AIRCRAFT TAXIING MODEL AT CONGESTED AIRPORTS

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Abstract

Steadily increasing air traffic has called for more efficient airport surface operations. Long queues of aircraft waiting for take-off are often seen at congested airports. However, these queues can be decreased by spot-out time management, which in turn leads to fuel savings. This paper investigates the possibility for taxiing improvement without changing the current traffic flow at Tokyo International Airport. To calculate the taxiing time more accurately, a new simulation model based on car traffic congestion model is used. The calculation result shows that the taxiing time is expected to be reduced by more than 200 minutes per day without delaying any aircraft.

1 Introduction

A 4D trajectory is a keyword for the future air traffic management. The concept of a 4D trajectory is based on aircraft control with 3D position and time constraints. An aircraft operation starts and ends at the airport spot, so it includes the ground phase, too. However, unlike the flight phase, the ground phase has been subject to little research. One of the reasons is that the ground operation is totally human-centered (pilots and air traffic controllers), while an autopilot system mostly works during the flight. Human operations include big uncertainty which makes the taxiing estimation difficult. Therefore, the well-known airport models[1][2][3] have been developed with many statistical parameters, i.e. it is assumed that the taxiing speed and the duration of spot-out, etc. are randomly distributed. The author believes, however, that heavy traffic at an airport results in mutual interaction between the aircraft, similar to car traffic congestions. If such an interaction is considered, the uncertainty is expected to decrease.

To model the airport taxiing operation more accurately, a new model based on car traffic congestion model has been developed[4]. The model can accurately simulate taxiing even at congested airports.

In this paper, using the proposed model, the possible taxiing improvement is investigated at Tokyo International airport, the biggest airport in Japan. Unlike in other research where ground delays are not considered, this research focuses on the ground inefficiency and its potential improvement.

This paper is organized as follows. Section 2 starts with an overview of Tokyo International airport, and briefly explains the proposed airport taxiing model considering congestion phenomenon. Taxiing models are constructed for several days, and the simulation accuracy is investigated. In section 3, using the obtained models, the possible taxiing improvement is investigated. The corresponding yearly economic benefit and CO_2 emission reduction are also provided. Finally, the paper is summarized in section 4.

2 Tokyo International Airport and Taxiing Model

2.1 Tokyo International Airport operation

Tokyo International Airport is the most congested airport in Japan, and is mostly used for domestic flights. In 2010, the fourth runway (D runway) was opened and more spots for international flights became available. It is expected that the annual traffic volume will increase to 447,000 flights in 2013, although it stood at 303,000 flights in 2010[5]. Note that this paper considers north wind operations only.

Fig. 1 shows the runway operations under north wind before the introduction of the new runway. Three runways were available. Departure and arrival aircraft used different runways, and each runway was operated independently. On the other hand, Fig. 2 shows current runway operations under north wind. Even though A runway is used independently by arrival aircraft, C runway is shared by departure and arrival aircraft. D runway cannot operate while an aircraft is approaching C runway.

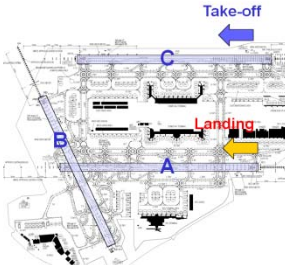

Fig. 1 Previous runway operation under north wind.

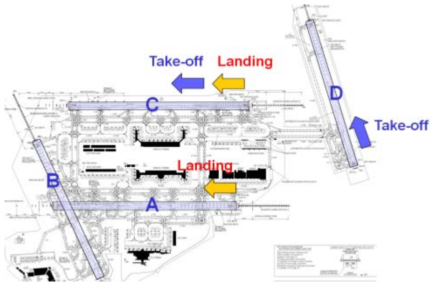

Fig. 2 Current runway operation under north wind.

