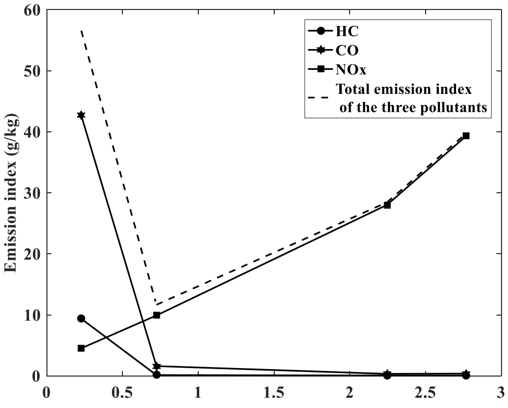


Figure 5. The diagram of the pollutant emission characteristics of A333 (equipped with CF6-80E1A2 engine)

Ravizza et al. (2013) revealed a trade-off between taxi time and fuel consumption, that is, the slower the average taxi speed, the longer the taxi time, the less the fuel consumption, and vice versa [10]. Therefore, when the average taxi speed becomes faster, the total taxi time becomes shorter, so the fuel consumption becomes larger in contrast. However, with the increase of the average taxi speed, the time spent in the acceleration phase increases, and the fuel flow becomes larger, which leads the total emission index number of the three pollutants to become smaller. Although the fuel consumption increases, the total emission index number of the three pollutants decreases, and the degree of the total index number change is sharper than that in fuel consumption, so the pollutant emission quantity is gradually reduced when the average taxi speed increases. It is worth noting that with the increase of the taxi speed, the emissions of HC and CO decrease while NOx increases continuously, and the total emissions achieve the minimum value at the fastest speed of A333.

As shown in *Fig. 4(b) (c)*, with the increase of taxi speed, both A320 and CRJ-900 show a different trend of decreasing first and then increasing, which indicates that for medium and light aircraft, the pollutant emission quantities are not optimal at the fastest taxi speed. The simulation results of A320 show that the pollutant emissions decrease linearly to the lowest point and then rise slightly. The taxi speed corresponding to the lowest point of pollutant emissions is 10.42m/s in this paper, while the CRJ-900 simulation results show that the pollutant emission quantity first decreases slowly to the lowest point, then increase significantly, and the taxi speed corresponding to the lowest point of pollutant emissions is 10.07m/s.

B. Relationship between taxi speed and emission cost

Fig. 6 shows the relationship between the average taxi speed and the pollutant emission cost of the three aircraft, and the lowest point of the pollutant emission cost is circled, respectively. With the increase of the average taxi speed, the pollutant emission cost increases first slowly then fast, which is related to the emissions and emission cost index numbers of the three pollutants.

We still take A333 as an example and draw the diagram of the pollutant emission cost index number characteristicof A333 (equipped with CF6-80E1A2 engine), which is defined as the product of pollutant emission index number and unit emission cost. As shown in *Fig.7*, the greater the fuel flow of the aircraft during taxiing, the higher the total cost index number of the three pollutants. Therefore, when the taxi speed increases, the time used to accelerate increases, and the fuel flow in the acceleration phase becomes larger, which means the fuel consumption and the total emission cost index number of the three pollutants both becomes higher. As a result, the cost of pollutant emissions shows an increasing trend. In addition, the emission of NOx raises slowly then quickly with the increase of taxi speed, so does the emission cost of NOx, which has a direct impact on the trend of the total emission cost because the unit price of NOx is far more than that of other two pollutants.

