Green Aircraft Taxiing Strategy Based on Multi-scenario Joint Optimization

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(Received 5 June 2015; revised 18 August 2015; accepted 28 August 2015)

Abstract: The issue of green aircraft taxiing under various taxi scenarios is studied to improve the efficiency of aircraft surface operations and reduce environmental pollution around the airport from aircraft emissions. A green aircraft taxi programming model based on multi-scenario joint optimization is built according to airport surface network topology modeling by analyzing the characteristics of aircraft operations under three different taxiing scenarios: all-engine taxi, single-engine taxi, and electronic taxi. A genetic algorithm is also used in the model to minimize fuel consumption and pollutant emissions. The Shanghai Pudong International Airport is selected as a typical example to conduct a verification analysis. Compared with actual operational data, the amount of aircraft fuel consumption and gas emissions after optimization are reduced significantly through applying the model. Under an electronic taxiing scenario, fuel consumption can be lowered by 45.3%, and hydrocarbon (HC) and carbon dioxide (CO) emissions are decreased by 80%. The results show that a green aircraft taxiing strategy that integrates taxiway optimization and electronic taxiing can effectively improve the efficiency of airport operations and reduce aircraft pollution levels in an airport's peripheral environment.

Key words: electronic taxi; fuel consumption; emission; genetic algorithm

CLC number: V351.11 **Document code**: A **Article ID**: 1005-1120(2016)02-0215-09

0 Introduction

In the wake of rapid development in the air transportation industry, it is increasingly difficult to meet the ever growing demands of air traffic with the relatively limited supply of airport capacity. Capacity flow imbalances cause frequent airport surface congestion and flight delays, which cause a substantial increase in aircraft surface taxiing time. In addition, because the fuel efficiency of aircrafts is the lowest during the surface taxi phase, the gas emissions index is the subsequently highest, and the emissions directly affect the airport's peripheral environment[1]. Issues such as aircraft fuel consumption, emissions, and noise have received widespread concern within the aviation industry as well as from the public. Under a backdrop of ever deepening concepts in global environmental protection, energy savings, and emissions reduction, methods of using highly effective scientific surface taxi strategies to maximize conflict avoidance in aircraft operations and reduce aircraft surface taxiing time have important implications for improving the efficiency of aircraft operations, lowering airline operating costs, and reducing pollution in the airport's peripheral environment.

Studies in China on airport surface taxi optimization have primarily concentrated on optimizing the taxiway. Under the premise of ensuring the safety of aircraft operation, taxiway optimization takes airport network topology modeling as backdrop, and utilizes mathematical programming models, multi-agent technology, Petri net theory, etc. to search for the optimal path for a departing scheduled flight that includes the shor-

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How to cite this article: Wan Lili, Hu Minghua, Tian Yong, et al. Green aircraft taxiing strategy based on multi-scenario joint optimization[J]. Trans. Nanjing Univ. Aero. Astro., 2016,33(2):215-223.
http://dx.doi.org/10.16356/j.1005-1120.2016.02.215

test taxiway or the least amount of taxi time[2-3]. However, aircraft all make use of main engine propulsion when taxiing, thus, the aircraft is in a state of low combustion efficiency and high emissions over the entire distance that it idles, and such operations have a relatively large impact on the airport's peripheral environment. Current studies in China on surface taxi optimization have not yet fully considered the needs of green aviation development and rarely taken aircraft fuel consumption and emissions as optimization objectives. However, studies conducted in other countries related to environmentally friendly aircraft taxiing have set up multi-scenario taxi systems for all-engine taxi, single-engine taxi, and electronic taxi, etc. to maximize the reduction of work time during engine idling[4-7]. The electronic taxi system, which uses an auxiliary power unit (APU), drives the electric motors that are installed on the landing gears, thus allowing the aircraft to taxi without being towed by a tug or propelled by the main engine. This method also has low fuel consumption, low emissions, and low noise levels, etc. Currently, companies such as Honeywell and WheelTug are developing this type of electronic taxi system, and certain products are already in an identification phase[8,9].

