Characterization of Gate Location on Aircraft Runway Landing Roll Prediction and Airport Ground Networks Navigation

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This study presents an aircraft landing simulation and prediction model. The model uses simple aircraft kinematics coupled with individual parameters to describe the landing process. A multiobjective optimization and a shortest path algorithm are used to predict the aircraft exit choice and taxiway path in the runway taxiway network. By recognizing pilot motivation during the landing process, several influence factors such as terminal location, runway, and weather conditions are considered in the aircraft landing simulation. Random variables such as aircraft runway crossing height, flight path angle, approach speed, deceleration rate, and runway exit speed are generated to represent the stochastic landing behavior of aircraft by using a Monte Carlo sampling technique. With real-time input data, the model could provide information on aircraft exit choice, runway occupancy times, and shortest taxiway path to an assigned terminal location for both the pilot and the air traffic controller in a ground traffic automatic control system. This model can also be used to solve runway exit location problems by providing the expected distribution of aircraft landing distances and predict aircraft runway occupancy times. An interactive computer program has been developed on an IBM RISC 6000 workstation to perform these tasks.

With the increase in air traffic demands, airport ground network operation analysis becomes more important to fully realize the capacity of airports. The use of new Air Traffic Control System (ATC) technologies in the near future could reduce the aircraft in trail separations in the airport terminal area thus making aircraft runway occupancy times become an important factor in determining airport capacity. The expected intensity of runway operations in the future will also influence the safety of these operations thus requiring more precise methods of determining aircraft state variables in real-time on a ground network. Landing aircraft processing is one of the key factors in airport ground network operation analysis. A better understanding of the aircraft landing process could help to improve airport ground operation management and the safety of aircraft operations. Furthermore, it could provide knowledge for ground network designs including the optimal runway exit location problem.

The Aircraft Landing Simulation and Prediction Model (ALSPM) described here has been calibrated using real aircraft landing data observed at five major airports in the United States. With real-time input data, this model could provide landing information instantly to both pilots and air traffic controllers in a ground traffic automatic control system. The information could include acceptable runway exits, the probability of each aircraft taking these exits, related runway occupancy times, and advisories on the shortest taxiway path to an assigned gate. The model described here can also provide information about the distribution of aircraft landing distance and runway occupancy times for determining optimal runway exit locations. This procedure is usually carried out in the planning stage of new runway facilities.

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BACKGROUND

Earliest efforts to describe aircraft runway landing process are found in runway exit optimization and capacity analysis (*1–3*). In 1974, Joline (*3*) used an aircraft deceleration model to predict the runway occupancy time in the runway exit location problem. Based on the aircraft landing data collected at Chicago's O'Hare airport, the model divided the landing process into three phases. Phase 1 accounts for the aircraft motion from threshold to the touchdown point with the vehicle flying at a constant speed profile. In phase 2 the aircraft uses a deceleration rate consistent with the use of reverse thrust until it reaches a coast speed. Phase 3 has two cases in which the aircraft either uses the deceleration rate in Phase 2 to reach an exit with the required turnoff speed (i.e., there is an exit located at that place) or the aircraft coasts for ΔT time and then uses the deceleration rate in Phase 2 to reach the exit with the required turnoff speed. This model does not consider any influence of airport layout and environmental factors such as the gate locations, runway grades, the weather conditions, and so on, which may cause significant deviations in aircraft landing operations at different airports.

Several empirical studies on aircraft landing behaviors were conducted in the late 1970s (*4,5*). Through analysis of observations collected at different airports, Koenig (*4*) found that a key factor influencing the aircraft selection of an exit is the terminal gate location. Other factors such as the traffic density, passenger comfort, and so on, also have influence on the landing performance. He found that pilots in many instances have the motivation to exit early in order to reach their assigned gate in shorter times. He pointed that this motivation factor could be used to reduce runway occupancy times.

