Modeling of Aircraft Surface Traffic Flow at Congested Airport Using Cellular Automata

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***Abstract*— To manage the recent growth of air transportation, effective air traffic control and a 4-dimensional trajectory control concept have been already developed. However, most studies consider the flight phase only, which makes the airport surface congestion a bottleneck. The control of the airplane during the ground phase is almost entirely in the hands of the pilot and its uncertainty makes the simulation of airport traffic difficult. In addition, a congestion is a complicated phenomenon, not investigated in detail yet. This paper proposes a new airport surface simulation method considering a congestion phenomenon based on cellular automata. The floor field model is applied, and an aircraft speed decision process involving long-range interaction is developed. The effectiveness of this method is verified by comparing the results obtained with actual airport surface traffic data.**

Keywords-component; airport surface; cellular automata; airport simulation; NS model

I. INTRODUCTION

The importance of air traffic management has been stressed on with the recent increase in air traffic. 4-dimensional (4D) trajectory control has become a keyword to the future air traffic control. Although recent aircraft can follow 3D trajectory very precisely, their arrival time is not estimated that accurately yet. The 4D trajectory concept considers time navigation, which aims at using airspace more effectively. However, the 4D trajectory is usually defined during the flight phase only, so the airport congestion becomes a bottleneck. Even if the aircraft can follow the 4D trajectory during the flight phase, this process becomes irrelevant if the aircraft cannot land at the airport on schedule. In addition, while many studies can be found about the 4D flight navigation, relatively small number of studies is observed about the airport traffic problem. The author believes that the airport congestion problem should be discussed in more detail, because considering airport surface traffic, the take-off and landing time of the aircraft can be estimated with high accuracy.

A straightforward approach could be a simulation of the airport surface traffic flow, if it were not for the obstacles stated below. First, the aircraft departure time is likely to be changed. If some passengers do not board the aircraft by the scheduled time, the aircraft has to wait for them. Second, there are many uncertainties in taxing. The aircraft taxing is mainly in the hands of the pilot, so the taxing time varies from pilot to pilot. In addition, the aircraft taxing is affected by other aircraft taxing. For example, if an aircraft blocks a taxiway, no other aircraft can proceed. If an aircraft goes slowly on the taxiway, other aircraft cannot overtake it. This paper focuses on the second problem, i.e., airport traffic congestion problem. Although there are some studies on the automation of airport surface traffic scheduling[1][2], the aircraft taxing dynamics is not understood fully enough, which can be a critical factor in the overall improvement of air traffic management. Moreover, while there are some famous tools to support airport surface scheduling and management such as Surface Management System (SMS) which is used to improve efficiency of surface operation[3], the aircraft taxing speed is assumed to be constant, which differs significantly from the actual airport surface traffic especially in the congested airport. Other papers propose the airport surface trajectory model where the taxing speed is carefully considered based on the statistical data[4], but only unimpeded traffic is considered. The airport traffic problem becomes critical when an airport is congested. In this paper, taxing dynamics of both impeded and unimpeded aircraft are simulated.

The congestion phenomenon is famous in the field of car driving, and many studies have been conducted to model it, e.g., optimal velocity model[5] and Nagel-Schreckenberg (NS) model[6]. In these models, traffic jam is simulated under the condition that all drivers follow the same driving rule. NS model is based on the cellular automata, which makes simulation simpler. Although the basic NS model is applied for a single traffic lane, it is extended to multiple traffic lanes and crossings[7]. The author thinks that NS model has a potential to simulate the airport surface traffic, so here the airport surface traffic is simulated based on NS model. Despite the dynamic differences between aircraft and car traffics, the NS model can be successfully adopted after some changes which reflect the characteristics of ground aircraft movement.

This paper is organized as follows. Section II starts with brief overview of NS model, followed by an explanation of certain airport traffic features which need to be considered explicitly when adopting NS model to ground air traffic. In section III, the problems are implemented in the proposed simulation model, which is discussed in detail. In section IV, using the actual airport surface data, a simulation model is constructed, and the simulation result is compared to the actual data. This paper is summarized in section V.

