

# Computer Simulation Model for Airplane Landing-Performance Prediction

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A simple computer simulation model that predicts airplane landing performance on runways to locate high-speed exits is presented. A Monte Carlo simulation algorithm and empirical heuristics derived from field observations were used to estimate landing-roll trajectories that can be programmed quickly in a personal computer. The modeling process demonstrates statistically the validity of treating landing-roll profiles of various airplane models individually to locate high-speed exits. The model developed can be applied to a variety of airports and airplane types and is offered as an alternative to conventional methods for locating high-speed exits as well as a complement to more rigorous optimization methods.

Runway occupancy time (ROT) is the time interval from the instant an airplane crosses a runway threshold to the instant it clears the runway completely; it has been identified as one of the critical factors affecting runway capacity. Studies of methods for increasing runway capacity by reducing ROT have been conducted by airport designers and engineers during the last several decades (1–6). The primary drawback of all previous models has been that airplanes can be classified into groups that do not account for all differences in performance characteristics (1–5). For example, Koenig (4) concentrated only on ROT data to identify factors affecting ROT and its potential reduction. Weiss and Barrer (2) also concentrated on ROT data and exit utilization. Ruhl (3) conducted a study on the airplane landing process by measuring approach speed, threshold crossing height, touchdown location, average braking deceleration, and other factors at four airports using video recording equipment.

Various models and their solution algorithms for locating exits optimally have also been developed by Horonjeff et al. (1), Daelenbach (7), Joline (8), Sherali et al. (9), and Trani et al. (6). A computer simulation model that can be employed to estimate the location of high-speed runway exits using simple numerical approximations to describe the landing-roll profile of various individual airplane models is described here. The computer model can be viewed as a method for preparing input data for more complex optimization models used to locate runway exits.

## AIRCRAFT LANDING MODEL

The landing process is broken down into five phases: flare, first free roll, braking, second free roll, and turnoff. This process has been described in detail by Trani et al. (10,11). The flare phase accounts for an airplane's maneuver from the runway threshold to the touch-

down point. The braking phase determines the ground deceleration distance, and the turnoff phase calculates the distance and time taken by the airplane to execute the turning maneuver, starting with the turnoff procedure and terminating at the runway clearance point. An airplane has cleared the runway when no portion of its wing or horizontal tailplane remains inside the runway boundary. The two free-roll phases account for gaps between the different airplane maneuvers.

## AIRFIELD OBSERVATIONS

A number of airplane landing operations from threshold crossing to clearance of runway were recorded using video equipment from the control towers of selected airports, including Washington National Airport (DCA), Charlotte Douglas International Airport (CLT), and Atlanta Hartsfield International Airport (ATL). Runway 36 of DCA, Runway 23 of CLT, and Runway 8L of ATL, the lengths of which are 2094 m (6,869 ft), 2286 m (7,500 ft), and 2742 m (9,000 ft), respectively, were exclusively used for arrivals at the times of recording. All operations occurred under visual meteorological conditions. Frame counter codes were later embedded on the video tapes to streamline the data acquisition procedures. From these tapes, velocity profiles of the landing roll were extracted for each airplane using the following steps.

1. Identify suitable reference points the positions of which are known on the active runway. Two adjacent reference points make an interval;
2. Record the frame counter code when an airplane nose passes a reference point, when the airplane is at touchdown, and at the clearance of runway. These data are used to find touchdown location and ROT;
3. Find an average interval speed by dividing the interval length by the interval time. The interval passing time is the difference between frame counter codes of two neighboring reference points; and
4. Connect the average interval speed to produce an approximated velocity profile for a landing operation. By overlapping the individual velocity profiles for a particular airplane type, a velocity profile band for that type for a certain runway can be generated.

For the accuracy and convenience of data reduction, an interface data collection and analysis software was developed that made possible the transfer of the frame counter code from the video tape player to an Apple Macintosh IIfx personal computer. The same program also performed computational tasks to generate velocity profiles, extract touchdown location points, and compute exit use and ROT. The estimation of the velocity profile feature was particularly

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useful for minimizing operator-induced errors because the resulting velocity profile of data points previously entered in the computer could be easily reviewed.

Figure 1 presents a typical velocity-distance profile of a Boeing B-727 landing on CLT Runway 23 and illustrates how the key data were extracted from the velocity profile. The touchdown speed ( $V_{td}$ ) was approximated as the speed at the main-gear touchdown location. Similarly, flare speed was estimated as the average speed during the air portion of the airplane trajectory from the threshold crossing point to the touchdown point. A braking initiation point was detected by either a sudden drop of speed in the velocity profile or the actual recording of thrust-reverse and spoiler activation. The threshold value of deceleration rate for braking detection was set to  $0.91 \text{ m/sec}^2$  ( $3 \text{ ft/sec}^2$ ) to distinguish the braking from the free-roll phase in which the airplane decelerates at about  $0.70 \text{ m/sec}^2$  ( $2.4 \text{ ft/sec}^2$ ). The final speed for landing distance computation was set to  $30 \text{ m/sec}$  ( $98 \text{ ft/sec}$ ) for transport airplanes, because developing a predictive model to estimate optimal location of high-speed runway exits was the study's goal. Table 1 provides the basic statistics of the key variables determining the landing distance. Among the key variables measured are the flare speed, the touchdown location, and the braking deceleration rate. Sample means of the key variables are plotted in Figure 2. The touchdown location plot in Figure 2(b) shows a clear tendency to increase touchdown distance at ATL over DCA. One explanation is that on long runways pilots perform smoother flare maneuvers and, consequently, add more distance to their landing rolls to reduce the sink-rate speed at touchdown. The runway length effects are quantified subsequently.