In 1990, Ruhl (*6*) presented an aircraft landing model which uses aircraft individual parameters to predict the aircraft runway occupancy time. In this model, aircraft runway landing operations are divided into five segments. In Phase 1 the aircraft crosses the threshold and travels at a constant speed until a flare maneuver is initiated. Phase 2 encompasses the flare maneuver and ends when the main gear touches down. Phase 3 starts from the point where the main gear touches down until the nose gear impacts the ground. Phase 4 starts at the nose gear touchdown point with the aircraft speed bleeding off at an average braking deceleration rate until reaching a suitable exit. It is assumed here that if the deceleration rate under normal condi-

tions allows the aircraft to accept an exit (means the aircraft could decelerate to the required speed before it reaches the exit) the pilot will adjust (decrease) the deceleration rate to meet the required exit speed at the time the aircraft reaches the exit. Phase 5 starts at the point the aircraft begins to turn off on the runway until it clears the runway. One shortcoming in this model is the obvious simplification of the aircraft deceleration phase (Phase 4). According to our observations, pilots use different strategies in this phase based on the exit location. For example, an aircraft may decelerate to a certain speed and coast for some time and decelerate again to reach its exit. Simplifications in this phase usually result in higher runway occupancy times than those observed in the field. Another problem is that there is no inclusion of motivational factors in this model. Ruhl mentioned the influence of the terminal location to the aircraft landing operation in his paper. However, the model did not consider this factor (*6*).

Another aircraft landing simulation model was developed to estimate aircraft runway occupancy time for runway exit location and runway occupancy time minimization at Virginia Polytechnic Institute (*7*). This model also divided the landing process into five phases including a flare phase, two free roll (or transition) phases, a braking phase, and a turnoff phase as shown in Figure 1. Several random variables, such as the approach speed, aircraft landing weight factor, and the deceleration rate during the braking phase, are generated using a Monte Carlo sampling technique. Factors that have influence on the aircraft landing operation are included in this model, such as weather conditions and the local effect of runway grades. Runway length as a pilot motivation factor is also considered and a more realistic braking phase related to the aircraft exit choice is used. However, the gate location influence was not considered to simplify the complexity associated with a runway exit optimization model and its portability on a personal computer (*7,8*).

This study addresses some of the limitations of previous models and describes a technique to predict landing roll performance in realistic airport operational conditions considering gate location as a causal factor in the exit choice model.

MODEL DEVELOPMENT

Based on the five-phase aircraft landing process shown in Figure 1, the model uses Monte Carlo simulation to perform 250 trails for each landing aircraft. Motivation factors, runway, and weather conditions factors are considered in the simulation to represent different airport environments. The most important improvement in this model is the consideration of the gate location as a motivation factor. A multi-objective optimization method is implemented here to link this factor to the aircraft landing performance and exit choice. The model describes the aircraft landing roll performance based on the consideration of a complete ground network. This provides more realistic results which could be used in automatic ground control system development and runway exit location optimization procedures.

Aircraft Landing Process Description

The aircraft landing process is broken down into five phases: flare phase, first free roll phase, braking phase, second free roll phase, and turnoff phase as illustrated in Figure 1.

The flare phase starts from runway threshold until the aircraft touches down. The landing distance, S_{air}, and travel time, t_{air}, are estimated by Equations 1 and 2 under the assumption that the aircraft uses a steady descent flight path angle g (3.0° typical) with a constant nominal acceleration during the flare maneuver at 1.2 g's (*9,10*).

$$s_{air} = \frac{h_{th}}{\gamma} + \frac{V_{fl}^2}{2g(n_{fl} - 1)} + \Delta S(rl) \quad (1)$$

$$t_{air} = \frac{2S_{air}}{V_{ap} + V_{td}} \quad (2)$$

where

h_{th} = threshold crossing height,
V_{fl} = flare speed,
n_{fl} = flare load factor,
$\Delta S(rl)$ = adjustment distance of S_{air} according to different runway length (rl),
V_{ap} = aircraft approach speed, and
V_{td} = touchdown speed.

The first free roll phase starts at the point where the main gear touches down and ends when thrust reverses and braking are

