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Estimation of Landing Stopping Distances From Flight Data

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16. Abstract

The need for improved capacity at airports to accommodate the rapid growth of air traffic has led to the investigation of operational landing performance as a safe and feasible means to increase the traffic flow. While the capacity issue becomes important, it is imperative that the increase in capacity does not let safety decline. A key task is to investigate the airplane landing performance to provide operations safety guidelines for reducing the risks of incidents and accidents associated with new technologies and procedures. For this, a clear knowledge of the day-to-day landing operations is required.

The objective of the present study was to derive and analyze methods for calculating the full-stop landing distance from flight operational data. In total, eight methods have been defined to calculate the ground distance from actual landing data. All these variants have been implemented in the processing software. After reprocessing all available cases, the statistical properties and possible correlations of each variant were investigated and presented. Based on these results, it was concluded that ground stopping distances obtained with the maximum instantaneous deceleration approach may be considered as the most useful or realistic candidate to serve as an indicator for the actual airplane landing performance.

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LIST OF ACRONYMS

ATSI   Air Transport Safety Institute
FAA   Federal Aviation Administration
LDA   Landing distance available
NLR   National Aerospace Laboratory

EXECUTIVE SUMMARY

The need for improved capacity at airports to accommodate the rapid growth of air traffic has led to the investigation of operational landing performance as a safe and feasible means to increase the traffic flow. While the capacity issue becomes important, it is imperative that the increase in capacity does not let safety decline. A key task is to investigate the airplane landing performance to provide operations safety guidelines for reducing the risks of incidents and accidents associated with new technologies and procedures. For this, a clear knowledge of the day-to-day landing operations is required.

The National Aerospace Laboratory Air Transport Safety Institute was commissioned by the Dutch Civil Aviation Authority and the Federal Aviation Administration William J. Hughes Technical Center to conduct an analysis of day-to-day landing operations using in-flight recorded data. In the first phase of the project, flight data for two different narrow-body, turbofan-engine airplanes, the B-737-400 and the A319/A320/A321, under various weather conditions, were collected and analyzed. Empirical distributions of a number of landing distance parameters, such as the approach speed at threshold, the touchdown point, and rollout distance, were derived. The present study's objective was to derive and analyze methods for calculating the full-stop landing distance from flight operational data.

In total, eight methods were defined to calculate the ground distance from actual landing data. All the variants were implemented in the processing software. After reprocessing all available cases, the statistical properties and possible correlations of each variant were investigated and presented. Based on these results, it was concluded that ground stopping distances obtained with the maximum instantaneous deceleration approach may be considered as the most useful or realistic candidate to serve as an indicator for the actual airplane landing performance.

1. INTRODUCTION.

1.1 BACKGROUND.

The need for improved capacity at airports in order to accommodate the rapid growth of air traffic has led to the investigation of operational landing performance as a safe and feasible means to increase the traffic flow. While the capacity issue becomes important, it is imperative that the increase in capacity does not let safety decline. The introduction of new technology and procedures for improving airport capacity must be integrated into the existing infrastructure so that maximum benefits for safety and efficiency are realized. A key task is to investigate the airplane landing performance to provide operations safety guidelines for reducing the risks of incidents and accidents associated with new technologies and procedures. For this, a clear knowledge of the day-to-day landing operations is required.

The National Aerospace Laboratory (NLR) Air Transport Safety Institute (ATSI) was commissioned by the Dutch Civil Aviation Authority and the Federal Aviation Administration (FAA) William J. Hughes Technical Center to conduct an analysis of day-to-day landing operations using in-flight recorded data. In the first phase of the project, operational flight data for two different narrow-body, turbofan-engine airplanes, the B-737-400 and the A319/A320/A321, under various weather conditions, were collected and analyzed [1 and 2]. Empirical distributions of a number of landing distance parameters, such as the approach speed at threshold, the touchdown point, and rollout distance, were derived [1 and 2]. However, full-stop landing distance could not be analyzed, as in the vast majority of all the operational landings, a full stop was not made. Still, there is a need to estimate the full-stop landing distances from the operational flight data to analyze landing performance.

1.2 SCOPE AND OBJECTIVE.

The present study's objective was to derive and analyze methods for calculating the full-stop landing distance from operational flight data. For this purpose, operational flight data collected in a previous project for the B-737-400 and the A319/A320/A321 were used.