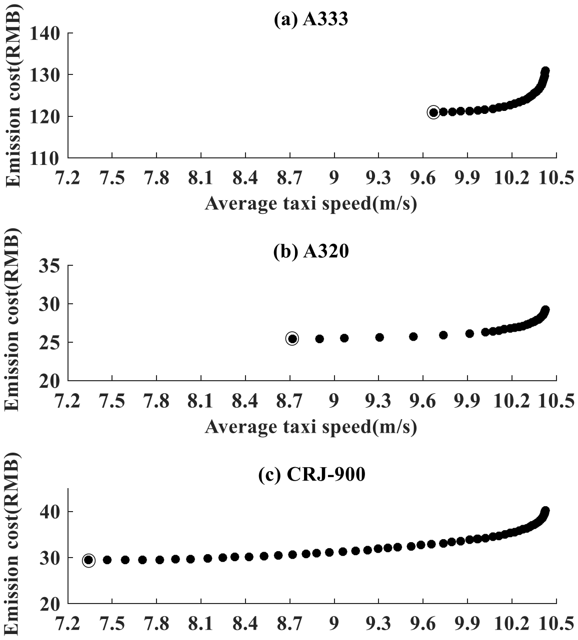


Figure 6. The diagram of the relationship between the average taxi speed and the emission cost of the three aircraft

The above discussion indicates that the faster the average taxi speed, the higher the cost of the pollutant emissions, vice versa. This shows that for the three aircraft in this case, the pollutant emission cost is not lowest at the fastest average taxi speed, but the highest. Therefore, slowing down the taxi speed can effectively reduce the cost of pollutant emissions.

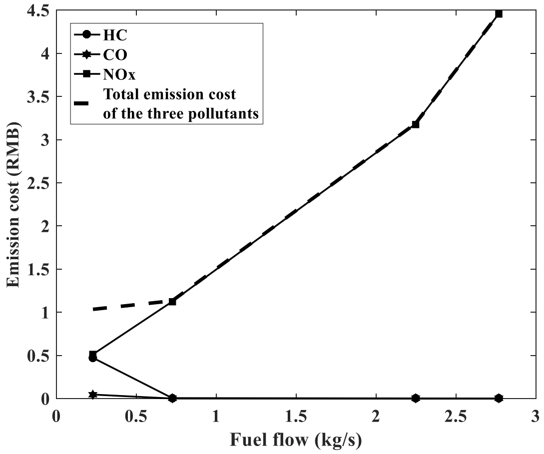


Figure 7. The diagram of the pollutant emission cost index number characteristic of A333 (equipped with CF6-80E1A2 engine)

C. *Optimal taxi speed profile analysis*

From the Pareto optimal solutions, the results of the taxi speed optimization with the minimum taxi time cost, the minimum pollutant emission, and the minimum pollutant emission cost are respectively selected to calculate the average taxi speed under different objectives, as listed in *Table IV.*

TABLE IV. THE AVERAGE TAXI SPEED OF THE THREE AIRCRAFT UNDER DIFFERENT OBJECTIVES

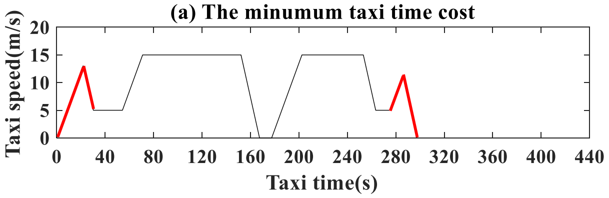
Objective	**Average taxi speed (m/s)**		
	A333	**A320**	**CRJ-900**
The minimum taxi time cost	10.43	10.43	10.43
The minimum pollutant emissions	10.43	10.42	10.07
The minimum emission cost	9.67	8.72	7.34

It can be seen obviously that all three aircraft have the same taxi speed optimization results under the objective of the minimum taxi time cost; this is because of the same range of taxi speed for three different aircraft in this study. In addition, under the objective of the minimum pollutant emissions or the minimum emission cost, the average taxi speed of A333 is faster than that of A320 and CRJ-900. This is due to the different emission index numbers of three pollutants of three aircraft.