The airport capacity increases with the opening of the new runway, but the number of flights rises and the runway operations get more complicated, too. Under this condition, it is unclear whether the congestion level increases or not after the opening of the new runway. Besides, it is unclear how much can be gained by any refined ground operations. In order to improve ground operations, a new procedure must be implemented. However, if the possible improvement is insufficient, it is meaningless to introduce the new procedure. This paper answers these questions, and estimates the possible improvement of taxiing.

2.2 Taxiing Simulation Model Considering Congestion

2.2.1 Stages of Taxiing and Spot-out Time Management

"Taxi-out time" is usually defined as the time between off-block time and the take-off time, but "taxiing" is an ambiguous word. To clarify the target of the paper, the flow of departure on the ground is explained.

1) Request ground control clearance (a few minutes)
2) Request pushback (spot-out)
3) Pushback and engine start (a few minutes)
4) Request taxi and pushback car release (a few minutes)
5) Taxi to runway (5 – 15 minutes)
6) Request clearance for take-off
7) Take-off

This paper focuses on taxiing improvement, but only 5) is potentially possible to improve. To decrease taxiing time, spot-out time management is a promising method. Less taxiing time leads to fuel burn reduction. However, fuel burn depends on the duration of engine working, so if the proposed improvements lead to increased duration of stages 3) or 4), the overall result will be negative. Therefore, the spot-out time management aims at decreasing taxiing time (stage 5)) without changing stages 3) and 4). In this paper, managing the time of stage 3), the duration of stage 5) is decreased.

One of the biggest problems of the spot-out time management is the conflict of aircraft. Suppose that a departure aircraft delays spot-out time to avoid taxiing congestion. If there is an arrival aircraft which is to enter the same spot, the spot-in time of the arrival aircraft will also be delayed. As a result, fuel saving of the departure aircraft leads to fuel increase of the arrival aircraft and delayed spot-in time. This model considers spot-out time management by implementing aircraft interactions.

2.2.2 Overview of the Model

A simulation is a straightforward approach to estimate the potential improvement of taxiing. However, the accuracy of improvement estimation depends on the simulation accuracy itself, which is a key for the analysis.

To conduct an airport simulation, various models[1][2][3] have been developed. However, all models assume constant taxiing speed, which differs from the actual operation especially during the congestion. Therefore, the author has developed a new taxiing model[4] based on the car congestion model called Nagel-Schreckenberg model (NS model). It is said that the congestion spreads backward, and the NS model can mimic the process of congestion propagation.

The dynamics of cars and taxiing aircraft are different, so the characteristics of taxiing aircraft are extracted and implemented in the model. Detailed descriptions are found in Ref. [4], and main following rules are summarized below.

- Take-off separation set based on the wake turbulence separation criteria.
- Gradual acceleration and deceleration.
- Speed decision algorithm based on the floor field model[6] which simulates the congestion wave propagation.

All extracted rules are parameterized and implemented in the model. The parameters are tuned via real-coded genetic algorithm. Taxiing data (taxiing start and end time, taxiing routes) are obtained, and the parameters are set to optimize the objective function (duration of taxiing and the passing time at specific point).

2.2.3 Model Extension to Multiple Runways

The proposed model reflected former runway operations only, i.e., departure and arrival aircraft used different runways, so no interaction between runways existed. However, under the current operations, interaction between arrival and departure aircraft on C runway and interaction between arrival aircraft on C runway and departure aircraft on D runway exist. In order to simulate the interaction, the following rules are added.

(1) When an arrival on C runway is scheduled at $t = t_{Carr}$, no aircraft can depart from C runway between $t_{Carr} - t_{befC}$ and $t_{Carr} + t_{aftC}$.

(2) When an arrival on C runway is scheduled at $t = t_{Carr}$, no aircraft can depart from D runway between $t_{Carr} - t_{befD}$ and $t_{Carr} + t_{aftD}$.

where t_{befC}, t_{aftC}, t_{befD}, and t_{aftD} are non-negative parameters of the model.