Aircraft fuel consumption and emissions model constructed under different taxi scenarios is presented, and it integrates the taxiway optimization method, which is applied to the Pudong International Airport for verification and the comparative analysis of environmental pollution under various taxi scenarios. The work presented in this paper will enable air traffic control authorities to set and provide methods of supporting highly effective, and environmentally friendly green aircraft taxiing strategies.

1 Multi-scenario Fuel Consumption and Emissions Models

The aircraft taxi process includes taxi-out and taxi-in processes. Taxi-out is the ground movement process by which an aircraft moves from the gate to the head of the runway prior to takeoff. Taxi-in is the ground movement process by which an aircraft moves to a gate after landing and leaving the runway. When taxiing, an aircraft can be powered by the engine or APU. According to selected power, the scenarios may include all-engine taxi, single-engine taxi, and electronic taxi[10].

1.1 Scenario one: All-engine taxi

All-engine taxi refers to a process in which all of the engines are turned on and remain in an idling state during aircraft taxiing, and it is the most commonly adopted method in aircraft operations at present. In past studies, fuel calculations were simplified by assigning an average value for the engine fuel flow rate. However, to accurately calculate fuel consumption and emissions during taxiing, fluctuations in the engine state and fuel flow rate as the aircraft moves must be considered. Studies have clearly shown that stopping the engine to wait decreases the fuel flow rate and subsequent acceleration significantly increases the fuel flow rate compared with taxiing at an even speed[11]. The fuel consumption F_i^A of aircraft i during all-engine taxi can be expressed as follows

$$F_i^A = \sum_j F_{ij} = \sum_j T_{ij} \cdot N_i \cdot f_{ij} \tag{1}$$

where F_{ij} is the fuel consumption amount of aircraft i under engine state j, T_{ij} the taxi time for aircraft i under engine state j, N_i the number of engines on aircraft i, and f_{ij} the fuel flow rate of a single engine on aircraft i under state j.

The hydrocarbon (HC), carbon dioxide (CO), and mono-nitrogen oxides (NO_x)[12] emitted by the aircraft will directly impact the local air quality index. After exposure to the sun's ultraviolet rays, HC can generate toxic photochemical smog that severely irritates the eyes, nose, and throat, whereas CO is a colorless and odorless poisonous gas, and NO_x can easily form acid rain and damage the ozone layer. Therefore, the aforementioned three gaseous pollutants are used to build an aircraft emissions model in this paper.

The amount of gaseous pollutant emissions from an aircraft is directly proportional to the fuel consumption amount and emissions indices. However, each gaseous pollutant has a different emissions index. The emissions amount E_{ik}^{A} of gaseous pollutant type k from aircraft i during all-engine taxi can be expressed as follows

$$E_{ik}^{A}=\sum_{j}F_{ij}\cdot I_{ijk} \tag{2}$$

where I_{ijk} is the emissions index of gaseous pollutant type k when aircraft i is under engine state j.

1.2 Scenario two: Single-engine taxi

Single-engine taxi is a taxiing method in which some of the engines are turned off during aircraft taxi while the rest are turned on and put in an idling state. During single-engine aircraft taxi, only the engines that are turned on will consume fuel and produce emissions. If single-engine taxi is used during aircraft taxi-out, the engines that are off will need to be started up prior to entering the runway for takeoff. The engine start-up time (ESUT) typically takes 2—5 min and is related to the model and engine model number of the aircraft and time of the engine has been shut off. If the engine has been shut off for six hours or more, ESUT will increase to 10—15 min. During single-engine aircraft taxi-in, the engines that are not used for taxiing after landing must also be cooled down. The engine cool-down time (ECDT) is similar to ESUT. Because the engines continue to consume fuel and produce emissions during the start-up and cool-down processes, these two time intervals must be considered when calculating single-engine taxi fuel consumption and emissions. The single-engine taxi fuel consumption F_{i}^{S} of aircraft i can be expressed as follows