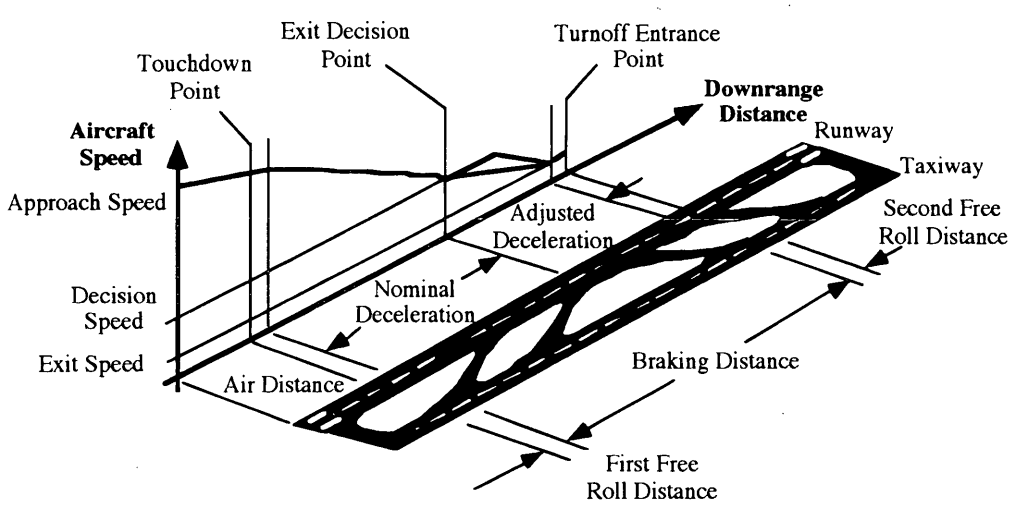

FIGURE 1 Aircraft landing phases.

applied. It is assumed that aircraft travels at a constant speed for about 1–2 sec.

$$S_{fr1} = V_{td} \times t_1 \tag{3}$$

where S_{fr1} is the first free roll distance, and t_1 is the travel time.

The braking phase starts from the ending point of the first free roll phase until the aircraft decelerates to an acceptable exit design speed (V_{ex}). The aircraft uses a nominal deceleration rate to decelerate to a speed called decision speed (V_{des}). The model checks for a possible coasting distance (S_{coast}), under the assumption that the aircraft uses the nominal deceleration rate to reach the selected exit after coasting. If this distance is within certain range (l_{dec}), the aircraft uses the adjusted deceleration rate to reach the exit's design speed without coasting. If the distance exceeds l_{dec}, the aircraft coasts for some time under the decision speed and then uses the nominal deceleration rate to decelerate to the exit. The nominal deceleration rate (dec), is calculated considering the manufacturer's published landing distance and subtracting an air distance (*7*). It is also adjusted by runway local gradient, surface conditions (wet or dry), aircraft landing weight information and the aircraft assigned gate location. The decision speed used in the model has been obtained through empirical data collected at various airports (*11*). Equations 4 and 5 are used to estimate the braking phase distance (S_{br}) and time (t_{br}).

$$S_{br} = l_{ex} - (S_{air} + S_{fr1} + S_{fr2}) \tag{4}$$

$$t_{br} = \begin{cases} 2 \times \dfrac{S_{br} - \dfrac{V_{td}^2 - V_{dec}^2}{2 \times \text{dec}}}{V_{dec} + V_{ex}} + \dfrac{V_{td} + V_{dec}}{\text{dec}} & \text{if } S_{coast} < l_{dec} \\ \dfrac{V_{td} - V_{dec}}{\text{dec}} + \dfrac{S_{br} - \dfrac{V_{td}^2 - V_{ex}^2}{2 \times \text{dec}}}{V_{dec}} & \text{if } S_{coast} \geq l_{dec} \end{cases} \tag{5}$$

where l_{ex} is the distance from a selected exit to the runway threshold, and S_{coast} is the possible coasting distance which can be calculated by using Equation 6.

$$S_{coast} = l_{ex} - \left(S_{air} + S_{fr1} + S_{fr2} + \frac{v_{td}^2 - v_{ex}^2}{2 \times \text{dec}}\right) \tag{6}$$

An exit choice model is used in the braking phase to determine the most likely exit to be used. This model will be described later.

The second free roll phase is scheduled after the braking phase just before the aircraft starts turning off from the runway. This phase is associated with the pilot identification and decision procedure to take a specific exit. The aircraft will travel at a constant speed (i.e., the exit speed) for about 1–3 sec.

$$S_{fr2} = V_{ex} \times t_1 \tag{7}$$

where

S_{fr2} = second free roll distance,
t_2 = travel time, and
V_{ex} = exit speed.

The turnoff phase is used to describe aircraft exit turnoff behavior and estimate the turnoff time. This phase starts from the point where aircraft begins the turnoff maneuver and ends at the point where the aircraft clears the runway. The turnoff time (t_{tof}) is estimated through numerical integration using a 4th order Rung-Kutta algorithm (*12*) as shown in Equation 8.

$$t_{tof} = f(V_{ex}, b_{tail}, b_{wing}, R_w, ET) \tag{8}$$

where

b_{tail} = aircraft tail plane span,
b_{wing} = aircraft wing span,
R_w = runway width, and
ET = selected exit type.