II. NS MODEL AND THE CHARACTERISTICS OF AIRPORT TRAFFIC

A. NS model

As the proposed model is based on NS model, firstly NS model is briefly explained. NS model is based on car traffic. The following explanation is about car driving. A simplified image of the model is shown in Fig. 1. A single lane road divided into cells of equal length is assumed. Each cell can contain a single car only, and each car is characterized by a non-negative integer velocity. The time is also discrete, where at each time step, each car moves its cell based on the velocity. All cars move in the same direction. The velocity is calculated based on the following rules. $v_i(t)$ and $x_i(t)$ indicate velocity and position of the *i* th car at time *t*, respectively. The cars are ordered from 1 st to *n* th.

a) Acceleration: $v_i(t+1) = \min(v_{\max}, v_i(t)+1)$

b) Crash avoidance: $v_i(t+1) = \min(v_i(t), x_{i-1}(t) - x_i(t))$

c) Randomization: $v_i(t+1) = \max(0, v_i(t)-1)$ with probability *p*.

d) Move: $x_i(t+1) = x_i(t) + v_i(t)$

where $v_{\max}$ and *p* are the parameters of the traffic.

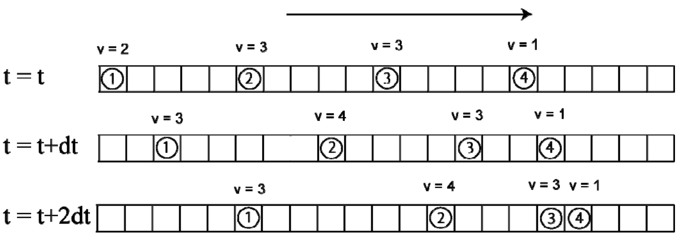

Figure 1. The patter diagram of NS model.

B. Characteristics of Airport Traffic

NS model is a simple, easily-applied model, but it cannot express complicated airport traffic. Many factors should be considered to reflect the unique characteristics of airport traffic as listed below.

1) Take-off and landing
2) Aircraft separation
3) Aircraft dynamics
4) Algorithm for speed decision
5) Crossing

1) A take-off and a landing are the most important keys for airport traffic. At any time, a runway is usually used by a single aircraft only while other aircraft wait for take-off at the taxiway. Aircraft waiting to land are given priority to use the runway, which delays take-offs even further. To deal with congestion problems, most major airports have multiple runways, with each runway being used for either take-off or landing. Since congestion usually has a greater impact on take-off aircraft, only aircraft for take-off are considered in this paper.

The time separation between take-off aircraft is usually not constant, mainly due to wake turbulence. As every take-off aircraft induces wake turbulence, the following aircraft cannot take off until the wake turbulence becomes negligible. Bigger aircraft induce stronger wake turbulence; the time separation for take-off varies with the type of aircraft pair. Other factors play a roll, too, e.g., the route after take-off, pilot judgment, aircraft speed. As for the route after take-off, wake turbulence should be considered for during flight, too, so if a pair of aircraft goes in the same direction after take-off, enough separation between the aircraft should be maintained. In terms of pilot judgment, wake turbulence cannot be seen, so the pilot tends to wait up to a minute or so on the runway when he feels the time separation is not enough. These factors should all be taken into account to estimate the precise time separation for take-off.

2) Aircraft separation is the distance between a pair of aircraft at a taxiway. As for car driving, the separation between two cars can be less than 1 meter, but this does not hold for aircraft. The separation between aircraft is in the hands of a pilot, and it varies with time.

3) Aircraft dynamics deals with the problem that aircraft have less agility than cars. The taxing speed is usually controlled by engine thrust, which has a slow response. Although there is a braking system installed in order to decrease speed, this system is seldom used and aircraft usually decrease speed gradually by drag.