Figure 2(c) shows that the overall average deceleration rates are highest at DCA, second highest at ATL, and lowest at CLT. This is true for three out of five airplane types. Possible explanations for these variations are runway grades, differences in flare speeds, and runway lengths. Deceleration rate decreases by  $0.01 \text{ m/sec}^2$  ( $0.033 \text{ ft/sec}^2$ ) per 0.1 percent grade change. The grades of the runways at DCA, CLT, and ATL airports are 0 percent,  $-0.5$  percent, and  $-0.3$

percent, respectively. Therefore, the deceleration rates observed at CLT and ATL can be transformed to the equivalent rates on a level runway by adding  $0.05$  and  $0.03 \text{ m/sec}^2$  ( $0.16$  and  $0.098 \text{ ft/sec}^2$ ) to the observed values, respectively. Whether the deceleration rate is related to the flare speed, the available runway for braking, or both, however, remains to be determined. Quantitative analysis on the relationship between the deceleration rate and both the flare speed and the distance of the available runway—which is defined as a portion of runway from the touchdown location to the end of the runway—is conducted in a subsequent section.

To statistically test airplane type differences and airport differences among the three key variables, the two-way analysis of variance (ANOVA) with unequal sample sizes was performed, setting the airplane type and the airport as main factors. The test results are presented in Table 2. The  $F$ -statistics were computed based on Type III sum of squares, as recommended for unequal-sample-size cases by Neter et al. (12) and the Statistical Analysis System Institute (13). It can be concluded that the interaction effects are weak or negligible and the main effects are significant. This implies that the landing performance prediction conducted for each airplane type should consider the variation caused by the airport. Because many uncontrollable factors such as landing weight factor, flap angle, and so forth are involved in the airplane landing operation, precise explanations for the test results are difficult. Among the distinguishable factors that can make the airport effects significant are the airfield elevation, the runway length, and the runway grade. For the parameter estimation in the following section, the airport effects are quantified on the basis of the distinguishable factors, assuming that the other uncontrollable factors are identical throughout the airports.

## SIMULATION MODEL

The purpose of the simulation model is to generate the probabilistic distribution of landing-roll distances for the airplane mix to decel-

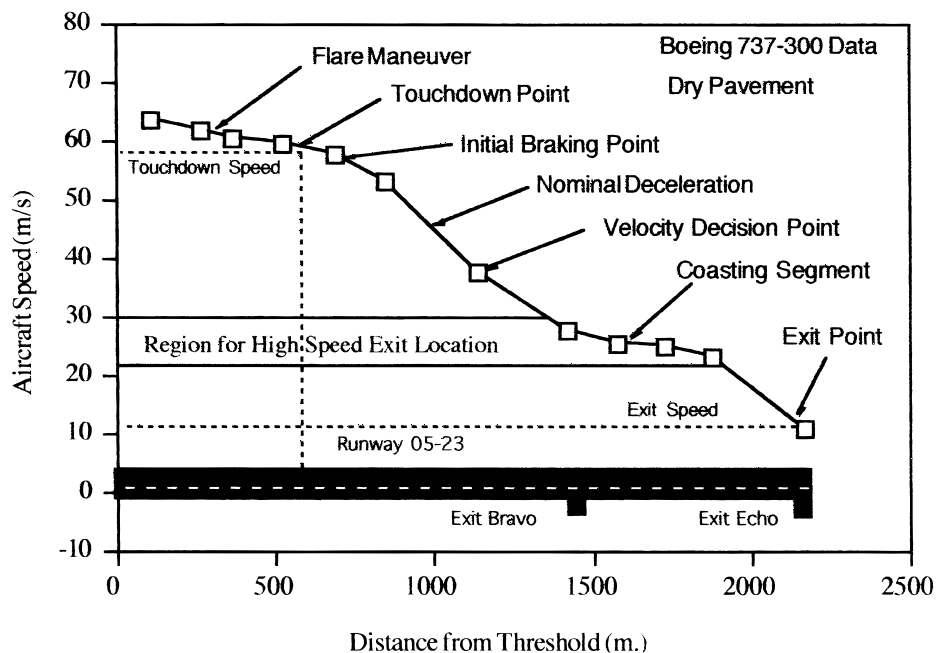


FIGURE 1 Sample airplane velocity profile showing landing-roll phases.