As described above, the aircraft runway occupancy time *ROT* can be estimated by adding all individual times in all phases.

$$ROT = t_{air} + t_1 + t_{br} + t_2 + t_{tof} \tag{9}$$

Figure 2 shows two Boeing 727-200 landing simulation trajectories to illustrate differences in landing roll behavior at two hypothetical runway exit locations.

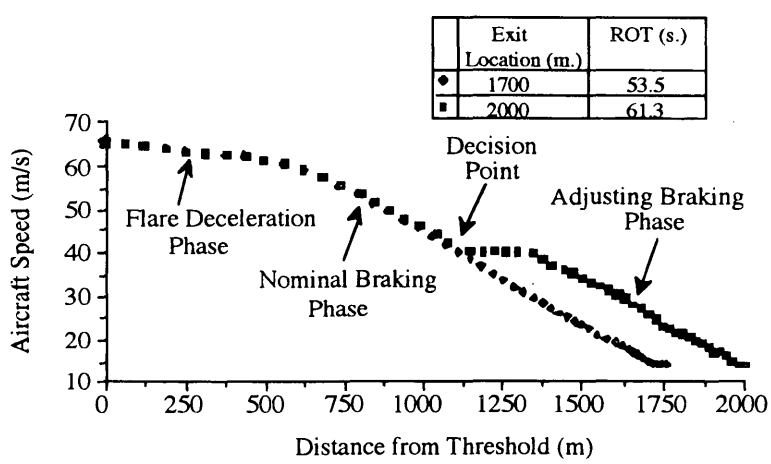

FIGURE 2 Sample velocity profiles (Boeing 727-200).

Aircraft Stochastic Landing Behavior

Monte Carlo sampling technique is used in runway landing simulation to represent the stochastic behavior of landing aircraft. Created random variables include aircraft landing weight factor (w_f) (*7*), runway crossing height (h_{th}), flight path angle (γ), flare speed (V_{fl}), deceleration rate in braking phase (dec), and exit speed (V_{ex}). All of these random variables are assumed to have normal distributions as shown in Equation 10.

$$X \sim N(\mu, \sigma) \tag{10}$$

where

X = random variable,
μ = mean value, and
σ = standard deviation.

The upper and lower boundary values are set for each distribution according to the landing observation analysis carried out by the Virginia Polytechnic Institute Transportation System Laboratory at five east-coast airports (*11*).

Terminal Location Influence on Landing Process

The terminal location is known to have influence on the aircraft runway landing behavior (*4,6,11*). In this model, two strategies are used to reflect this influence.

Strategy 1

If under the nominal deceleration rate an aircraft passes over the perpendicular plane of the terminal location, a more aggressive deceleration rate is used by the model to reflect the pilot's motivation for attempting an earlier exit.

$$\text{dec} = \begin{cases} \text{dec}_{\text{nor}} & \text{if} \quad lr < f(GL) \\ (1 + \lambda) \times \text{dec}_{\text{nor}} & \text{if} \quad lr \geq f(GL) \end{cases} \tag{10}$$

where

dec_{nor} = nominal decoration rate,
γ = landing motivation factor,
lr = aircraft nominal landing distance, and
$f(GL)$ = function of terminal location GL.

Figures 3 and 4 show Boeing 727-200 landing distributions (to a speed of 15 m/sec) simulated by the model for two values of the landing motivation factor. The terminal location for this example is assumed to be near the active runway threshold (i.e., pilots could be heavily motivated to shorten their landing rolls to reach the terminal location).

Strategy 2

The shortest aircraft taxiing time to the terminal location is used as a factor to influence aircraft exit choice. It is assumed that the landing aircraft will choose the acceptable exit which can minimize its runway occupancy time plus its weighted shortest taxiing time (see Exit Choice Model in detail).