2.3 Parameter Tuning of Taxiing Model

In order to simulate airport operations, airport surface data is required. Tokyo International Airport has recently installed airport surface surveillance system based on a multilateration system. The position of each aircraft can be obtained every second with an accuracy of 7.5 meters according to the specification of ICAO A-SMGCS manual[7]. The necessary information such as taxiing start and end time, taxiing routes, spot position are obtained from the position data. Fig. 3 shows the taxiway map and the main taxiing routes under the current operation. The blue line indicates departure taxiing routes, while the red line indicates arrival taxiing routes. Most aircraft follow the main routes except in the case when another aircraft blocks the taxiway. Aircraft always go taxiing in the direction of the arrows shown in the figure.

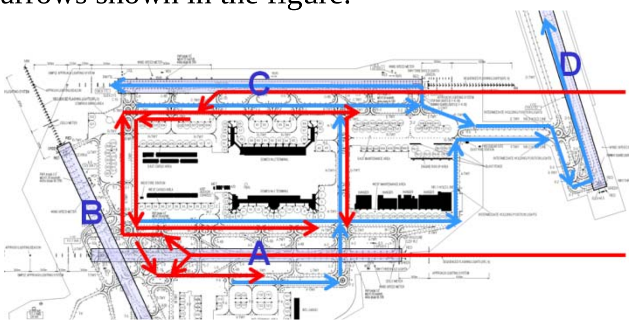

Fig. 3 Taxiway map and main taxiing routes.

This time, a total of eight days data between 6:30 and 22:00 are obtained, when the north wind operation is used throughout a day. Four days are chosen before the new runway was opened, and the rest of four days are under the new runway operations.

Parameters are tuned for each day, so eight models are constructed. Simulation results are shown in Table 1. Most models can simulate the taxiing within 30 seconds of accuracy, and the maximum errors are less than 150 seconds. Using the models, the potential taxiing improvement is investigated.

3 Potential Taxiing Improvement

3.1 Definition of Improvement

3.1.1 Factors Considered for Taxiing Improvement

When taxiing improvement is discussed, it is not obvious how this "improvement" is defined. A simple definition can be "reduction of taxiing time" which leads to fuel savings, too. A reduction to taxiing time zero is impossible, but a reduction of taxiing time wasted in congestions is possible. Such a simple definition, however, might be insufficient, because flight delays should be considered, too. Fuel savings should not be done at the cost of flight take-off delays. Therefore, in this paper, "taxiing improvement" is defined as altered taxiing operations which do not cause any flight delay.

3.1.2 Several Levels of Taxiing Improvement

Since there is a distance between the runway and the aircraft spot, a certain minimum taxiing time is required. The minimum taxiing time that an aircraft needs to reach the runway is closely related to the distance between the departure runway and aircraft's spot position. Therefore, taxiing distance can be reduced by appropriate spot allocation, but it would complicate the problem even more, so here such a situation is not considered. Fig. 4 shows the relationship between taxiing distance and taxiing time for aircraft departing from D runway. The horizontal axis indicates the taxiing distance, while the vertical axis indicates the taxiing time. The figure shows a clear relationship between taxiing distance and minimum taxiing time as shown by the red line. The time above the red line indicates the additional taxiing time compared to the minimum taxiing time. This taxiing time is defined as "maximum reduction time."

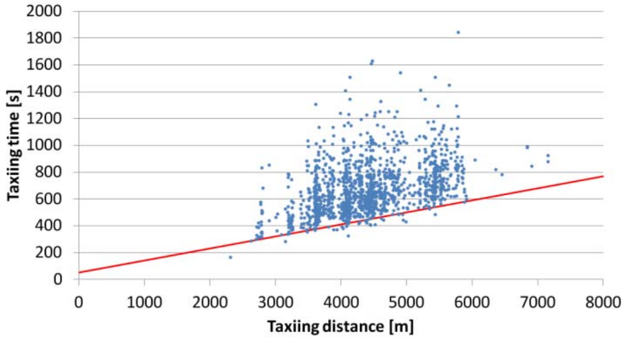

Fig. 4 Relationship between taxiing distance and taxiing time.