$$F_{i}^{S}=\sum_{j}F_{ij}=\sum_{j}T_{ij}\cdot N_{i}^{S}\cdot f_{ij}+\min\{T_{i},T_{E}\}\cdot(N_{i}-N_{i}^{S})\cdot f_{\text{idle}} \tag{3}$$

where T_{i} is the taxi time for aircraft i, N_{i}^{S} the number of engines turned on by aircraft i during taxiing, T_{E} the time required for engine start-up or cool-down, and f_{idle} the fuel flow rate of a single engine on aircraft i during engine start-up or cool-down.

The emissions amount E_{ik}^{S} of gaseous pollutant type k from aircraft i during single-engine taxi can be expressed as follows

$$E_{ik}^{S}=\sum_{j}F_{ij}\cdot I_{ijk} \tag{4}$$

1.3 Scenario three: Electronic taxi

Electronic taxi is a process in which the engines are turned off during aircraft taxiing and only APU is used to drive the electric motors installed on the landing gears for taxiing. Thus, an electronic taxi system is used for taxiing.

APU is an aircraft auxiliary power unit typically located at the tail end of the aircraft. Although its small turbine engine core consumes fuel during power output, the fuel consumption and emissions are far lower than that of the main engines. In addition, there are notable advantages in its use, such as low noise and extended engine life, etc. The fuel consumption F_{i}^{E} of aircraft i when using the electronic taxi system is as follows

$$F_{i}^{E}=T_{i}\cdot f_{i}^{\text{APU}} \tag{5}$$

where f_{i}^{APU} is the fuel flow rate of APU on aircraft i.

The emissions amount E_{ik}^{E} of gaseous pollutant type k from aircraft i during electronic taxi can be expressed as follows

$$E_{ik}^{E}=F_{i}^{E}\cdot I_{ik}^{E} \tag{6}$$

where I_{ik}^{E} is the emissions index of gaseous pollutant type k when aircraft i is using the electronic taxi system to taxi.

Similar to single-engine taxi, when an aircraft uses the electronic taxi system to taxi, all engines that are off prior to entering the runway must be started for takeoff and all engines must be cooled off after landing. If these two segments are executed independently, the taxi time is increased and may even lead to extra delays. To shorten taxi time, APU-driven taxiing can be integrated with the engine start-up and cool-down segments. Taking a twin-engine aircraft as an example, the process of using APU-driven electronic taxiing is indicated in Fig. 1[13].

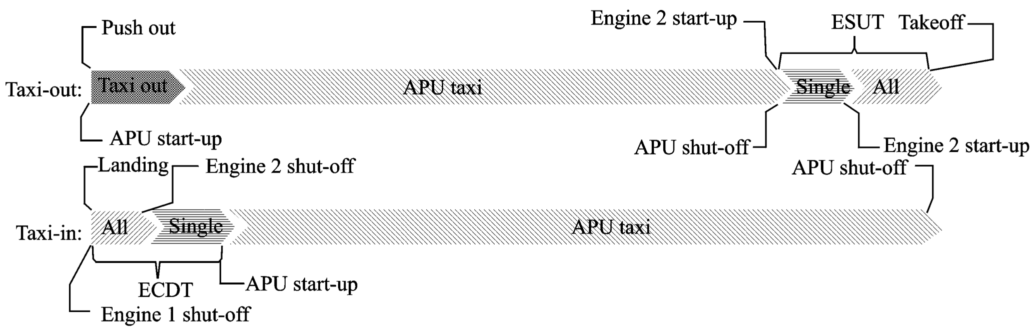

Fig. 1 Process diagram of use of APU-driven electronic taxiing

During the taxi-out process, aircraft engines can provide power to the remainder of ESUT prior to takeoff. Otherwise, the aircraft is driven by APU during taxi time. During the taxi-in process, the aircraft changes to APU-driven taxiing only after ECDT following landing. The fuel consumption of aircraft i when using the electronic taxi system is as follows

$$F_i^E = (T_i - T_E) \cdot f_i^{\mathrm{APU}} + T_E \cdot N_i \cdot f_i^{\mathrm{idle}} \tag{7}$$

where f_i^{idle} is the fuel flow rate of aircraft i in an idling state.