The Exit Choice Model

A multiobjective integer optimization model is developed to find the exit for landing aircraft. Minimizing the aircraft runway occupancy time (*ROT*) and minimizing taxiing time (*TT*) are the two objectives. A taxiing time weight factor is used to combine these two objectives. The following two assumptions are made in the model: 1) The landing aircraft will choose the acceptable exit which can minimize its *ROT* plus its weighted *TT*. 2) The aircraft *ROT* is at least equally important with *TT*. This fact is used to achieve a balance between individual and collective (system wide service times). The model can be described mathematically as follows:

$$\text{Minimize} \sum_{i=1}^{n} (ROT_{ik} + wf_k + TT_{ik})x_i$$

$$\text{Subject to} \sum_{i=1}^{n} x_i = 1 \tag{11}$$

$$l_{ex}(i) \geq S_{air} + S_{fr1} + S_{fr2} + S_{br}$$
$$x_i = 0 \text{ or } 1$$
$$i = 1, \ldots, n \text{ and } k = 1, \ldots, m$$

where

i = runway exit index number,
n = total number of exits,
$l_{ex}(i)$ = location of the ith exit,
k = terminal index,

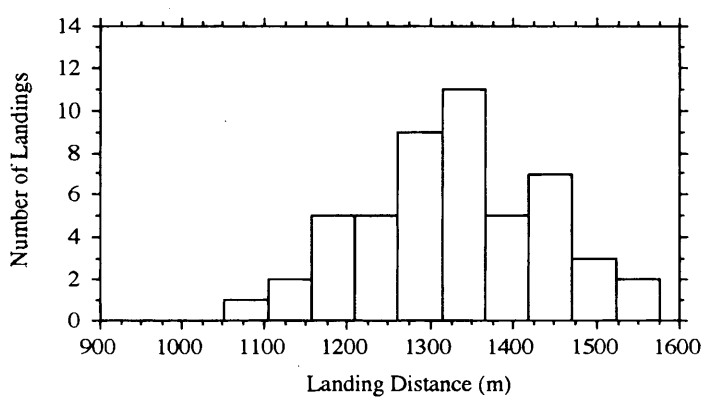

FIGURE 3 Boeing 727-200 landing distribution (λ = 0).

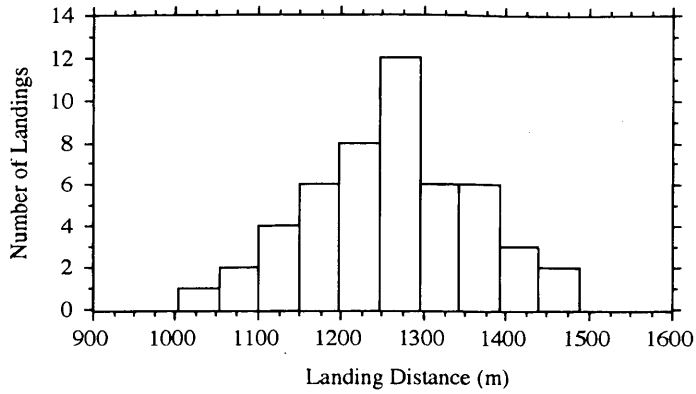

FIGURE 4 Boeing 727-200 landing distribution ($\lambda = 0.1$).

wf_k = taxing time weight factor for airline k, and
x_i = binary variable which indicates the aircraft will either take exit i (1) or not (0).

Since the number of runway exits is limited, we use a numerical method to solve this integer program problem. The determination of wf_k will be discussed in following section.

Taxiing Time and Taxiway Path Prediction

The aircraft shortest taxing time and taxiway path can be estimated by solving the following shortest path optimization model.

Suppose we have a taxiway network G with m nodes, n arcs, and a cost c_{ij} associated with each arc (i, j) in G. The shortest path problem is to find the least costly path (i.e., shortest path) from node i to node j.

The mathematical description is to find the shortest path from node l to node k:

$$\text{Minimize} \sum_{i=1}^{m} \sum_{j=1}^{m} c_{ij} x_{ij}$$

$$\text{Subject to} \sum_{j=1}^{m} x_{ij} - \sum_{k=1}^{m} x_{ki} = \begin{cases} 1 \text{ if } i = l \\ 0 \text{ if } i \neq l \text{ or } k \\ -1 \text{ if } i = k \end{cases} \tag{12}$$

$$x_{ij} = 0 \text{ or } 1$$
$$i, j = 1, \ldots, m$$

where x_{ij} is a binary variable which indicates arc (i, j) is either in the path (1) or not (0), and c_{ij} is the travel time that the aircraft spends on link (i, j). To simplify this model at this stage we assume that the aircraft taxiing speed is constant on each taxiway link.