TABLE 1 Summary Airplane Landing-Roll Statistics Collected at Three Airports

Airport	A/C Type	No. of Obs.	Flare Speed (m/s)		Touchdown Location (m.)		Average Deceleration (m/s <sup>2</sup> )		Landing Distance <sup>a</sup> to reach 30 m/s (m)	
			Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
DCA	B-727	72	66.62	3.03	455	132.1	2.26	0.382	1223	167.9
	B-737	36	65.77	3.99	399.2	80	2.3	0.422	1118	96.5
	B-757	26	65.30	5.78	424.9	97.7	2.14	0.675	1131	125.8
	DC-9	36	65.02	3.54	434.9	105.8	2.08	0.397	1183	158.5
	MD-80	51	68.29	4.51	424.3	94.1	2.14	0.428	1255	169.1
CLT	B-727	13	68.18	3.16	546.9	169.8	1.83	0.511	1733	193.7
	B-737	34	66.08	3.57	400.0	77.4	2.21	0.573	1336	257.5
	B-757	4	61.55	2.11	489.6	139.7	1.62	0.231	1490	291.6
	DC-9	8	67.34	3.46	425.2	79.6	2.08	0.56	1483	285.6
	MD-80	7	66.6	2.55	550.6	188.3	1.81	0.381	1698	239.5
ATL	B-727	13	70.87	3.87	621.7	164.2	2.11	0.423	1674	166.4
	B-737	12	68.74	4.34	603.3	75.9	2.08	0.497	1563	237.1
	B-757	10	65.28	5.29	699.9	115.4	1.79	0.337	1670	190.5
	DC-9	13	68.85	3.9	594	137.9	1.83	0.341	1690	197.1
	MD-80	28	68.57	4.97	569.7	124.6	1.9	0.302	1625	250.6

a. Landing distance required to decelerate to 30 m/s.

erate to a predefined, designed exit speed. The simulation model is formulated according to the breakdown scheme of the landing process previously presented.

### Flare Phase

The flare distance is defined as the distance from the runway threshold point to the touchdown point and may be estimated on the basis of the following equation from Lan and Roskam (14) and modified for the described study:

$$S_{\text{air}} = \frac{H_T}{\gamma} + \frac{(V_{fl})^2 \gamma}{2g(n_f - 1)} + \delta(RL) \quad (1)$$

where

- $V_{fl}$  = landing flare speed (usually taken as 95 percent of the threshold crossing airspeed),
- $\gamma$  = effective descent flight path angle (i.e., 3 degrees for normal approach operations),
- $n_f$  = flare load factor,
- $H_T$  = height above the threshold,
- $RL$  = runway length, and
- $\delta$  = correction factor for the touchdown distance caused by runway length.

The first term of Equation 1 accounts for the linear descending distance from the runway threshold to the touchdown aiming point.

The second term accounts for a circular-arc flare maneuver distance to transition to a touchdown attitude with a minimum sink rate. If the flare distance ( $S_{\text{air}}$ ) is known, the flare time ( $t_{\text{air}}$ ) can be obtained by simply dividing the flare distance by  $V_{fl}$ .

$V_{fl}$  is closely related to the stalling speed because pilots try to maintain a conservative margin above the stalling speed of the aircraft in the landing configuration. The flare speed can be approximated at about 1.25 times the stalling speed ( $V_{\text{stall}}$ ) or 95 percent of the approach speed at the runway threshold. The stalling speed, with a near maximum landing weight at sea level altitude, may be found in the literature (15). The variation induced by changing atmospheric conditions can be calculated from Equation 2:

$$V_{\text{stall}} = \sqrt{\frac{2mg}{\rho CL_{\text{max}} S}} \quad (2)$$

where

- $V_{\text{stall}}$  = stalling speed (m/sec),
- $m$  = aircraft mass (kg),
- $g$  = acceleration of gravity,
- $\rho$  = air density (kg/m<sup>3</sup>) at known airport conditions (i.e., temperature and altitude),
- $CL_{\text{max}}$  = maximum lift coefficient developed by the aircraft (a nondimensional aerodynamic factor), and
- $S$  = aircraft gross wing area (m<sup>2</sup>).

The flare speed is usually 95 percent of the approach speed or 1.24 times the stalling speed. The observed ratio of  $V_{\text{flare}}$  and  $V_{\text{stall}}$  was