4) Algorithm for velocity decision considers the differences and similarities between aircraft and automobile in terms of velocity decision. Drivers usually relay on visual cues from the preceding car only to decide and control their car's velocity.. On the other hand, aircraft can get information about the current status of congestion at the airport. If the pilot knows that the airport is congested, the aircraft will go taxing slower than usual. Furthermore, thanks to the wide field of view of the pilot, they are aware of relative position of a lot of aircraft.

5) Crossing is not a distinct characteristic of an airport, but it should be considered. If the aircraft go through a crossing without turning, their speed is not reduced. However, when turning is necessary, the speed is reduced to a certain value. At the same time, the trajectories of turning and going straight are also different. In addition, as the order of take-off aircraft is decided by the control tower, an aircraft may have to wait before the crossing until the preceding aircraft passes the crossing.

In order to model the airport traffic, all of the above factors should be considered. However, the more complex the model, the higher the number of parameters and lower the generality. The model should be constructed taking these factors into account, too.

III. PROPOSED AIRPORT TRAFFIC MODEL

In the previous section, NS model as explained, and five factors accounting for airport traffic were discussed. In this

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section, each factor is converted to several model rules, which are set in the model.

A. Take-off and Landing

In this paper, only take-off aircraft are considered. As mentioned before, several factors should be considered for the time separation between take-off aircraft. Here, a pair of aircraft and pilot judgment are considered. Firstly, a pair of aircraft is explained. The time separation for take-off depends on the size of aircraft, so heavy, medium, and light aircraft types are considered. Heavy aircraft are represented by B747, B777, A340; medium by B767, A300, and light by B737, A320. Take-off separation (t_{sep_1}) is defined by the following expression. $t_{\min}$ is the minimum time separation for take-off, and Δt is defined in Table I.

$$t_{sep\_1} = t_{\min} + \Delta t \tag{1}$$

TABLE I. CONDITIONS OF Δt

following/preceding	Heavy/Medium	Light
Heavy/Medium	t_0	0
Light	t_1	t_0

Note that heavy and medium aircraft fall in the same category in terms of Δt, so two parameters (t_0, t_1) are needed.

Next, the pilot judgment factor is explained. This factor indicates that the pilot waits for the wake turbulence effect to abate. Therefore, time separation (t_{sep_2}) is defined by the following expression.

$$t_{sep\_2} = \begin{cases} d + \Delta d & (d < d_{\mathrm{limit}}) \\ d & (d \ge d_{\mathrm{limit}}) \end{cases} \tag{2}$$

where d is the time separation between the preceding aircraft take-off time and following aircraft arriving on the runway time, and Δd is the pilot judgment with respect to d_{limit}. Two parameters (Δd, d_{limit}) are necessary. Total time separation (t_{sep}) is defined as follows.

$$t_{sep} = \max(t_{sep\_1}, t_{sep\_2}) \tag{3}$$

B. Aircraft Separation

Aircraft separation sometimes varies throughout time, but in this paper, it is assumed to be constant. Therefore, the minimum distance separation between two aircraft is a constant number of cells ($x_{\min}$).

C. Aircraft Dynamics

As previously mentioned, the breaking system is rarely used during taxing. However, according to NS model, deceleration is unlimited although acceleration is at most 1 cell per 1 time unit. Therefore, the expression of crash avoidance in NS model is revised, i.e., the maximum deceleration is set to 1 cell per 1 time unit.

Let me assume that the aircraft needs x units of separation and the current speed is v. The aircraft has to start decelerating in order to decelerate by 1 cell per 1 time unit if the following expression is satisfied.

$$x \le \sum_{s=1}^{v} s = \frac{v(v+1)}{2} \tag{4}$$

Therefore, crash avoidance expression in NS model is replaced by the following expression. The original crash avoidance term is still kept to account for the case when an aircraft appears on the runway suddenly.

$$\begin{aligned} & v_i(t+1) = \min(v_i(t) - 1, x_{i-1}(t) - x_i(t) - x_{\min}) \\ & if\ x_{i-1}(t) - x_i(t) - x_{\min} \le v_i(t)(v_i(t)+1)/2 \end{aligned} \tag{5}$$