Procedures in Landing Simulation and Prediction

The landing simulation and prediction include following steps:

1. Airport environmental data input: these data include information on runway and taxiway network, the prevailing airport weather condition, and terminal locations.
2. Taxiing time weight factor determination: to calibrate wf_k, aircraft landing roll data should be collected and analyzed. Running the model for different values of taxiing time weight factor wf_k, and comparing the results with field data, we can find the best suitable taxiing time weight factor.
3. Aircraft landing simulation: two hundred and fifty landings are generated using a Monte Carlo sampling technique. The model generates random trajectories according to variations in the runway crossing height, flight path angle, landing weight factor, aircraft deceleration rate, and exit speed. Each landing follows the five landing phases described before.
4. Simulation results: by sorting the simulation results of each landing and recalculation, the model will provide the exit choice probabilities to each exit, runway occupancy times, and the shortest taxiway path.

APPLICATION

Operations at Washington National Airport have been studied to test the validity of this model. This airport has also been used to see the possible effect of terminal location on landing roll performance. Based on this application, sensitivity analysis has been done by changing the terminal location and the value of taxing time weight factor.

As mentioned before, the model could also be used in a ground traffic automatic control system. With real-time information such as the aircraft approach speed and the touchdown distance which could be provided by airport radar system or on board equipment, the model could serve as an advisory system to pilots and air traffic control personnel to automate the aircraft runway exit choice and find the shortest path to an assigned gate thus saving fuel and minimizing runway occupancy times. Model predictions with known approach speed (i.e., extracted from radar or differential GPS transmitters) could also reduce the standard deviation of runway occupancy times thus contributing to a better utilization of runway infrastructure.

1. Case Study

We used runway 36 at the Washington National Airport as an example to test the proposed model. The length of this runway is 2040 meters and the runway exit information is shown in Table 1.

Figure 5 shows the runways and related taxiway network at this airport. Landing events for USAir Boeing 737-300 aircraft are predicted and compared with field observations collected at the airport. The selection of one airline and one aircraft model is made to narrow the scope of the possible correlation of parameters in the model.

TABLE 1 Runway 36 Exit Information

Exit Name	Exit Type	Location From Threshold (m)	Exit Speed (m/s)
G	Pseudo 90 Deg.	950	10
H	Pseudo 45 Deg.	1025	15
I	45 Deg.	1325	15
RWY	Pseudo 30 Deg.	1470	18
J	90 Deg.	2040	10

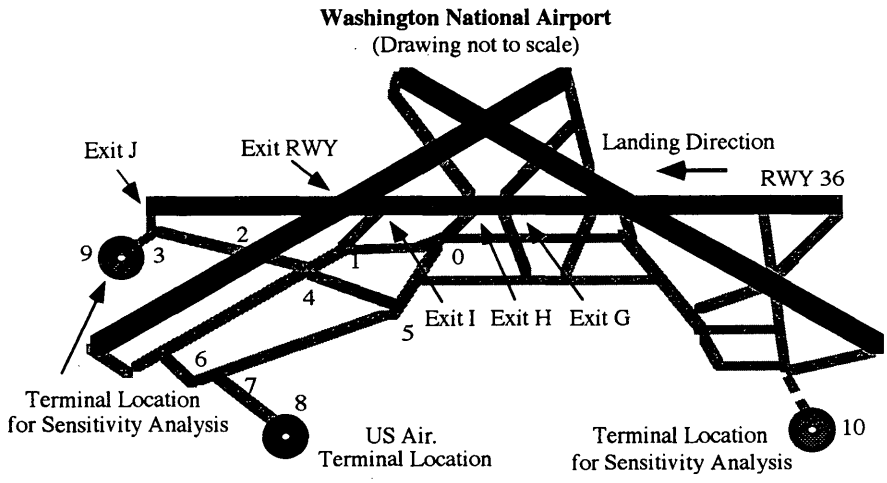

FIGURE 5 The ground network of Washington National Airport.

The USAir terminal is also particularly suitable in this analysis because its location is near the end of runway 36.

Preliminary analysis of 36 observed Boeing 737-300 landings found that the most suitable taxiing time weight factor for this aircraft/runway combination to be 0.4. Figure 6 shows the exit choice predictions and the observed exit choice distribution. Figure 7 shows the runway occupancy time prediction and the observed values. Note that in both cases there is good agreement between predicted and observed values.

The model prediction is sensitive to the airline terminal location. Hypothesizing different terminal locations (indicated as nodes 9 and 10 in Figure 5) and using the same taxiing time weight factor (0.4), we have the different predictive results. Figure 8 shows the exit choice predictions for three different terminal locations.