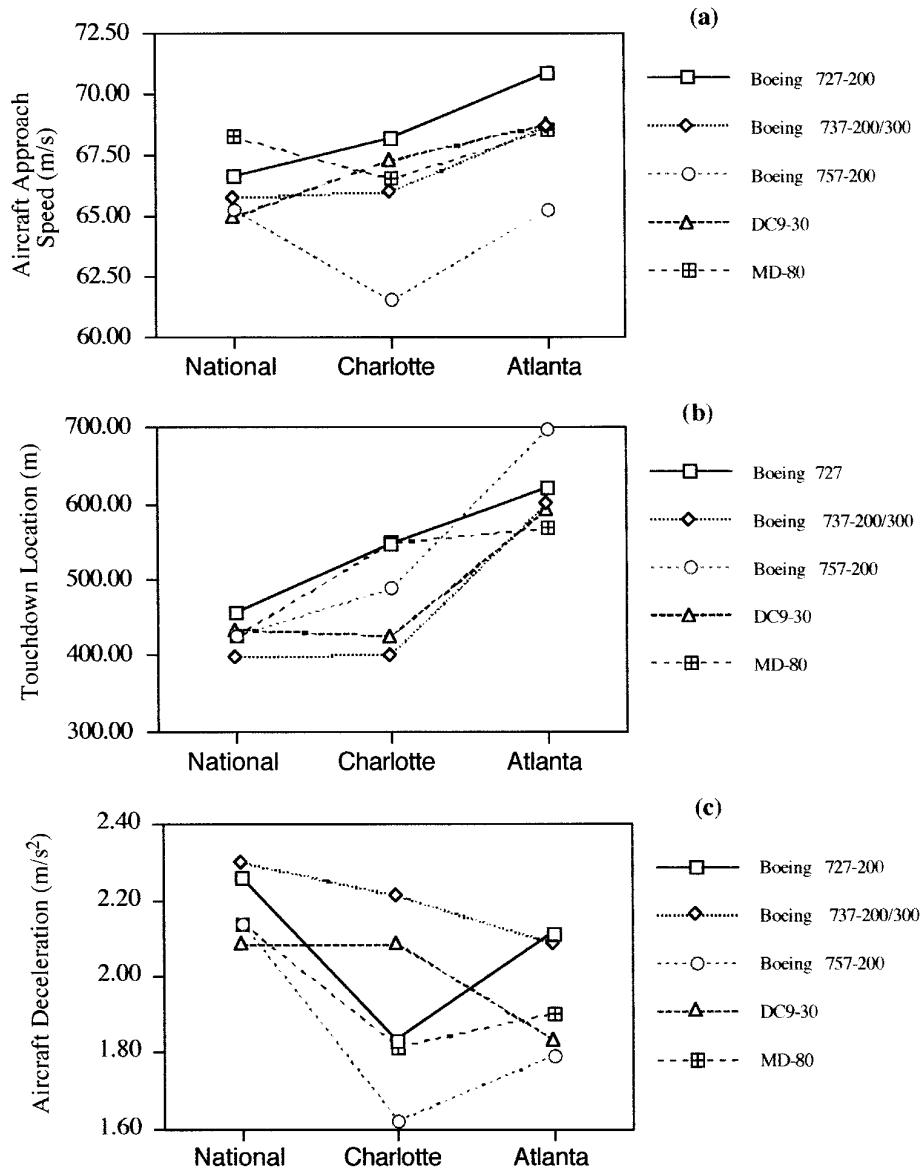


FIGURE 2 Mean-value plots at three airports.

close to 1.24 for all Boeing aircraft, which is a good multiplier to convert the stalling speed to flare speeds. However, it is unclear why this ratio was somewhat higher (1.29) for Douglas aircraft (i.e., DC-9s and MD-80s).

According to FAA regulations  $H_T$  is 15.2 m (50 ft) (16). Even though it is not possible to measure this parameter with the data collection method used, no reason was found to alter the  $H_T$  stipulated by the regulations. Moreover, empirical data indicate that  $H_T$  has an average value of 15 m with a standard deviation of 3 m. Instrument landing systems are usually calibrated for flight path angles ranging from 2.5 to 3 degrees. Therefore, the mean and the standard deviation of the angle approach and the flight path angle are assumed to be 2.75 and 0.08 degrees, respectively. Recommended values for  $n_f$  range from 1.1 to 1.3 (14). Considering the field observations on the touchdown location, 1.1 seems a reasonable value for  $n_f$ .

The touchdown location distances in Fig. 2 increase with runway length. Equation 1 accounts for the effects of runway length. To quantify these effects, the minimum, maximum, and mean values of

the touchdown locations for all airplane types at each airport were plotted. The runway length effects are near linear when the runway length varies from 2100 to 2800 m (6,890 to 9,186 ft). It can be assumed that the marginal effects diminish when the runway length is long enough (more than 2800 m) and no strong pilot motivational practices are present. A heuristic rule is added to the model, using the third term in Equation 1, whereby the touchdown location is affected by the runway length available beyond a minimum needed for each airplane type. From the observed data it was found that touchdown locations shift downrange at the rate of 25 m (82 ft) for every 100 m (328 ft) of runway length (beyond 2100 m) for runways ranging from 2100 to 2800 m in length. The rule is truncated at the low and high end points because further analysis is needed to demonstrate the linearity of the relation for very long runways.

The analysis shows that airplanes usually decelerate moderately in the flare phase because of low thrust and high aerodynamic drag conditions. This results in touchdown speeds slightly lower than the flare speed previously estimated. The data collected suggest that the

TABLE 2 Summary of ANOVA Procedures

Variable	Factor	F-statistics	F-criteria <sup>a</sup>	p-value	Conclusion <sup>b</sup>
Flare Speed (m/s)	A/C Type	5.44	2.37	0.0003	H <sub>1</sub>
	Airport	8.59	3.00	0.0002	H <sub>1</sub>
	Interaction	2.00	1.94	0.0461	Marginal
T. D. Location (m)	A/C Type	3.95	2.37	0.0038	H <sub>1</sub>
	Airport	69.09	3.00	0.0001	H <sub>1</sub>
	Interaction	2.36	1.94	0.0173	H <sub>1</sub>
Braking Dec. (m/s <sup>2</sup> )	A/C Type	3.64	2.37	0.0064	H <sub>1</sub>
	Airport	11.36	3.00	0.0001	H <sub>1</sub>
	Interaction	1.10	1.94	0.3617	H <sub>0</sub>

a. F-criteria is set for 5% significance level

b. H<sub>0</sub>: the factor does not affect the variable in question (H<sub>1</sub>: not H<sub>0</sub>)

average touchdown speed is about 95 percent [or 3.2 m/sec (10.5 ft/sec) less for the transport aircraft surveyed] of the flare speed on average with a standard deviation of 2.4 m/sec (7.9 ft/sec). No statistical evidence was found for the correlation between the touchdown location and the speed loss in the flare phase.