D. Algorithm for Speed Decision

The aircraft speed is determined by the level of airport congestion. Needless to say, the separation from the preceding aircraft is important, but the aircraft speed is also affected by many other factors. Consequently, it is assumed that the aircraft speed is affected by all aircraft which are on the way to take-off. The closer the aircraft, the larger the impact on speed decision. In order to describe mathematically such an effect, the floor field model is introduced[8]. The floor field model was originally developed to express the long-range interaction, and in this example, the 2-dimensional dynamics of pedestrians is modeled using cellular automata. In the floor field model, each cell is assigned a value which keeps the cell status and memorizes the past information. This value is called floor field. The floor filed model consists of the dynamic floor field (for past and long-range interaction information) and the static floor field (for cell status), here, only the dynamic floor field is considered. The dynamic floor field is modified by the presence of pedestrians and has its own dynamics, i.e. diffusion and decay. Each pedestrian leaves a “trace”, so the floor field of the occupied cells increases. The floor field is decayed and delivered to the next cell, and thus the previous presence of pedestrian can be accounted for. In this paper, the dynamic floor field is applied, assuming that each aircraft leaves a trace. According to the floor field which are on the way to take-off, the aircraft speed is determined. The floor field and the aircraft speed are calculated based on the following expressions.

Trace: (x is the aircraft position)

$$F(x,t) = F(x,t) + f_{trace} / v_i(t) \tag{6}$$

Runway:

$$F(x_{runway}, t) = F(x_{runway}, t) + f_{runway} \tag{7}$$

Reference of aircraft speed :

$$v_i^{ref}(t+1) = \max\left(v_{\max} - \frac{\sum_{ontheway} F(x,t)\exp(-d/k)}{\sum_{ontheway} \exp(-d/k)}, 1 \right) \tag{8}$$

Acceleration and deceleration:

$$v_i(t+1) = \begin{cases} v_i(t)+1 & if\ v_i^{ref}(t+1) \geq v_i(t)+1 \\ v_i(t) & otherwise \\ v_i(t)-1 & if\ v_i^{ref}(t+1) \leq v_i(t)-1 \end{cases} \tag{9}$$

Decay:

$$F(x, t+1) = \delta F(x, t) \tag{10}$$

$F(x,t)$ indicates the floor field at the position *x* and time *t*. δ indicates the decay parameter. f_{trace} is a constant value which expresses "trace" effect. It is assumed that the aircraft taxing route is fixed in advance and the reference of aircraft speed ($v_i^{ref}(t+1)$) is calculated considering all floor fields which are on the way. According to the reference speed, the aircraft speed is determined. *d* indicates the number of the cells from the current position. The closer the floor field is, the bigger its effect is. *k* is the speed parameter, and a capital *k* indicates that the aircraft speed is affected strongly by the long-range floor field. Note that only the decay process is considered. Moreover, if the aircraft approaches the runway, the aircraft tends to decrease the speed, so the runway always leaves an extra of the floor field.

E. Crossing

At a crossing point, the aircraft may need to decrease the speed, so the maximum speed at a crossing point v_{curve} is defined. In order to conduct a smooth deceleration, the deceleration should begin under the following condition.

$$d_{curve} \leq \sum_{s=v_{curve}+1}^{v} s = \frac{v(v+1)}{2} - \frac{v_{curve}(v_{curve}+1)}{2} \tag{11}$$

d_{curve} is the distance to the nearest curve from the current position.

F. Others

According to actual data, additional aspects should be considered. Although the aircraft which is close to the runway decrease the speed according to the runway floor field term, the aircraft actually accelerate when no other aircraft is waiting to take off before the aircraft. Therefore, if the runway is not occupied and no aircraft is on the way to take-off, the speed is calculated with the notion that the floor field is equal to zero.