1.3 REPORT ORGANIZATION.

In section 2, the different approaches for deriving full-stop landing ground roll distances from operational flight data are discussed. In section 3, the results obtained with the developed approaches are presented and discussed. Section 4 gives the conclusions and recommendations.

2. ANALYSIS OF METHODS FOR ESTIMATING LANDING STOPPING DISTANCE.

Andrew Cheng [3] discussed different approaches to estimate the airplane stopping distances under standard operating procedures. In the present report, these approaches are further elaborated using the available landing data at NLR-ATSI.

Cheng [2] indicated three possible approaches:

- Selection of appropriately short landing runways, such that the airplane is required to perform a full stop;

- Simulation of the dynamics of deceleration forces and mechanisms and interfacing that with the recorded data;

- Extrapolation of the deceleration pattern.

Cheng addresses the third approach, which translates the extrapolation of the deceleration pattern to a practical method for determining the landing distance based on the deceleration pattern. Several variants of the proposed method are also described in detail.

2.1 THE DECELERATION PATTERN EXTRAPOLATION METHOD.

The idea behind the deceleration pattern extrapolation method [2] is to estimate the nominal deceleration during the initial part of the landing run and then to extrapolate this deceleration until the point in time where zero groundspeed would be achieved. By integrating this profile, the stopping distance can subsequently be determined. This procedure is shown in figure 1.
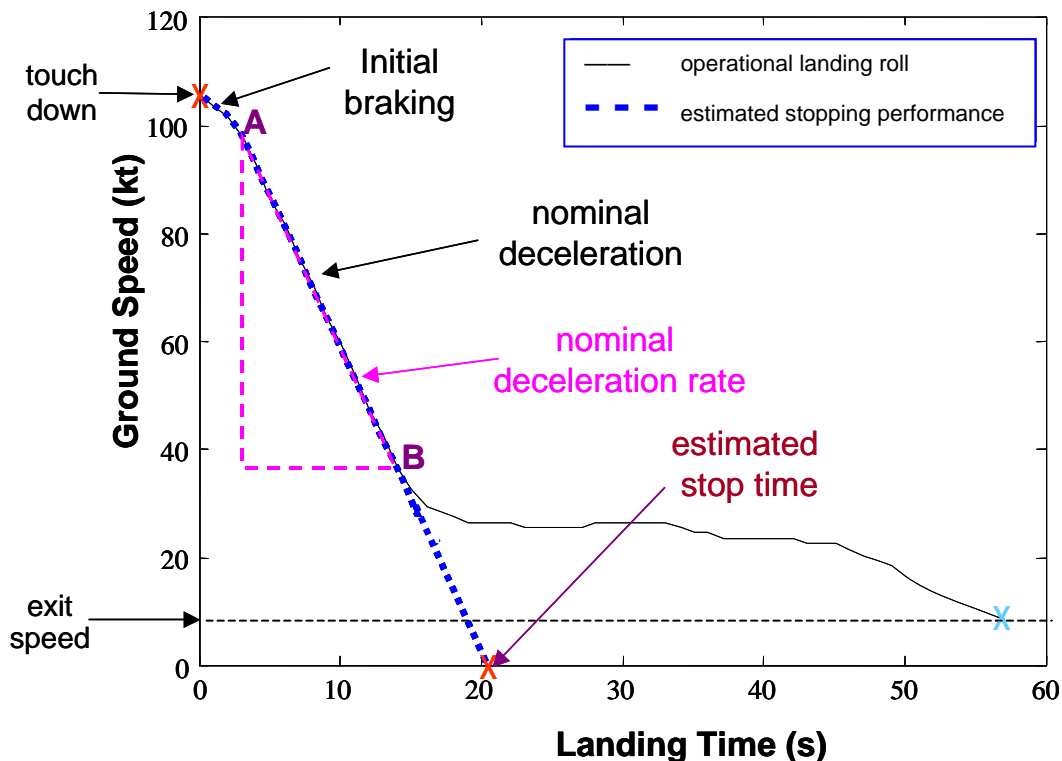
Figure 1. Cheng's Method for Estimating Stopping Distance Based on Continuous Deceleration

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A variant of this procedure [2] proposes not to extrapolate the deceleration, but to remove the coasting part of the landing run and to match the final deceleration rate with the initial deceleration rate to construct a new deceleration pattern consisting of an initial (nominal) part and a final part. Again, by integrating the deceleration profile, the stopping distance can be estimated. However, from inspection of a substantial number of cases from the available landing data, it was concluded that this method cannot be applied in a consistent and general way because many of the landing deceleration profiles do not match the generic profile, as shown in figure 1. In many cases, a clear period of coasting ($\Delta V \sim 0$) cannot be determined, and moreover, the final deceleration rate is, in general, not clearly identifiable.