Since the reasons for increased taxiing time are complex, it is not possible to achieve absolute reduction of all maximum reduction time. There are many reasons to cause additional taxiing time. If the additional taxiing is caused by the waiting departure queues at the runway, it can be reduced. However, if it is caused by the congestion wave propagation or conflict between aircraft, it cannot be physically reduced. Here, the remained taxiing reduction time which can be reduced is defined as "possible reduction time."

It is still impossible to realize all possible reduction time, because aircraft taxiing induces uncertainty. When the spot-out time is delayed,

Table 1 Simulation accuracy of each model.

Operation	Date	Number of aircraft	Take-off time		Spot-in time	
			Absolute mean error [s]	Maximum error [s]	Absolute mean error [s]	Maximum error [s]
Old	04/22/2010	889	24.24	100	22.87	115
	04/23/2010	887	29.91	115	26.21	130
	04/24/2010	899	28.26	125	23.67	115
	10/07/2010	899	31.21	120	24.82	140
New	12/23/2010	942	24.80	105	19.72	105
	02/21/2011	955	24.41	140	23.45	150
	02/22/2011	963	28.23	115	23.41	115
	02/23/2011	963	24.89	115	21.51	100

the uncertainty of taxiing should also be considered, otherwise take-off time might be delayed. The actual reduction time considering the uncertainty is defined as "expected reduction time". The possible reduction time and the expected reduction time are not explicitly related. Assume the average possible reduction time for 100 aircraft is 1 minute. If the possible reduction time of 1 aircraft is 100 minutes and that of others is 0, the average expected reduction time is close to 1 minute, because the remaining reduction time considering uncertainty is still 98 or 99 minutes. However, if the possible reduction time of all aircraft is 1 minute, the expected reduction time is 0, because 1 minute is absorbed by uncertainty. A few aircraft which have large possible reduction time would be most efficient.

3.2 Calculation of Taxiing Improvement

3.2.1 Calculation of Maximum Reduction Time

Maximum reduction time is easily calculated based on the taxiing time and taxiing distance of each aircraft. The relationship between taxiing time and taxiing distance can differ among runways aircraft use, so it is calculated separately. It can be used to understand the upper limit of taxiing time reduction, but it should be treated as a rough estimation only.

3.2.2 Calculation of Possible Reduction Time

Possible reduction time should be calculated considering the congestion phenomenon and aircraft conflict, which covers the proposed simulation method. As no delays should be caused, the original take-off order is kept unchanged.

To decrease the taxiing time, the departure aircraft should control their spot-out time. Therefore, the latest possible spot-out time of each aircraft is calculated iteratively. The flow of the calculation is shown as follows:

```
for k=1:max_departure
        t_max_spot(k) = t_act_spot(k)
for i=1:max_departure
        for j=1:max_cal
                for k=1:max_departure
                        t_spot(k)=t_max_spot(k)
                end
                t_spot(i)+=dt
                simulation with t_spot()
                if traffic is not changed
                        t_max_spot(i)+=dt
        end
        pos_t(i) = t_max_spot(i) – t_act_spot(i)
end
```

where max_departure stands for the number of departure aircraft. i is decided by the order of take-off. t_act_spot(i) indicates the spot-out time of i th aircraft obtained from actual traffic. t_spot(i) indicates the spot-out time used in the simulation. max_cal is the maximum number of the calculation, which should be set large enough. t_max_spot(i) indicates the obtained latest spot-out time without changing the traffic. pos_t(i) indicates the possible reduction time of i th aircraft.

The obtained spot-out time is the latest spot-out time, which provides the minimum taxiing time considering aircraft conflict and congestions. Possible reduction time is more realistic result than maximum reduction time, but it requires iterative simulations, so takes a long time calculation.