G. Parameter Tuning

In order to conduct a simulation, many parameters defined above have to be set. Actually, the parameters are $t_{\min}$, t_0, t_1, Δd, d_{limit}, $x_{\min}$, δ, f_{trace}, f_{runway}, k, $v_{\max}$, v_{curve}. All parameters are identified through simulations. Actual airport taxing data is acquired first, and the taxing start time/position and take-off time and the taxing route is obtained for each aircraft. Through simulations, assuming that the initial time, the initial position, and the taxing route are fixed, take-off time can be calculated. Therefore, the parameters which minimize the difference between actual take-off time and simulation should be chosen. The objective function is defined as follows:

$$J = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(t_i^{act} - t_i^{sim})^2} \tag{12}$$

t_i^{act} and t_i^{sim} are the actual take-off time and that in simulation for *i* th aircraft, respectively. *J* has the unit of time, which can be used to evaluate the simulation accuracy. It is called a time index.

Finally, the factors discussed in this section are summarized in Table II.

TABLE II. THE FACTORS CHARACTERIZED FOR AIRPORT TRAFFIC IN THIS PAPER.

Factors	Details
Take-off and landing	The take-off time separation is determined by a pair of the aircraft size. The pilot instincts about wake turbulence are also considered.
Aircraft separation	The aircraft separation is a fixed number of cells, set by parameter tuning.
Aircraft dynamics	The maximum value of both the deceleration and the acceleration is set to 1 cell per 1 time unit.
Algorithm for speed decision	Using the floor field model, the aircraft speed is determined by the past and long-range interaction information which are on the way to the runway.
Crossing	The maximum speed at a crossing point is set.
Others	If the aircraft is too close to the runway, the aircraft speed follows a different rule.
Deceleration randomization	Not implemented.

IV. SIMULATION RESULTS

A. Airport and Data Acquisition

In order to confirm the validity of the proposed modeling method, airport surface data is necessary. In Japan, Tokyo (Haneda) International Airport has recently installed multilateration system, a surveillance system for the airport surface aircraft. 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[9]. Fig. 2 shows the map of Haneda airport. During certain hours, the runway is used for either take-off or landing, and this time, the runway (shown in blue) and the aircraft which take off from right to left, shown in the figure, are considered. The green parts are the taxing way, and the yellow parts are the crossings where the maximum speed is equal to v_{curve} with the exception when aircraft go straight through the yellow part. Note that taxiways are divided in 5 meters cells, and the corners consist of two straight lines (not an arc).

The data used in this research was obtained between 5 pm and 9 pm on July 26th 2007. 114 aircraft took off during this period. The data is divided into two parts (A: 5:00 to 6:30 for 39 aircraft, B: 6:30 to 8:40 75 aircraft). The parameters are set by data B only, and the simulation result is discussed by both data A and B. Data B is treated as teaching data, and Data A as validation data. Note that the time interval in each simulation is 5 seconds. The maximum and average taxing times among the aircraft are 1120 s and 502 s, respectively.

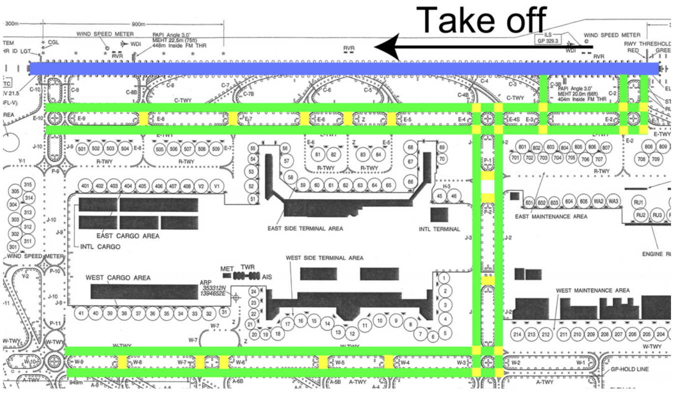

Figure 2. Haneda airport.

B. Parameter Settings and Simulation Results

The parameters are set to minimize the objective function. Firstly, the ranges of the parameters are determined, and in each combination of parameters, the objective function is calculated through a simulation. As the ranges of the parameters are adjusted by trial and error, the obtained parameters are not necessarily optimized. However, the ranges of the parameters are easily estimated to some extent, so it is considered that the parameters can be very close to the optimal ones.