Figure 2 shows a landing deceleration pattern where no clear period of coasting or final deceleration rate occurred. This example is not an exception, but is one of many cases present in the landing data set. For this reason, it was decided to exclude this variant further, and focus on the extrapolation method of the nominal deceleration profile.
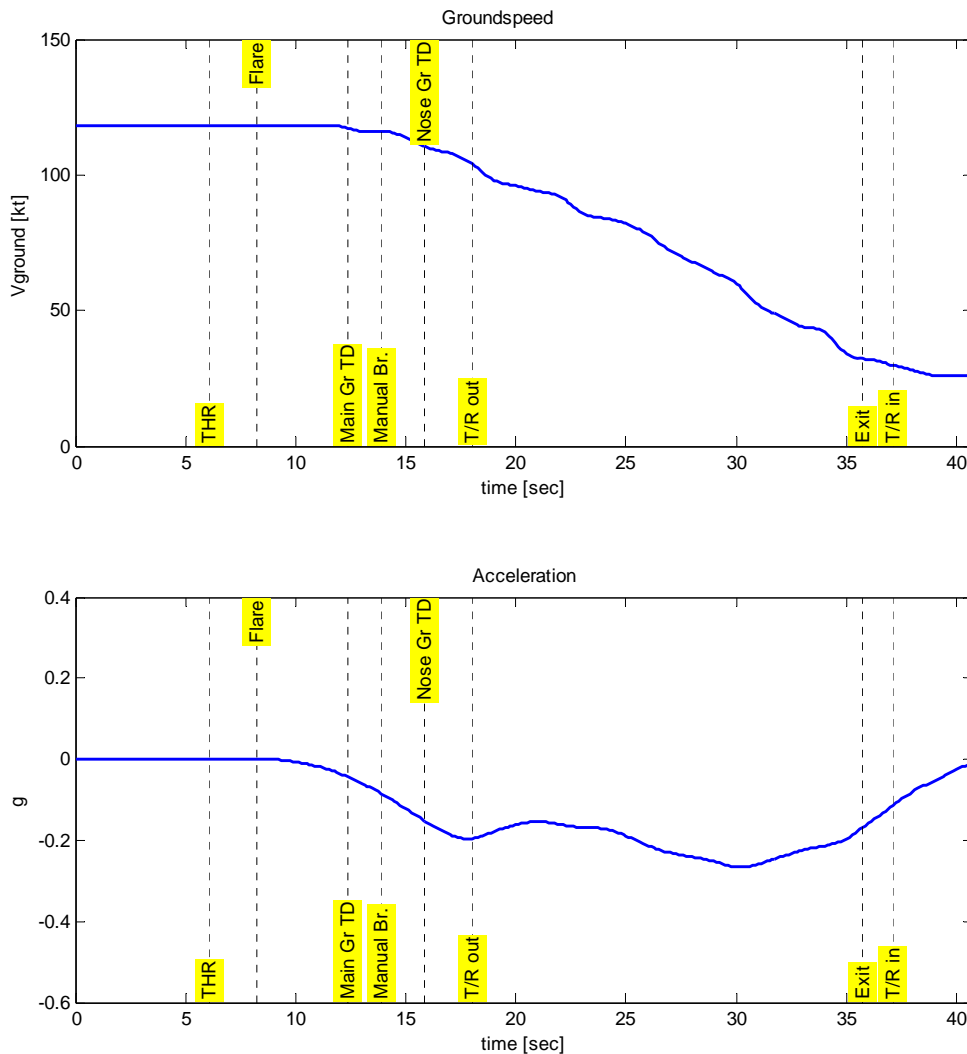
Figure 2. Example of Landing Deceleration Pattern

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The basic idea, as shown in figure 1, assumes that it is possible to estimate the nominal deceleration during the initial part of the landing run based on a sustained period of constant deceleration (in figure 1, from A to B). In practice however, this is not so straightforward because many of the landings do not exhibit a sustained period of constant deceleration. Therefore, it is not always possible to determine points A and B, as shown in figure 1. This is illustrated in figure 3.