2 Taxiway Optimization

2.1 Taxiway optimization model

To obtain the optimal green taxi strategy, the taxi method must be integrated with route optimization. When building a taxiway optimization model, the topological network diagram $G=(R, E)$ can be used to indicate the airport surface taxi system, where R represents the set of taxiway nodes r and E represents the edge set of taxiway intersections[14]. The constructed taxiway optimization model is presented as follows

$$\min \sum_i F_i \tag{8}$$

$$U_i = \{u_{i1}, u_{i2}, \cdots, u_{ih}, u_{i,h+1}, \cdots, u_{in}\} \tag{9}$$

$$T_i = \sum_{u_{ih} \in R_i} T_i^{u_{ih}} \tag{10}$$

$$T_i^{u_{ih}} = \sum_{m \in M, p \in P} \lambda_{im} g_{ip} \left| u_{ih} u_{i,h+1} \right| / \bar{v}_{ih} \tag{11}$$

$$\bar{v}_{ih} = (v_{ih} + v_{i,h+1})/2 \tag{12}$$

$$\lambda_{im} = \begin{cases} 1 & \text{flight } i \text{ on runway } m \\ 0 & \text{otherwise} \end{cases} \tag{13}$$

$$g_{ip} = \begin{cases} 1 & \text{flight } i \text{ on gate } p \\ 0 & \text{otherwise} \end{cases} \tag{14}$$

$$\sum_m \lambda_{im} = 1 \tag{15}$$

$$\sum_p g_{ip} = 1 \tag{16}$$

where $m \in M$ is the set of runways and $p \in P$ the set of gates.

Eq. (8) takes the minimum total fuel consumption of all aircraft as an objective function. Each aircraft can select Eqs. (1), (3), (7) to calculate the fuel consumption F_i corresponding to the different taxi scenarios. Eq. (9) is the set of taxiway nodes U_i of aircraft i, where $u_{ih} \in R, (u_{ih}, u_{i,h+1}) \in E$. Eq. (10) is the total taxi time T_i of aircraft i, where $T_i^{u_{ih}}$ is the taxi time of aircraft i on taxi segment $(u_{ih}, u_{i,h+1})$. In Eq. (11), $|u_{ih} u_{i,h+1}|$ is the length of taxi segment $(u_{ih}, u_{i,h+1})$. In Eq. (12), $\bar{v}_{ih}$ is the average taxiing velocity of aircraft i on taxi segment $(u_{ih}, u_{i,h+1})$, and v_{ih} is the velocity of aircraft i when passing taxiway node u_{ih}. In Eqs. (13), (14), λ_{im} and g_{ip} are the decision variables for runway and gate. Eqs. (15), (16) are the unique constraints in runway and gate assignment. In addition, taxiing aircraft must satisfy relevant airport operating rules and safety intervals.

2.2 Optimization algorithm

When an aircraft encounters another aircraft during the taxi process, situations such as deadlock conflict, intersection conflict, and one aircraft overtaking another may occur. When optimizing aircraft taxiway, all types of conflicts must be considered and solutions must be provided so that conflicts between aircrafts do not occur and each aircraft can continue to taxi along the relief path to a predetermined position. In order to improve the overall efficiency of the operation of the taxiway and meet other special requirements, the speed adjustment strategy is adopted according to the flight priority. It can ensure that the aircraft which priority is higher or who first reach the conflict position preferentially pass. The taxiway optimization model is a non-deterministic polynomial (NP) problem and difficult to find the global optimal solution by algorithm precise in acceptable time. Genetic algorithms are classic intelligent optimization methods that simulate biological survival of the fittest evolutionary processes, and they are frequently applied in the field of route optimization because of their high efficiency in search for the global optimal solution. The specific steps of the genetic algorithm in this paper are listed below.