Firstly, the optimized parameters are shown in Table 3. Using these parameters, a simulation is conducted, where the time index for data B is 28.96 s. The average taxing time for data B is 502 s, and the normal take-off time separation is about between 80 and 120 s. The time accuracy of simulation is less than a half of take-off interval and 5 % of the taxing time. Moreover, using the same parameters, the time index for validation data A is 27.87 s, where the parameters are not set based on this data. The accuracy is almost the same as that of data B, which indicates that this model is general enough.

TABLE III. THE OPTIMIZED PARAMETERS

$t_{\min}$	70 s	Δd	30 s	δ	0.93	k	50 cells
t_0	15 s	d_{limit}	90 s	f_{trace}	35.5	$v_{\max}$	12.75
t_1	40 s	$x_{\min}$	25 cells	f_{runway}	4.0	v_{curve}	4.0

However, the time index is only the function of the difference between the real take-off and simulated take-off time. Therefore, the time histories of the aircraft trajectory are also shown. Fig. 3 shows the time histories of each aircraft trajectory when the airport is not so crowded. The horizontal axis indicates the time [second] from 0:00, and the vertical axis indicates the number of the cells to the runway. The black dots show the simulation result, and the red dots show the actual aircraft data. Note that each aircraft has a different initial position and follows a different route, so the trajectories sometimes cross each other. According to the figure, some aircraft in the simulation go faster than those in actual data especially when they are far from the runway. As for the rest, most of the aircraft trajectories agree with the actual trajectory, which means the simulation works well to some extent.

Fig. 4 shows the time histories of each aircraft trajectory during a congestion. The figure format is the same as the previous one. During this period, since many aircraft go to the runway, its capacity is exceeded. This is when our model is most advantageous. While the first aircraft proceeds to the runway relatively smoothly, the following aircraft are gradually delayed. The 10 th aircraft has to decrease its speed when it is as far as 200 cells from the runway, which verifies the simulation. In order to validate the speed decision algorithm, simulations not taking into account the floor field were conducted. These results are shown in Fig. 5. It is clearly seen that all aircraft move at the maximum speed until the minimum separation to the following aircraft is infringed. It should also be noted that the last aircraft took off about 200 s earlier than actual data nevertheless the take-off time separation is considered. This implies that the runway capacity depends on the airport congestion, too.

These results show that the proposed model has a great potential to model airport traffic even when the airport is congested. Since each aircraft has uncertainty during taxing, the model cannot simulate all phenomena. However, by considering and implementing additional factors, the model can be further developed and improved. Moreover, the data used in the simulations presented in this paper is limited to a single day at a single airport and runway. Thus, extended simulations in various conditions are needed to confirm the general validity of this model.

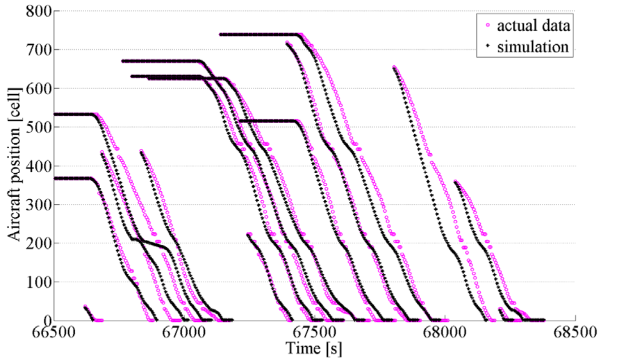

Figure 3. Simulation result for the not congested case.