It is obvious that the taxiing time weight factor has no influence on the landing predictions when the terminal location is at Node 10. This is because minimizing the aircraft runway occupancy time will minimize the aircraft taxiing time automatically in the exit choice model. In this case the difference is attributed to changes in the landing motivation factor. Landing aircraft use more aggressive deceleration behavior in the braking phase.

The model predictions are also sensitive to the value of taxiing time weight factor. Figure 9 shows the exit choice predictions under different taxiing time weight factor values (with the terminal loca-

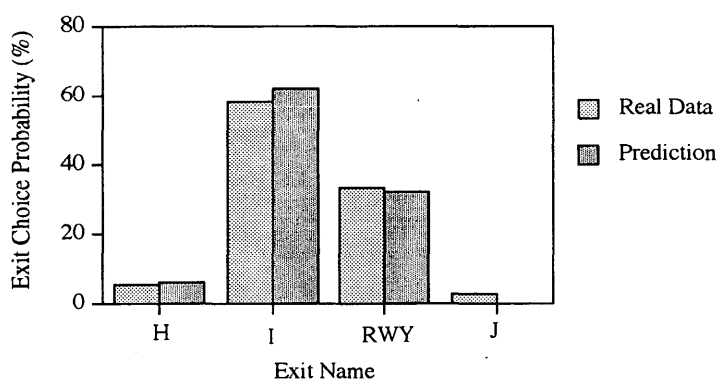

FIGURE 6 Exit choice observation and prediction.

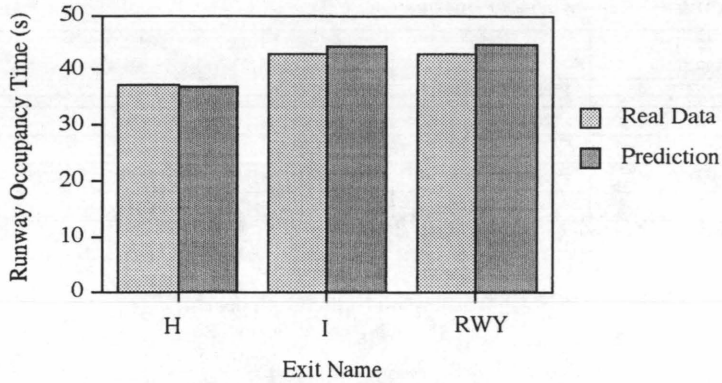

FIGURE 7 Runway occupancy times observations and predictions.

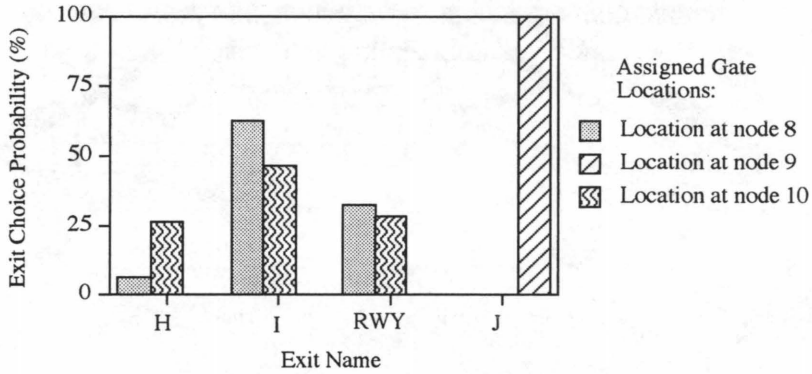

FIGURE 8 Influence of terminal location on exit choice probability.

tion at Node 8). We can see that the landing aircraft will have a tendency to take the exits closer to the terminal when the taxiing time weight factor is increased. This is representative of motivated pilots who are willing to trade off some runway occupancy time (*ROT*) for taxiing time. This fact, when taken to an extreme, could affect the runway acceptance rate due to longer *ROT* values.