**First Free-Roll Phase**

The first free-roll phase accounts for a relatively small portion of the landing operation and is assumed to be deterministic to make the model simpler. The average free-roll time and deceleration rate are found to be 2.3 sec and 0.70 mg/sec<sup>2</sup>, respectively.

**Braking Phase**

The braking distance, which is defined as the distance required for an aircraft to decelerate to a specified terminal speed  $V_{ter}$  from an initial speed  $V_{ini}$  is estimated on the basis of the simple kinematic relationship in Equation 3. In the analysis of high-speed runway turnoff

a nominal terminal speed of 30 m/sec was used. Braking distance is calculated as follows:

$$S_{br} = \frac{(V_{ini}^2 - V_{ter}^2)}{2dec} \tag{3}$$

where

- $S_{br}$  = braking distance,
- $V_{ter}$  = terminal speed of the braking phase,
- $V_{ini}$  = initial speed of braking speed, and
- $dec$  = is an average ground deceleration rate.

Values for  $\overline{dec}$  were estimated from the field data and are provided in Table 1.

The deceleration rate plays a major role in computing the braking distance and can be estimated using an averaging method for each airplane analyzed. For more accurate estimation, it is important to determine the deceleration rate correlated to the available runway length, the flare speed, or both. To make this determination, x-y scatter plots of the deceleration rate versus landing-roll ratio were made in Figure 3, and regression analyses were performed for each air-

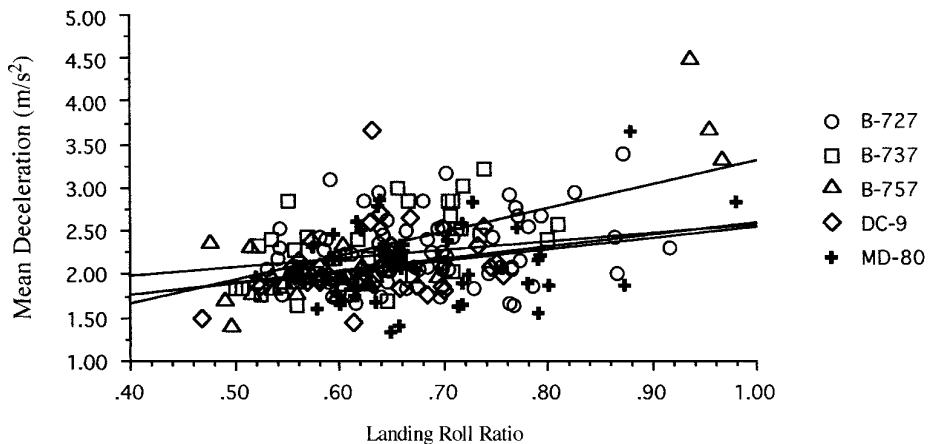


FIGURE 3 Scatter plots of landing-roll ratio versus deceleration.

plane type as summarized in Table 3. The landing roll ratio  $l_{rr}$  is defined as the ratio of the landing-roll distance used in the deceleration phase and the runway distance remaining once the airplane touches down. Statistical analysis indicated that  $l_{rr}$  was a feasible parameter for estimating deceleration rate. The rationale for using this nondimensional parameter was to correlate situations wherein pilots would be willing to brake hard on short runways.

The mean values of deceleration rate in Table 3 indicate that pilots, in consideration of passenger comfort, decelerate well below the maximum braking capability of the modern airplane, which is about  $5 \text{ m/sec}^2$  ( $16.4 \text{ ft/sec}^2$ ) (14). Within a reduced sample population of 363 transport airplanes analyzed, there was only one landing in which the deceleration rate was close to the upper limit. The regression equations are meaningful because they reflect the changes of pilot braking maneuvers according to situation. The  $R^2$  values turned out to be low, indicating that dispersions around the regression line are large. Nonlinear regressions using second- and third-order polynomials were tried with no improvement in the correlation results.

**SIMULATION MODEL BUILDING**

On the basis of observations and quantitative analyses, a Monte Carlo simulation model was developed to predict the landing distance necessary to decelerate to 30 m/sec, to account for the differences resulting from airplane type and airport. The logic of the model is depicted in Fig. 4. The random variables included in the model are  $V_n$ ,  $\gamma$ ,  $H_T$  and  $dec$ . The stalling speed for each airplane type is calculated using Equation 2 and considering the airport elevation effects. The standard deviation of the flare speed is set to 6 percent of the mean, as suggested by the observations. The mean and the standard deviation of the final approach flight path angle are set to 2.75 and 0.08 degrees, respectively. The mean and the standard deviation of the threshold crossing height are set to 15 and 3 m (49 and 9.8 ft), respectively. The flare load factor in Equation 1 is assumed to be constant and set to 1.1. Normal distributions truncated at  $\pm 3$  standard deviations about mean are used for all the random variables. The inverse transformation method is used for normally distributed random number generation using the polynomial approximation of the normal cumulative density function developed by Beasley and Springer (17). Random number generation from truncated distributions is found in Law and