Step 1 Obtain flight plan data, including flight arrival and departure times, information of gates and runways.

Step 2 Build a topological network diagram of the airport surface taxiway system and establish relationship matrices of taxiway node sets, taxiway edge sets, and vertex edges.

Step 3 Generate the initial parent population according to the flight information of gate and runway and randomly assign taxiways.

Step 4 Perform the genetic manipulation, such as selection, crossover, and mutation, etc., on the inital parent population according to the vertex edge relationship matrix, then form a progeny population.

Step 5 Calculate the time at which a flight passes each taxiway node according to the flight arrival or departure time and perform conflict detection and resolution.

Step 6 Determine whether the current evolutionary process satisfies the termination condition. If so, end the algorithm; Otherwise, return to Step 5 and continue the iteration.

3 Case Study

The flight plan data from July 25, 2013 at Shanghai Pudong International Airport is selected for a case study. Shanghai Pudong International Airport is a famous hub airport with intensive air traffic flow and complex surface taxiing that can effectively support the verification analysis of the method presented in this paper. On the day in question, Pudong International Airport used three runways and 193 gates and ran a total of 1 089 flights, of which 545 are arrivals and 544 are departures. A topological structure is constructed (See Fig. 2) according to the structure of the Pudong International Airport surface taxi system for calculating fuel consumption and emissions while integrating each taxi scenario with the taxiway optimization model and comparing simulated data with actual operating data.

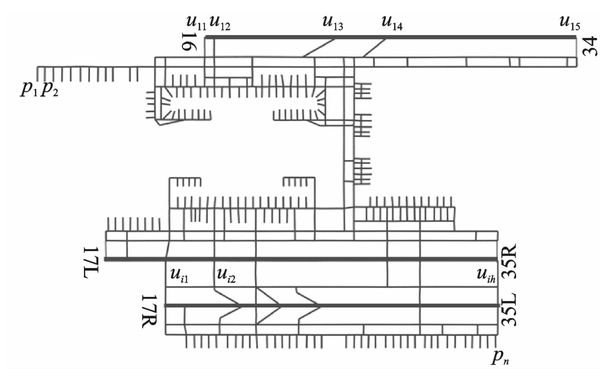

Fig. 2 Surface topological map of Shanghai Pudong International Airport

3.1 Fuel consumption

The fuel consumption by an aircraft can be calculated according to the fuel flow rate of all aircraft models under various states, which is provided by the International Civil Aviation Organization (ICAO) Engine Emissions Databank[15]. The total amount of fuel consumption by all aircraft that taxied on the surface at Pudong International Airport can be minimized through simulated optimizations. Fig. 3 illustrates genetic algorithm optimization process of Scenario 1.

The population optimization curve within 100 generations shows that the total amount of fuel consumption rapidly decreases from 237 071.8 kg to 172 764.9 kg, whereas between 100 to 400 generations, the total amount of fuel consumption changes less rapidly, falling to 156 187.5 kg, and after 400 generations, the changes are small and gradually converge after 450 generations. In the optimal solution corresponding to the maximum evolution generation, the total fuel consumption is 154 087.9 kg.