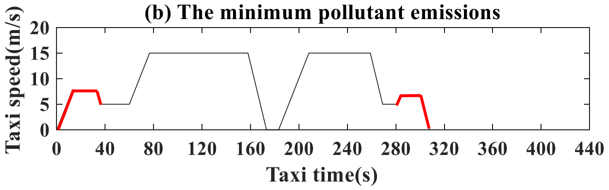
We take CRJ-900 as an example and draw the optimal speed profiles of CRI-900 under the three different objectives, as shown in *Fig. 8*. The differences between the three figures are marked by a bold red line. Under the objective of the minimum taxi time cost, the aircraft has the fastest taxi speed as 10.43m/s and the shortest taxi time, which accelerates to the maximum speed on each segment then taxis at a constant speed and finally decelerates to turn or stop waiting (as shown in *Fig. 8(a)*). However, under the objective of the minimum pollutant emissions, the taxi speed of the aircraft is relatively slow, which is 10.07m/s. Under the objective of the minimum emission cost, the taxi speed is the slowest as 7.34 m/s, while the total taxi time is the longest. In the latter two situations, the aircraft only chooses to accelerate to a certain speed on a shorter segment and then taxi at a constant speed so as to reduce the acceleration and deceleration time (as shown in *Fig. 8(b) (c)*), which can reduce fuel consumption and pollutant emission costs.

As seen from the above analysis, if aircraft pursue the minimum taxi time cost by taxiing at high speed, although the operational efficiency can be guaranteed, it will consume more fuel and bring higher fuel cost and pollutant emission cost; if aircraft pursue environmental benefits, to reducing the cost of pollutant emissions, it will inevitably sacrifice the operational efficiency, resulting in an increase in taxi time cost. Therefore, according to the specific needs of stakeholders such as airports and airlines, aircraft should choose the appropriate taxi speed method to achieve a balance between economic and environmental benefits.

(a) The minumum taxi time cost



(b) The minimum pollutant emissions



(c) The minimum pollutant emission cost

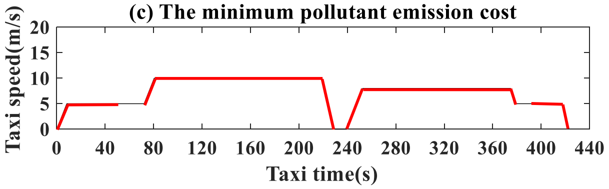


Figure 8. Speed profiles of CRJ-900 under different objectives

V. CONCLUSIONS

Different settings of aircraft taxi speed result in different airport operational efficiency, aircraft fuel consumption, and pollutant emissions. In order to discover the relationship between aircraft taxi speed and pollutant emissions, this paper studied the aircraft taxi speed model and taxi aerodynamics model firstly. The taxiing is divided into five phases based on the speed variations, and the relationship between thrust and taxi speed is obtained through force analysis. Secondly, the aircraft multi-objective taxi speed optimization model with consideration of taxi time, fuel consumption, and pollutant emissions (i.e., HC, CO, and NOx) are established. Finally, three different aircraft categories—light (CRJ-900), medium (A320) and heavy (A333), are selected for simulation analysis at Shanghai Hongqiao Airport, revealing the relationship between taxi speed, pollutant emission quantity and emission cost, and comparing the average taxi speed and optimal speed profiles under different objectives. The research conclusions are summarized as follows:

(1) In acceleration and uniform phases, when the accelerated velocity is determined, the thrust is proportional to the square of the taxi speed, which can be used to calculate the real-time thrust level based on the real-time taxi speed.

(2) As the average taxi speed increases, the pollutant emission quantity of A333 gradually decreases, while the pollutant emissions of A320 and CRJ-900 decrease first and then increase, indicating that the pollutant emissions are not necessarily optimal when the taxi speed is the fastest.

(3) For the three types of aircraft, the larger the average taxi speed, the higher the pollutant emission cost, which increases slowly first then fast with the increase of the speed. This indicates that the pollutant emission cost is not optimal but it is worst when the taxi speed is the fastest. Thus, slowing down the taxi speed can reduce the cost of pollutant emissions.

(4) By weighing aircraft taxi time cost, fuel consumption cost, and pollutant emission cost, the model can provide multiple taxi speed methods for an aircraft on a designated route. In addition, stakeholders such as airports and airlines can generate the optimal taxi speed method according to specific needs so as to achieve a balance between economic benefits and environmental benefits.

Under the background of vigorously advocating "green civil aviation," optimizing the taxi speed has certain positive significance for reducing fuel consumption, fuel cost, and pollutant emissions. This study has a certain significance for the further research of taxiing scheduling and planning. Due to the limited ability, there are still some points in this paper that need to be further deepened and improved. In the near future, we can consider the wind force into the force analysis so that the taxi speed optimization model can be more general.

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