3.2.3 Calculation of Expected Reduction Time

No uncertainty is considered in the calculation of the possible reduction time, so in reality the actual reduction time might be less than the calculated one. If the possible reduction time is 10 seconds only, there is no point in delaying the spot-out time, so a minimum spot-out shift time should be set. If the possible reduction time is 10 minutes, the aircraft will not shift the spot-out time by exactly 10 minutes, but 8 or 9 minutes to absorb the uncertainty. These two factors are considered in the expected reduction time (exp_t). It is calculated by the possible reduction time (pos_t) in the following manner.

for i=1:max_aircraft

 if pos_t(i) – t_{unc} < min_{delay}

  exp_t(i) = 0

 else

  exp_t(i) = max(0, pos_t(i) – t_{unc})

end

where min_{delay} is the minimum shift time in spot-out time management. t_{unc} is a constant value to account for uncertainty. The larger the t_{unc} is, the lower the expected reduction time is. Therefore, the uncertainty should be as low as possible, which depends on the estimation accuracy. As for min_{delay}, the larger the min_{delay} is, the less expected reduction time is. However, at the same time, the larger the min_{delay}, the less aircraft have to delay the spot-out time, which leads to less ATC workload. min_{delay} should be set considering these two trade-off factors. In this paper, min_{delay} is set to 2 minutes, while t_{unc} is set to 90 seconds.

3.3 Calculation Results

3.3.1 Result on a Sample Day

First, the result on February 23 2011 is shown as a sample. Fig. 5 shows the possible reduction time for each aircraft ordered by take-off time. The maximum possible reduction time of 8 minutes is observed at night time. The possible reduction time differs significantly by aircraft, and is not evenly distributed. This is due to uneven traffic.

Fig. 6 shows the possible reduction time and the traffic volume in each time range. Aircraft are categorized by take-off time, not by spot-out time. Large possible reduction time is observed around 10 am and 7 pm, and large departure traffic demand is observed during these time ranges. However, large reduction time is not observed around 7 am when the departure traffic is the highest. The taxiing inefficiency is caused by total traffic, not by departure traffic only. On the other hand, in other time ranges, the possible reduction time and the traffic volume are not necessarily correlated. Although the traffic volume must be one of the factors to increase inefficiency, other factors such as traffic patterns or randomness also contribute the inefficiency.

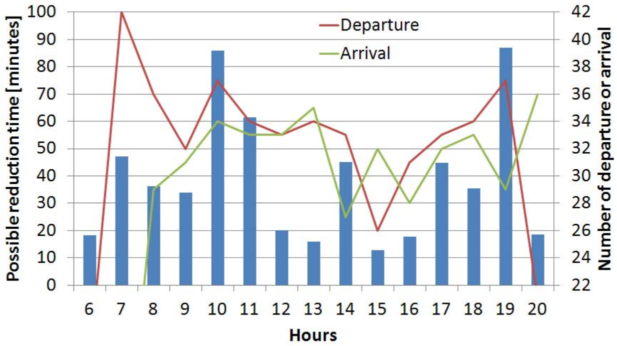

Fig. 6 Possible reduction time and traffic volume in each time range on February 23 2011.

In addition, Fig. 7 shows the relationship between the three calculated time parameters (maximum reduction time, possible reduction time, and expected reduction time) in each time range. These three functions have the similar trend in each time range. This infers that the expected reduction time might be estimated from the maximum reduction time which can be calculated easily.