Kelton (18). The touchdown speed is computed considering the flare speed and the in-air speed loss of 3.2 m/sec (10.5 ft/sec).  $V_{ini}$  has been observed to be 2.07 m/sec (6.8 ft/sec) lower than the touchdown speed for most transport aircraft. The touchdown speed ( $V_{td}$ ) and the initial  $V_{ini}$  are also random variables in the model calculated by subtracting constant values from  $V_n$ , which is a random variable in the model calculated as the product of  $V_{stall}$  and a multiplier determined empirically from the observations. Mathematically,  $V_{td}$  and  $V_{ini}$  are calculated as follows:

$$V_{td} = V_n - k_1 \tag{4}$$

$$V_{ini} = V_{td} - k_2 \tag{5}$$

where  $k_1$  and  $k_2$  are empirical constants that were found to be 3.20 and 2.07 mg/sec, respectively.

These values have been obtained from empirical data and apply to small, medium, and heavy transport airplanes (6).

The free-roll phase is deterministically accounted for by a duration  $t_{fr1}$  of 2.3 seconds and by an average deceleration  $a_{fr1}$  of  $0.70 \text{ m/s}^2$ :

$$S_{fr1} = V_{ini}(t_{fr1}) - \frac{1}{2} a_{fr1}(t_{fr1})^2 \tag{6}$$

The terminal speed for the braking phase is set to 30 m/sec because the purpose of the model is to locate high-speed runway exits. The mean deceleration rate is estimated using the regression equations in Table 3, and the standard deviation is set to 6 percent of the mean value for all airplane types according to the empirical observations. The estimation of mean deceleration requires the estimation of  $l_{rr}$ . For a given  $RL$  and the previously defined  $S_{br}$  (Equation 3), the landing roll ratio is calculated as follows:

$$l_{rr} = \frac{S_{br}}{RL - S_{fr1} - S_{air}} \tag{7}$$

from which a new  $dec$  is calculated using the regression equations in Table 3. The adjusted braking distance is  $S_{br[adj]}$  and the total distance to 30 m/sec  $S_{total}$  is then as follows:

$$S_{br[adj]} = \frac{(V_{ini}^2 - V_{ter}^2)}{2(dec)} \tag{8}$$

**TABLE 3 Regression Analysis Results**

Aircraft Type	Regression Equation	R <sup>2</sup>	Mean ( <i>dec</i> ) (m/s <sup>2</sup> )	Std. Dev. (m/s <sup>2</sup> )
B-727	$dec = 1.604 + .967 (l_{rr}^a)$	0.18	2.19	0.416
B-737	$dec = .569 + 2.743 (l_{rr})$	0.36	2.25	0.471
B-757	$dec = -.442 + 4.159 (l_{rr})$	0.75	2.01	0.478
DC-9	$dec = 1.205 + 1.396 (l_{rr})$	0.15	2.03	0.414
MD-80	$dec = 1.233 + 1.323 (l_{rr})$	0.23	2.05	0.387
Other Transports	$dec = 1.453 + 1.124 (l_{rr})$	0.21	2.08	0.433

a. landing roll ratio (dimensionless)