Figure 3. Example of Landing Without a (Clear) Sustained Period of Constant Deceleration

This example shows that the deceleration constantly changes over time. For this reason, points A and B, which signal the start and end of the constant deceleration period, cannot be d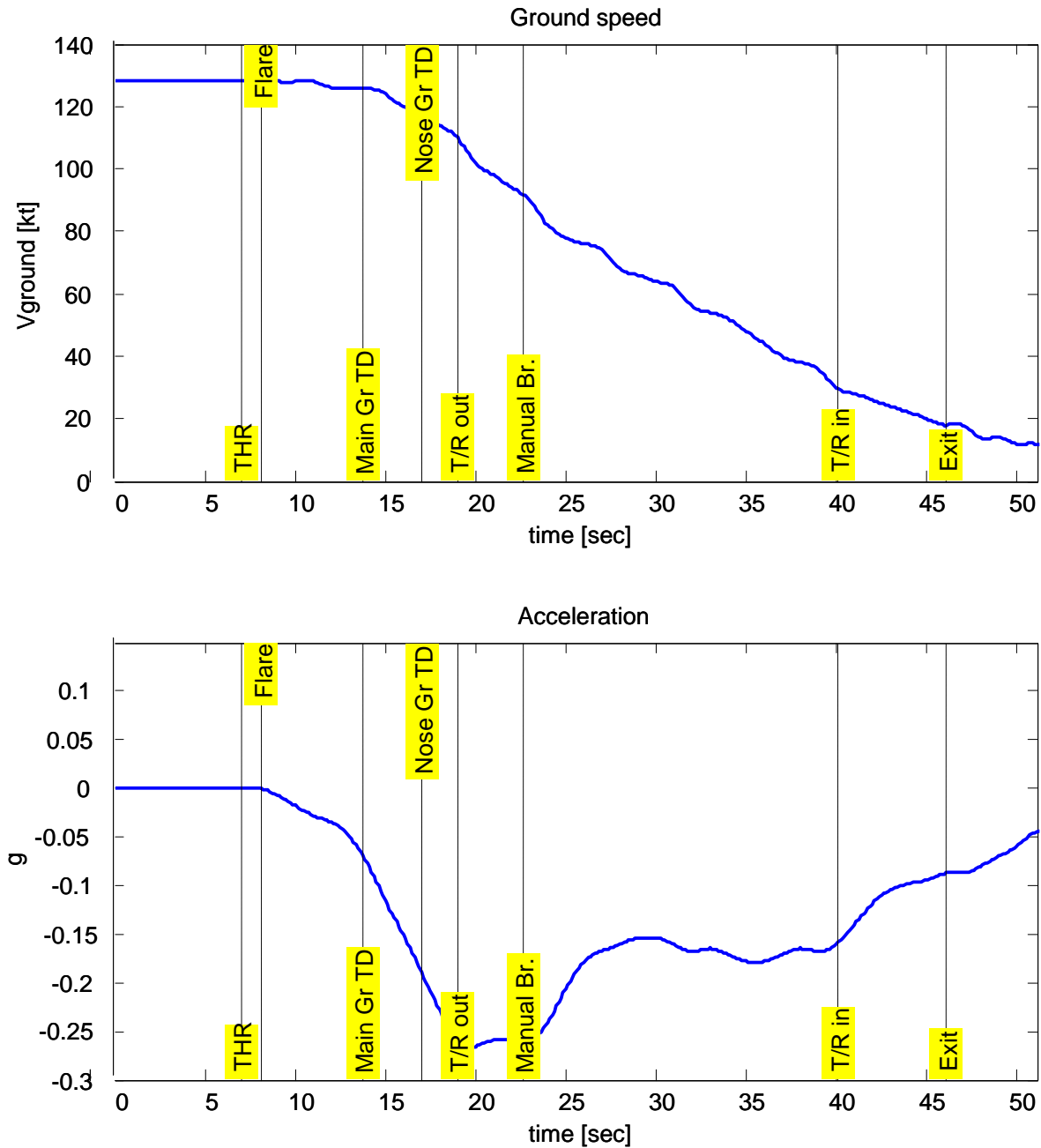etermined unambiguously. Therefore, a slightly different approach is proposed that maintains the idea of nominal deceleration extrapolation, which can be established unambiguously (and automatically) on a case-by-case basis. This is discussed in the next section.