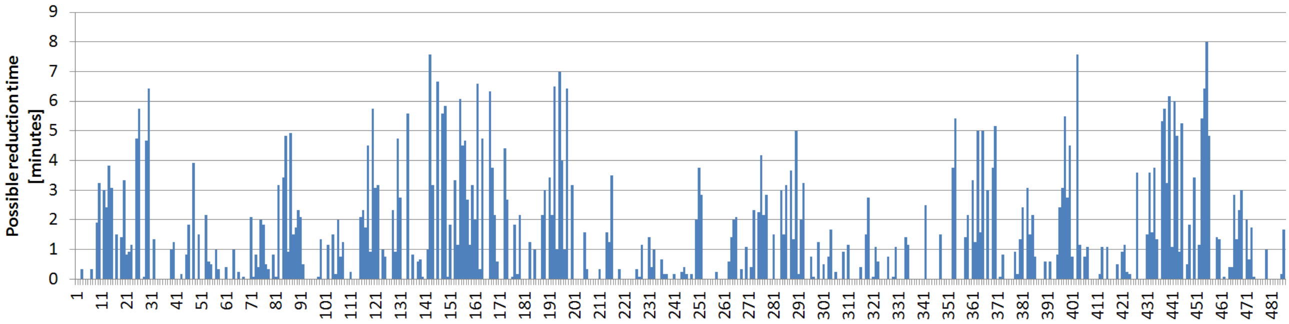

Fig. 5 Possible reduction time of each aircraft on February 23 2011.

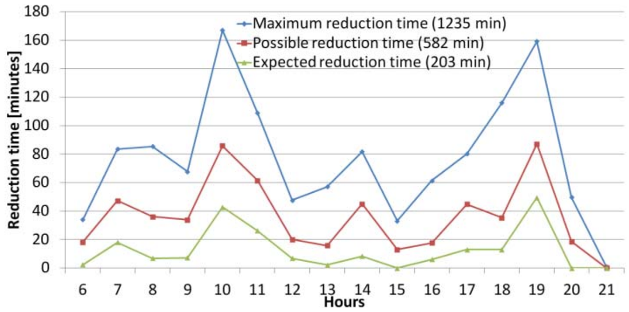

Fig. 7 Maximum reduction time, possible reduction time, and expected reduction time in each time range on February 23 2011.

3.3.2 Result Daily Fluctuations

Next, the difference between days is investigated. Table 2 shows the three time indices on each day. After opening the new runway, the traffic increases by about 7 %, but the maximum reduction time is not significantly changed. This infers that the new runway operation can respond to the increased traffic well. The possible reduction time corresponds to about 45 % of the maximum reduction time on each day. This means that almost half of taxiing inefficiency is caused by departure waiting queues. Furthermore, the expected reduction time is on average shorter than the possible reduction time by about 350 to 400 minutes.

Although the trend of the three values is explained well, the difference from day to day is also significant. Especially under the current operations, the expected reduction time on December 23 2010 is about three times larger than that on February 22 2011. Considering the fact that the traffic volume and traffic pattern are similar to each other under the same operations, the randomness of the traffic also affects the inefficiency.

Fig. 8 shows the expected reduction time in each time range on each day. This figure shows that large expected reduction time is observed in different time range on each day. Around 8 am, large expected reduction time is observed on December 23, but little on other days. Around 7 pm, most days show large expected reduction time, but little on February 22. Around 10 or 11 am and 4 or 5 pm, relatively large expected reduction time is observed. On the other hand, between 1 and 3 pm, little taxiing time can be reduced. The expected reduction time is basically linked to the traffic volume in each time range, but the randomness is also important.

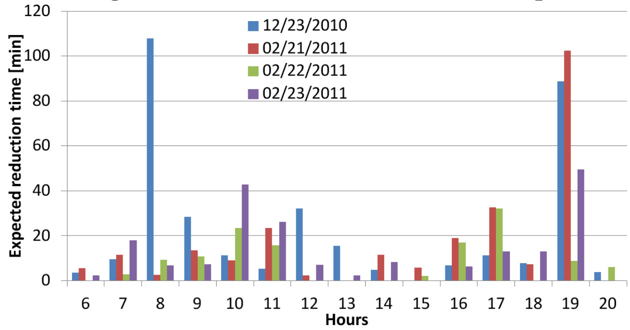

Fig. 8 Expected reduction time in each time range on each day.