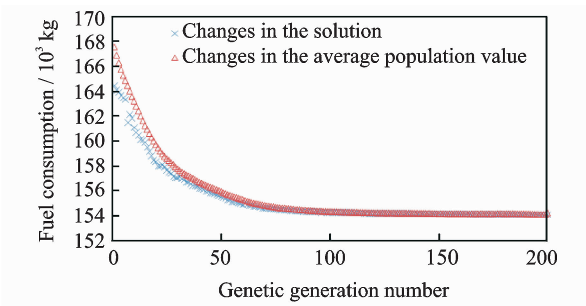

Fig. 3 Trends of fuel consumption in population evolution process

Similarly, optimization can be performed on Scenarios 2 and 3. A comparison of the fuel consumption prior to taxiway optimization and after optimization under different taxi scenarios is shown in Fig. 4. The total fuel consumption prior to taxiway optimization is calculated based on the surface surveillance data.

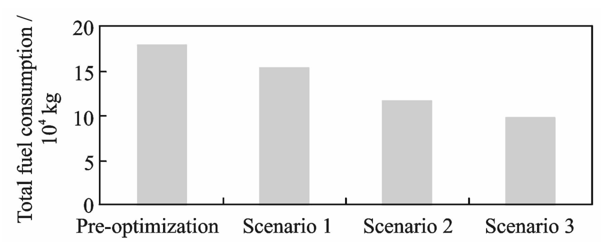

Fig. 4 Comparison of fuel consumption pre-optimization and post-optimization under different taxi scenarios

Fig. 4 shows that using the same all-engine taxi scenario, taxiway optimization saves 13.5% in fuel compared with the amount pre-optimization. Using single-engine scenario and electronic taxi senario, the fuel consumption can be further reduced by 34.9% and 45.3%.

In addition, the fuel savings of different aircraft models during the optimization process are also different. Fig. 5 represents the average fuel consumption of different aircraft models at Pudong International Airport. Because the fuel flow rate in the main engines of heavy aircraft is greater during all-engine and single-engine taxi, the fuel savings after using the electronic taxi system is greater compared with that of mid-sized aircraft, such as aircraft models A340, A380, B747, MD11, etc. Because the fuel flow rate in the main engines of aircraft models E90 and CRJ is smaller, the amount of fuel consumption will present a greater relative increase during electronic taxi.

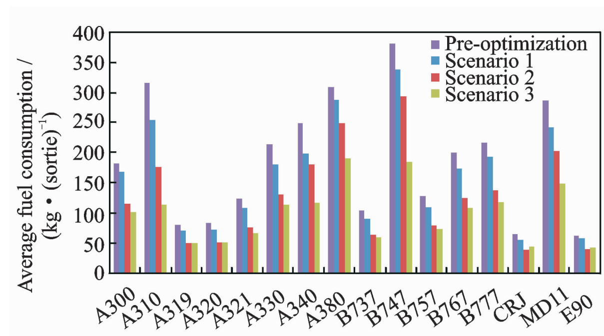

Fig. 5 Average fuel consumed by each aircraft model under different scenarios

3.2 Taxi time

After optimizing the aircraft surface taxiway, fuel consumption is reduced and flight taxi time is optimized. Fig. 6 shows the taxi time distribution of each aircraft model after optimization under Scenario 1, where pre-optimal taxi time (PET) represents the average pre-optimization taxi time and post-optimal taxi time (POT) represents the average taxi time after optimization. The average aircraft taxi time after optimization is within a 10- to 20-minute range and represents a reduction of approximately 7% compared with pre-optimization amounts.