2. Prediction With Real-Time Data

With real-time data updates this model could provide more accurate predictions. Automated updates could come in the form of aircraft state variable information extracted from aircraft surveillance radar data or information download from on-board navigation equipment and differential position sensors on the ground. Figure 10 shows the expected landing distribution for Boeing 737-300 aircraft with no real-time update data. Figure 11 shows the landing distribution with known approach speeds (55 m/sec) and touchdown point location (450 m). We can see from these two figures that with more information the aircraft landing behavior tends to be more predictable and the resultant dispersion of runway occupancy times could result in slightly higher runway acceptance rates. This could prove to be useful if in-trail separations under Instrument Meteorological Conditions (IMC) are reduced further from current values as the mag-

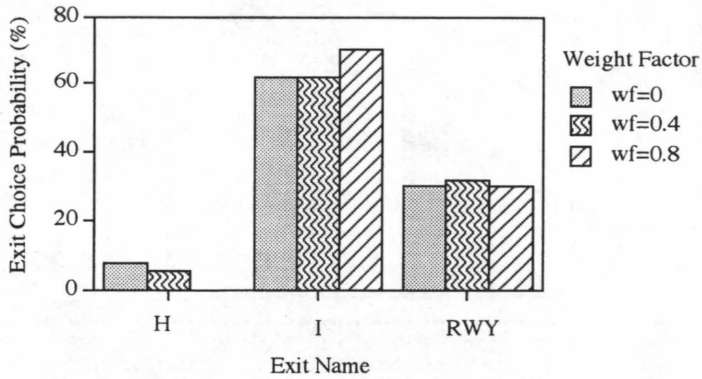

FIGURE 9 Influence of taxiing weight factor.

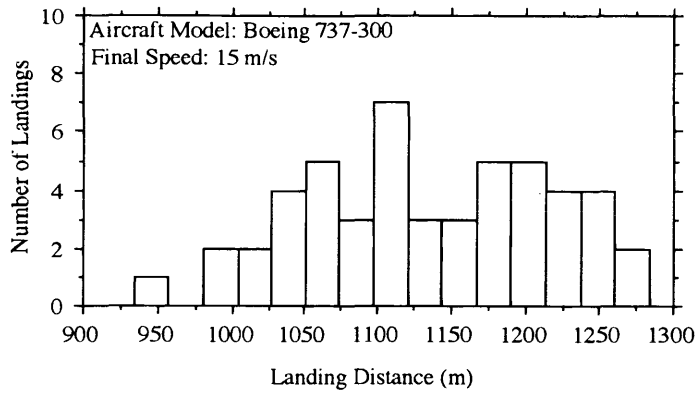

FIGURE 10 Landing distributions with no real-time update data.

nitude of runway occupancy times will be closer to in-trail separation. Also, under current Visual Meteorological Conditions (VMC) with heavy banks of flights, a reduction in the mean and standard deviation of *ROT* could enhance the safety of operations by increasing the gaps between successive arrivals.

CONCLUSIONS AND FURTHER RESEARCH

The preliminary results presented in this study indicate that the model described provides a more realistic way to analyze landing aircraft behaviors in complete airport ground networks. The use of individual aircraft parameters and a calibrated model using observed landing data made the analysis more accurate. The most important improvement in this model is the consideration of terminal location influence on landing behavior. This consideration makes it possible to explain the aircraft landing roll phenomena consistent with a particular ground network with more accuracy.

Providing landing predictions to the pilot and air traffic controller in the ground traffic control system, the model could help to solve ground network traffic congestion problems and enhance operational safety. The model results could also be used in the runway exit location problem to increase runway capacity.

Further studies are needed to improve the model prediction capability, including the influence of traffic density on aircraft landing behavior, the determination of landing motivation factor for a multitude of airport/aircraft combinations, and their associated taxiing time weight factors. Also, the development of a time dependent traffic assignment algorithm would help in the predictions for an advanced ground control ATC system.

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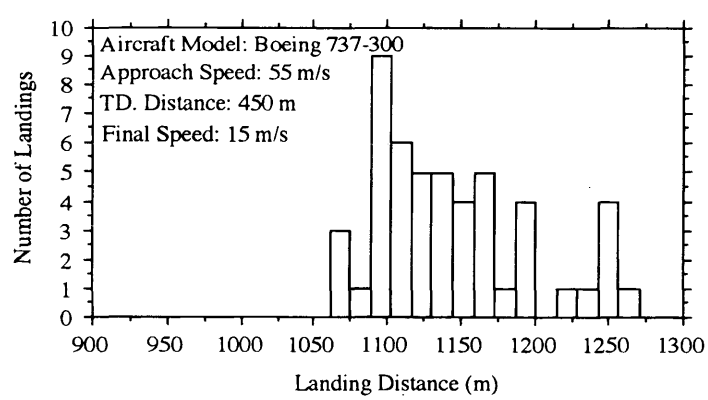

FIGURE 11 Landing distributions with known approach speed and touchdown distance.

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