2.2 MODIFIED METHOD FOR DECELERATION PATTERN EXTRAPOLATION BASED ON TANGENTIAL VELOCITY.

The problem of deceleration pattern extrapolation hinges on the capability to consistently estimate the nominal deceleration during the initial part of the landing run and the determination of the groundspeed from which to extrapolate the deceleration to a full stop.

Peter van der Geest developed a procedure to improve the estimate of the nominal deceleration [4]. The procedure [4] determines a period of fairly constant deceleration in the landing patterns, calculates the nominal deceleration between the nosewheel touchdown and the time of peak jerk (change in deceleration), and identifies the tangential speed point. The tangential speed is the groundspeed from which the deceleration profile is extrapolated, using the nominal deceleration, to a full stop.

Using this procedure, the full-stop distance is calculated by assuming that the level of deceleration achieved at the tangential speed is maintained until a full stop is achieved. In this way, the extrapolated (nominal) deceleration profile is connected seamlessly (without jumps) to the actual deceleration profile.

The full-stop ground distance is calculated by integrating the actual groundspeed from main gear touchdown until tangential speed is reached and subsequently integrating (below this airspeed) the extrapolated (nominal) deceleration profile until full stop. Figure 1 also shows the result of the actual full-stop distance calculation using this procedure. In this particular case, a distance of 941 m (3087 ft) was calculated.

2.3 USING ALTERNATIVES FOR THE NOMINAL DECELERATION AND TANGENTIAL SPEED.

The nominal deceleration, as determined in the previous section, may depend on many factors (auto-brake setting, manual braking initiation, full/idle reverse, etc.) that, in turn, are affected by the specific landing conditions (runway length, runway condition, etc.). Given favorable conditions (long/dry runway), the nominal deceleration may be quite low in many cases. Values in the order of 0.15 g are commonly observed.

One may question the significance of the landing distance when it is based on such low nominal deceleration values, while in reality (when required by circumstances), much higher deceleration would be achievable. For this reason, a number of alternative deceleration values are taken into consideration.

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2.3.1 Maximum Instantaneous Deceleration.

The landing distance could be calculated by using the maximum instantaneous deceleration encountered during the landing run. It has been shown that the airplane is capable to achieve this level of acceleration, and it may be assumed that the airplane could sustain this level throughout the entire landing (once below tangential speed). The landing distance calculated in this way is called the maximum instantaneous distance and is always somewhat shorter than the nominal distance. This distance can be considered representative for what actually could be achieved given the present conditions.

2.3.2 Maximum Dry Runway Deceleration.

Another approach is to use a fixed deceleration based on the airplane capabilities on a dry runway. From contacts with a large European operator, this method is used within its internal Flight Data Management program to estimate actual landing distances from operational data.

The value used by this operator is 0.35 g and is considered to be representative for the maximum manual braking performance on a dry runway. This value also matches very well with (manual braking) values found during manual rejected takeoffs. Based on this assumption, the lowest achievable landing distance (lower limit) on a dry runway can be calculated independently from the actual conditions experienced during a particular case. This is called the maximum dry distance and is calculated with a fixed value of 0.35 g instead of the nominal deceleration.

2.3.3 Maximum Wet Runway Deceleration.

This approach is similar to the calculation of the maximum dry distance, but instead of the maximum deceleration on a dry runway, the maximum manual braking deceleration on a wet runway is used. In this way, the lower limit is calculated, assuming that the runway was wet. From contacts with the aforementioned European operator, 0.25 g is an average value that can be used to represent the manual braking performance on a wet runway. The landing distance calculated in this way is called the maximum wet distance and is thus calculated with a fixed value of 0.25 g instead of the nominal deceleration.

To get an idea of the sensitivity of the calculated ground distance for the various (above mentioned) deceleration levels, a few illustrative examples are presented here.

The first case is presented in figure 4, showing a case with a fairly average nominal deceleration of ~ -0.2 g. In this case, the results for the various ground distances are:

- Maximum dry: 1002 m
- Maximum wet: 1214 m
- Maximum instantaneous: 1340 m
- Nominal: 1368 m

Because the nominal deceleration is less than the maximum deceleration achievable on a dry or wet runway, the nominal distance is the longest.