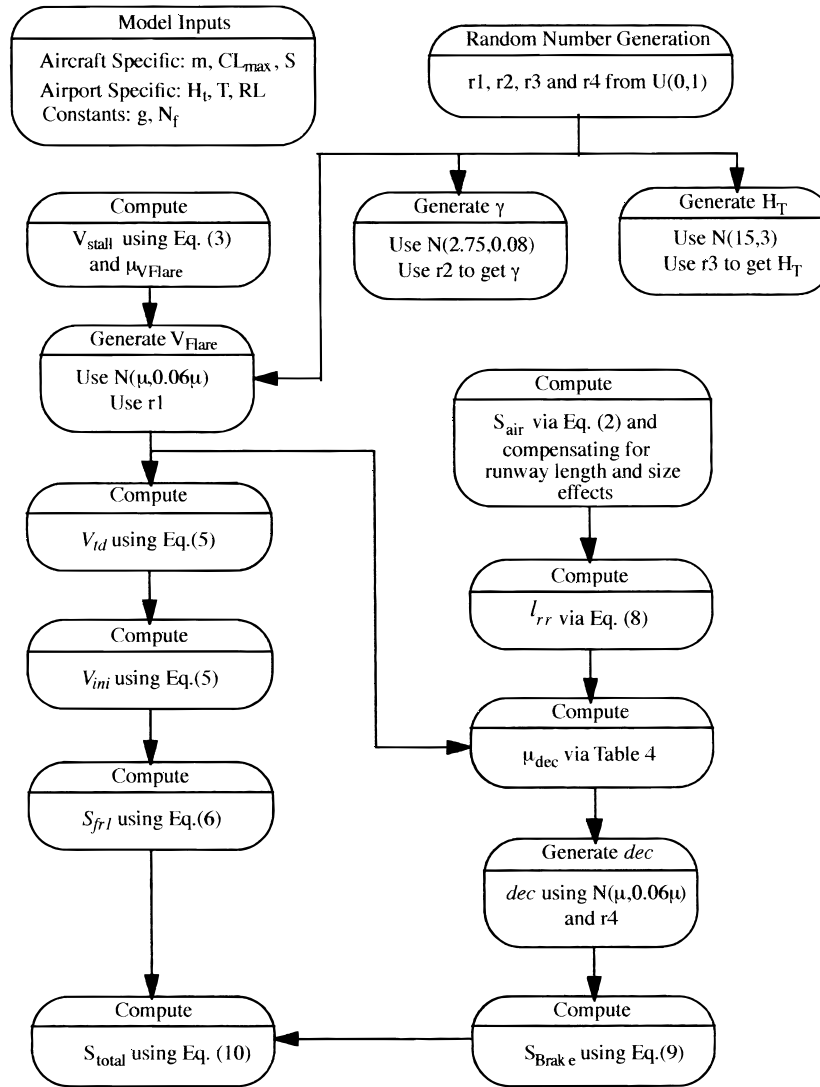


FIGURE 4 Flowchart of Monte Carlo computer simulation model.

$$S_{total} = S_{br|adj} + S_{air} + S_{fr1} + S_{fr2} \quad (9)$$

In this last expression a second free roll ( $S_{fr2}$ ) has been added to account for possible perception and identification of the high-speed runway exit. Typically, the value of  $S_{fr2}$  is just 1.5 sec multiplied by  $V_{ter}$ .

### MODEL CORRELATION

To investigate how well the simulation model predicts the airplane landing performance, the observed data and the model-generated data are compared for each airplane type. For every combination of airplane type and airport, 1,000 landings are generated using the proposed model. Mean, minimum, and maximum speed values are extracted from the computer-generated velocity profiles and overlaid on the observed data, as presented in Figure 5. The plots indicate that the model predicts the landing performance well for most airplane types at runways with more than three runway exits (i.e., DCA runway 36 and ATL runway 8L). The model underestimates

the landing distance for several airplane types at CLT. The discrepancies between the model and the field data observed at CLT airport can probably be attributed to the low number of exits present on runway 23. On this runway only two right-angle exits, placed at 1455 and 2170 m (4,774 and 7,119 ft) from the threshold, are available for transport-type airplanes. The pilots who were not able to use the first available exit employed light braking and seemed to deliberately maintain a high ground-roll speed to quickly reach the second exit. This produces low deceleration patterns, as can be seen in Figure 5(c). The second effect of the limited exit availability is the division of the velocity profiles into two groups, as shown in the same Figure. If more exits had been available, more evenly distributed velocity profiles would have been produced.

To statistically test whether the observed values and the predicted values are homogeneous, a chi-square test for the more than 25 observed combinations of airplane types and airports was conducted using the procedure described in Mood et al. (19) and Law and Kelton (18). The test results were mixed because some of the combinations of aircraft types and airports did not successfully prove that the predicted values and observed values are homogeneous. It was

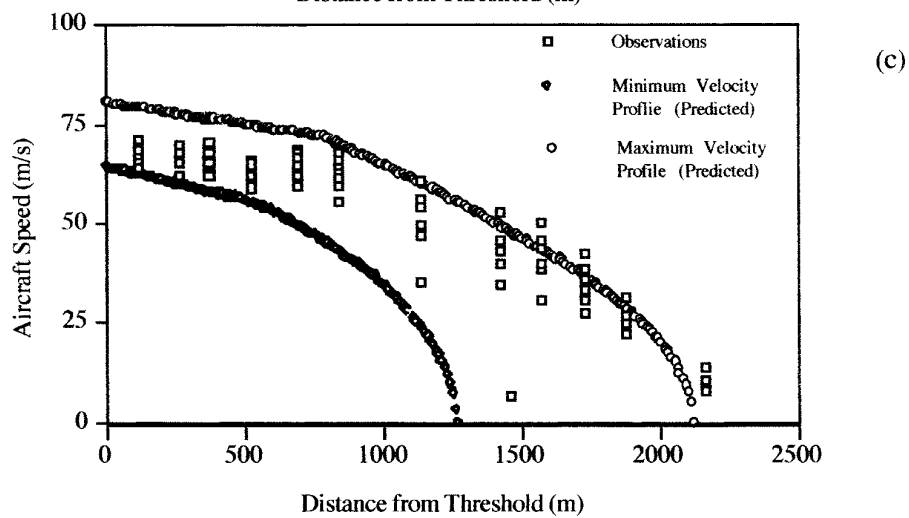
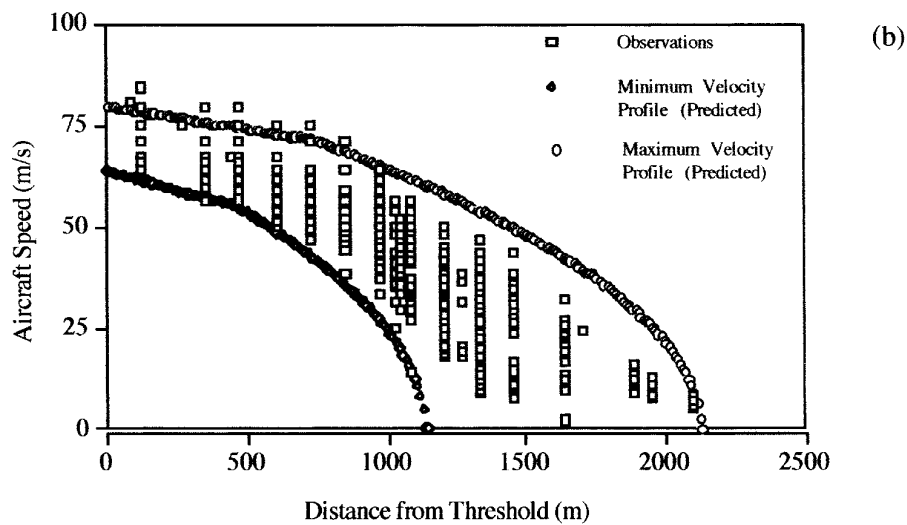
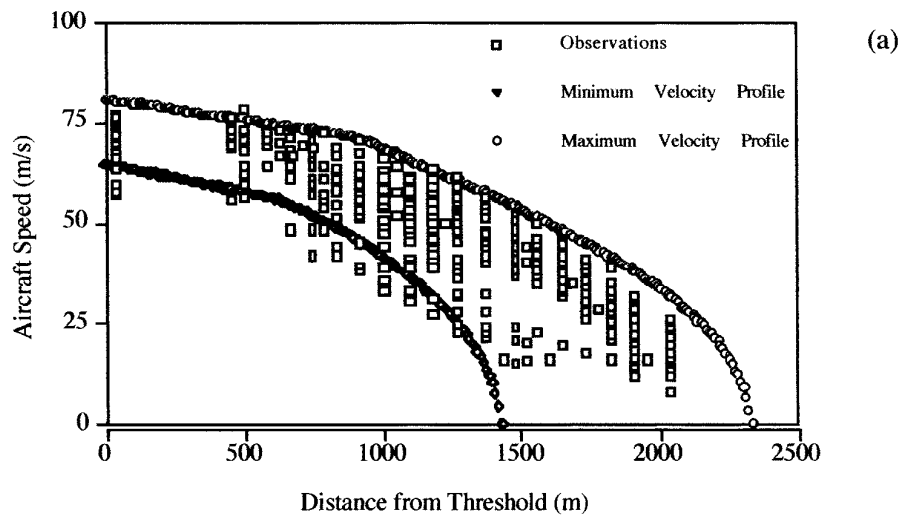