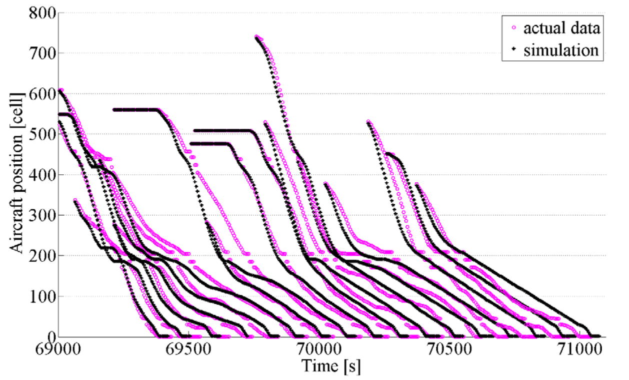

Figure 4. Simulation result for the congested case.

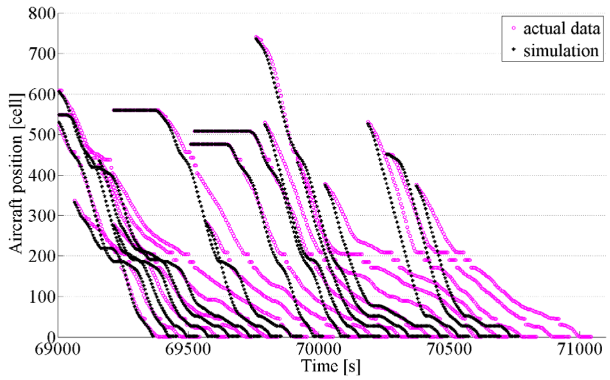

Figure 5. Simulation result for the congested case. (floor field is not considered)

V. CONCLUSIONS

So far, the airport surface congestion problem was not been examined in detail even though it can be critical for the future 4D trajectory concept. This paper focused on the airport congestion phenomenon, which was simulated based on the Nagel-Schreckenberg (NS) model. NS model was originally developed to describe highway car driving congestions, which differed significantly from aircraft ground congestions. In order to adopt this model to airport surface traffic, several key factors characterizing airport traffic were extracted. Then, they were implemented into the rules in the model. The simulation results indicated that the airport surface traffic was simulated well under the scenario of a congested airport. Further improvements of the model will be considered in future work.

REFERENCES

[1] Gracia, J., Berlanga, A., Molina, J. M., and Casar, J. R., "Optimization of Airport Ground Operations Integrating Genetic and Dynamic Flow Management Algorithms," AI Communications, Vol. 18, No. 2, pp. 143-164, 2005.

[2] Roling, P. C., and Visser, H. G., "Optimal Airport Surface Traffic Planning Using Mixed-Integer Linear Programming," International Journal of Aerospace Engineering, Vol. 2008, No. 1, 2008.

[3] Atkins, S., Jung, Y., Brinton, C., Stell, L., Carniol, T., and Rogowski, S., "Surface Management System Field Trial Results," AIAA 4th Aviation, Technology, Integration and Operations Forum, AIAA-2004-6241, 2009.

[4] Gong, C., "Kinematic Airport Surface Trajectory Model Development," 9th AIAA Aviation Technology, Integration and Operations Conference, AIAA-2009-7076, 2009.

[5] Bando, M., Hasebe, K., Nakayama, A., Shibata, A., and Sugiyama, Y., "Dynamical Model of Traffic Congestion and Numerical Simulation", Physical Review E, Vol. 51, pp. 1035-1042, 1995.

[6] Nagel, K., and Schreckenberg, M., "A cellular automaton model for freeway traffic," J. Phys. I France, Vol. 2, No. 2, pp. 2221-2229, 1992.

[7] Esser, J., and Schreckenberg, M., "Microscopic Simulation of Urban Traffic Based on Cellular Automata," International Journal of Modern Physics C, Vol. 8, No. 5, pp. 1025-1036, 1997.

[8] Burstedde, C., Klauck, K., Schadschneider, A., and Zittartz, J., "Simulation of Pedestrian Dynamics Using a 2-dimensional Cellular Automaton," Physica A: Statistical Mechanics and its Applications, Vol. 295, No. 3-4, pp. 507-525, 2001.

[9] International Civil Aviation Organization, ICAO A-SMGCS manual, §4.2.2.