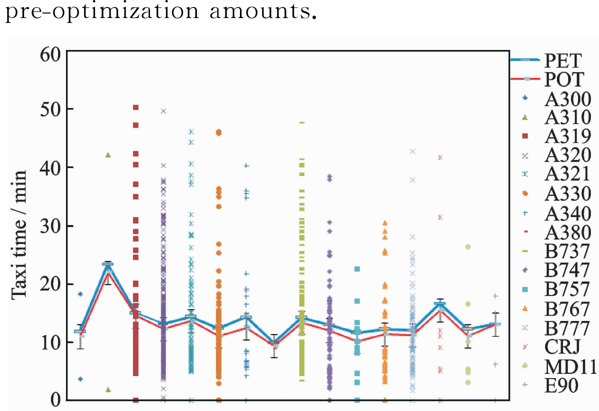

Fig. 6 Comparison of taxi time for scenario one before and after optimization

Based on ESUT before takeoff and ECDT after landing in Scenarios 2 and 3, the taxi time after optimization is slightly longer than that of Scenario 1. However, compared with pre-optimization time, there is still a reduction in average taxi time for all other aircraft models, as shown in Fig. 7, with the exception of A300 and A310 aircraft models, which have a small optimization opportunity because of the small number of flights. Thus, Increased taxi time is presented.

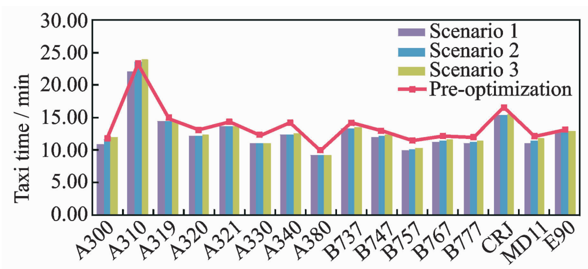

Fig. 7 Average taxi time of each aircraft model in different taxi scenarios

3.3 Gaseous pollutant emissions

The amount of gaseous pollutant emissions from each aircraft model operating on the surface of Pudong International Airport can be calculated according to the HC, CO, and NO_x gaseous pollutant emission indices for each aircraft model provided by the ICAO Engine Emissions Databank. The calculation results are shown in Fig. 8.

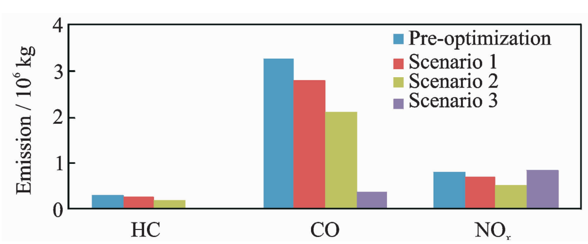

Fig. 8 Amount of pollutant emissions at Shanghai Pudong International Airport by different taxi methods

The amounts of HC and CO gaseous pollutant emissions clearly decrease after surface optimization, with approximately 13% and 35% in Scenarios 1 and 2, respectively, and steep decrease of 80% in Scenario 3. The average airport surface taxi time of A320 and B737 series aircraft is 10—15 min, which provides sufficient time for engine start-up and taxiing and reduces the amount of gaseous pollutant emissions by approximately 30%. Because a three-engine or four-engine aircraft is driven by more than one engine, the reduction in gaseous pollutant emissions is relatively smaller in proportion, with a decrease of 10%—15%, as shown in Figs. 9, 10.

The reduction in emissions proportion of NO_x gaseous pollutant emissions in Scenarios 1 and 2 after optimization is similar to that of HC and CO (See Fig. 11). However, the higher NO_x emissions index during APU operation causes an increase in NO_x gaseous pollutant emissions in Scenario 3 by approximately 6% compared with the amount pre-optimization and approximately 22.64% and 62.29% compared with the amounts in Scenarios 1 and 2, respectively.