FIGURE 5 Predicted versus observed velocity profiles for the McDonnell Douglas MD-80 airplane at (a) ATL (b) DCA, and (c) CLT.

found that the model predicts the central value and the range of dispersion well but does not predict the skewness of the observed values if the number of exits is small, such as in the case of CLT Runway 23 [see Figure 5(c)]. The effect of the limited exit availability at CLT contributed to the multimodality observed for low values of speed (i.e., below 30 m/sec). In other words, the model produces the landing distances that are symmetric around the mean and predicts the central tendency and the degree of dispersion to some extent, whereas the observed values present the skewness and the multimodality in an unpredictable manner. A model proposed by Gu et al. (20) attempts to explain this multimodality using gate location as part of a heuristic motivation factor added to the landing-roll algorithm. This model however, incorporates an integer programming algorithm in the exit-choice assignment and as a result is computationally more complex. The model described in its present form seems to be applicable for quick landing performance prediction, especially in the design of high-speed runway exits on a runway where a decision about an exit location has not been made. This model is offered as an alternative to the traditional simplistic models used to locate high-speed exits at airports.

## SUMMARY

An empirical study was conducted on the landing performance of the transport-type airplane by analyzing the data collected from three different airports. Three key variables were computed from the obtained velocity profiles and analyzed quantitatively. The results of the study support the following principles regarding landing operation:

- The landing distance for a group of transport airplanes is probabilistic and its dispersion is quite large;
- The runway length has a strong influence on the touchdown location in transport operations;
- The deceleration rates observed in this study demonstrate that airplanes decelerate well below their maximum capabilities; and
- The deceleration rate has a weak correlation with the flare speed and the length of runway available for braking.

These principles have been quantified and incorporated into the simulation model proposed by Trani et al. (11). The modified model has reproduced velocity profiles close to the observed ones for airports with medium and high runway exit densities. The limited exit availability at one airport contributed to the underestimation of some profiles because a multimodal solution was present in the observed data. The model in its present form has the capability to predict behavior of individual airplane models for most transport models with reasonable results. Five individual airplanes analyzed (Boeing 727, Boeing 737, Boeing 757, Douglas DC-9, and McDonnell Douglas MD-80) constitute 86 percent of the transport airplane population currently operating in the United States. Therefore, the model offers a significant enhancement of the simple approximations used in the airport-planning literature to estimate high-speed runway exit locations and does not use more complex optimization methods. The model is easy to implement using a personal computer and could be further enhanced with additional field data.

## RECOMMENDATIONS

The results of this model should be tested under a wider range of airport conditions. Such tests should expand knowledge of airplane

runway operations and would increase confidence in the use of the model. The model could be easily expanded to cover more airplane types with more field data encompassing heavy transports, commuter, and general aviation airplanes. This model could also be used to generate simple approximations for runway occupancy time and optimal exit locations for a wide variety of runway scenarios. These results, in turn, could be made available to practitioners as part of standard airport-planning and design documents (e.g., additions to advisory circulars) to further facilitate their use.

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