Furthermore, the difference between departure runways is discussed. Under the current runway operations (shown in Fig. 2), the number of departure aircraft is not evenly distributed between the departure runways (C and D runways). Actually, the number of aircraft departing from D runway is about 2 times larger than that from C runway. Therefore, if the expected reduction time is evenly distributed to each aircraft, the expected reduction time of aircraft departing from C runway will be 1/3 of the total expected

Table 2 Maximum reduction time, possible reduction time, and the expected reduction time on each day.

Operation	Date	Number of departures	Maximum reduction time [min]	Possible reduction time [min]	Expected reduction time [min]
Old	04/22/2010	444	1210.8	559.4	179.1
	04/23/2010	449	1548.8	570.6	197.6
	04/24/2010	449	1345.5	641.6	225.5
	10/07/2010	454	1362.4	565.4	144.3
New	12/23/2010	474	1605.0	705.6	341.3
	02/21/2011	483	1382.7	628.2	245.9
	02/22/2011	486	1185.2	466.4	127.7
	02/23/2011	486	1235.5	582.2	202.5

reduction time. Fig. 9 shows the expected reduction time of aircraft departing from C runway only. The scale of the vertical axis is 1/3 of that in Fig. 8, so both figures can be compared graphically.

Around 7, 10, 11 am, the expected reduction time on C runway is relatively high. However, around 8 am or 7 pm when large expected total reduction is observed, the contribution of C runway is quite low. In total, 85 % of the expected reduction time is induced by aircraft departing from D runway. This result can be understood via queueing theory. According to this theory, the number of aircraft and the waiting time are not related linearly, but have exponential relationship. For effective taxiing time reduction, it would be better to consider aircraft departing from D runway only.

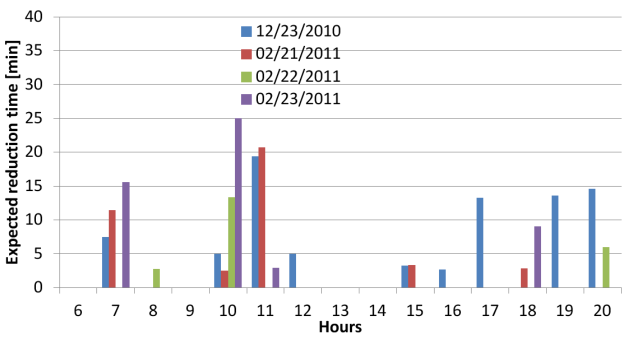

Fig. 9 Expected reduction time of aircraft departing from C runway only.

3.3.3 Economic and Environmental Impacts

According to Table 2, the average expected reduction time under the new operations is about 230 minutes per day. Assuming that the taxiing time is reduced by 230 minutes every day, the economic and environmental impacts are calculated.

The average size of aircraft at the airport is assumed to be B767-300. According to the ICAO emission data bank[8], the fuel consumption on the ground is about 0.44 kg/s and the CO_2 emission is 1.39 kg/s. The kerosene price is assumed to be 130 US$/barrel.

The yearly economic benefit will be 2.3 million US$, and the yearly reduction of CO_2 emission will be 7000 tons. Besides, the airport capacity is still increasing, and the final target for airport capacity is more than 10 % larger than that in February 2011. Therefore, the benefit will also increase in the future, because the runway operation is not to be changed. Spot-out time management is just a single component to achieve efficient airport operation, and it will play an important role for the future airport collaborative decision making system.

4 Conclusions

This paper showed how much taxiing time can be reduced by spot-out time management at Tokyo International Airport. In order to obtain accurate results, a new airport taxiing model considering congestion phenomenon was used. The result showed that the larger taxiing time can be reduced under the heavier traffic, but the effect of the traffic randomness was also significant. In addition, the yearly expected economic effect was estimated to be about 2.3 million US$. Future work includes the development of effective spot-out time management strategy which can result in the improvements presented in this paper. Future work includes the development of effective spot-out time management strategy which can result in the improvements presented in this paper.

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