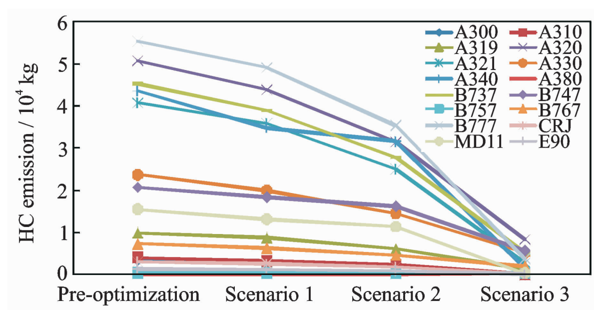

Fig. 9 Amount of HC emissions of each aircraft model in different taxi scenarios

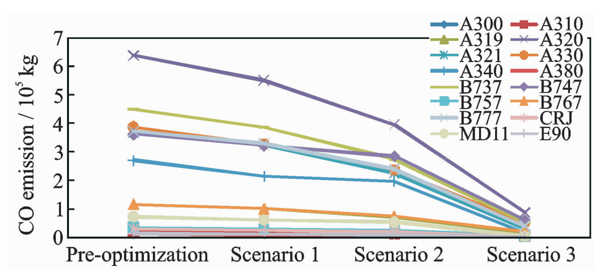

Fig. 10 Amount of CO emissions of each aircraft model in different taxi scenarios

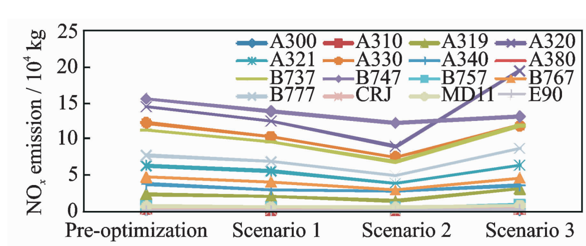

Fig. 11 Amount of NO_x emissions of each aircraft model in different taxi scenarios

3.4 Electronic taxi system with fuel addition

Although an electronic taxi system can significantly reduce fuel consumption and emissions during the surface operations phase, the drive system that must be installed on the landing gears will increase the basic operating empty weight (OEW) and the extra fuel consumption for the aircraft in other flight phases. Assuming an electronic taxi system makes OEW average increase in 400 kg weight, the amount of extra fuel consumption of each aircraft model caused by the increase in OEW must be calculated according to the aircraft performance indices provided by the BADA3. 11 database. The results are shown in Fig. 12.

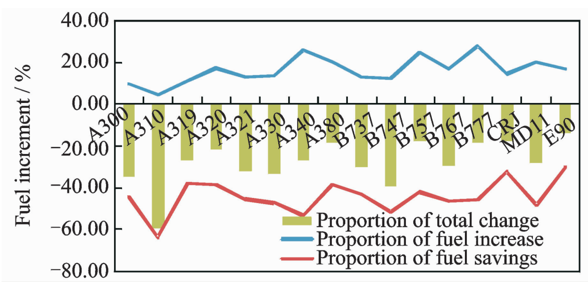

Fig. 12 Changes in aircraft fuel consumption when using an electronic taxi system

The amount of fuel saved when using an electronic taxi system is approximately 45% of the taxi fuel, and the increased fuel consumption in the cruise phase is approximately 16% of the taxi fuel. Thus, the proportion of fuel saved when using APU to taxi is far greater than the increased fuel consumption in the cruise phase, and the aircraft's total fuel consumption decreases. Although the increment of fuel consumption caused by increase of OEW is larger, the fuel consumption saved in taxi phase for a heavy aircraft is relatively more. Therefore, the use of an electronic taxi system in a heavy aircraft can conserve more fuel over the entire flight period.

4 Conclusions

A green aircraft taxi strategy based on multi-scenario joint optimization is proposed by analyzing aircraft fuel consumption and exhaust emissions under different taxi scenarios, such as all-engine taxi, single-engine taxi, and electronic taxi, and by integrating these scenarios with the taxiway optimization model to improve the efficiency of flight operations, reduce delays, and decrease negative impacts on the environment. The example of Shanghai Pudong International Airport shows that the amount of aircraft fuel consumption and gas emissions after taxiway optimization can be lowered by about 13%, combined with environmentally friendly technology, such as single—engine taxi and electronic taxi, the performance of airport surface operations can be further improved, For example, electronic taxi can reduce fuel consumption by 45. 3%, reduce HC and CO emissions by 80%, and increase NO_x emissions by 6%.

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(Executive Editor: Xu Chengting)