This sequence of ground distances (i.e., from shortest to longest; maximum dry, maximum wet, maximum instantaneous, and nominal) occurs in many cases, but not in all cases.
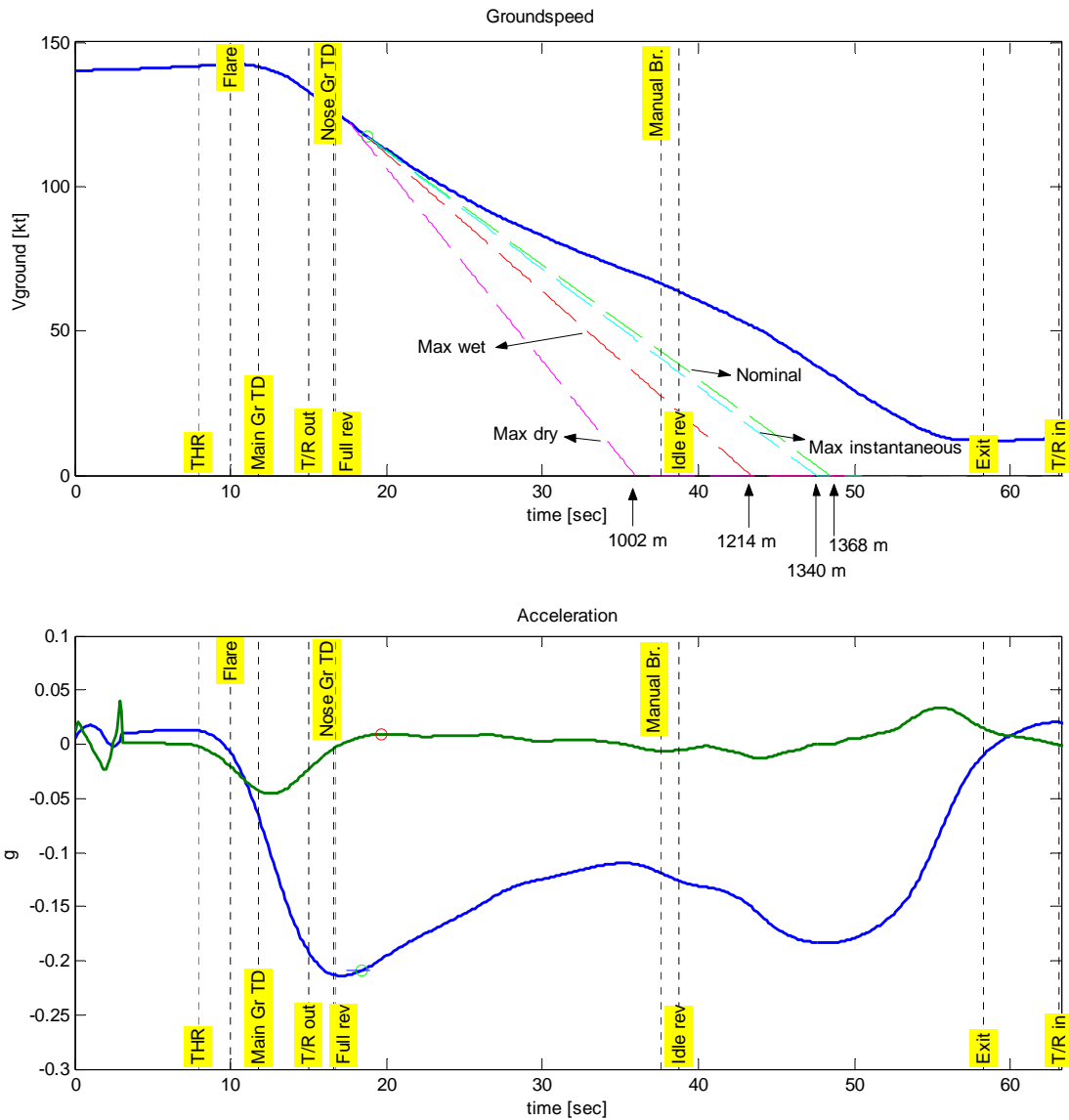

Figure 4. Example 1—Effects of Various Deceleration Profiles on Calculated Ground Distances

The second example, see figure 5, shows a case of fairly high nominal deceleration (~ -0.3 g). Because this nominal level exceeds the deceleration on a wet runway, it is clear that another sequence of distances occurs:

- Maximum dry: 821 m
- Maximum instantaneous: 845 m
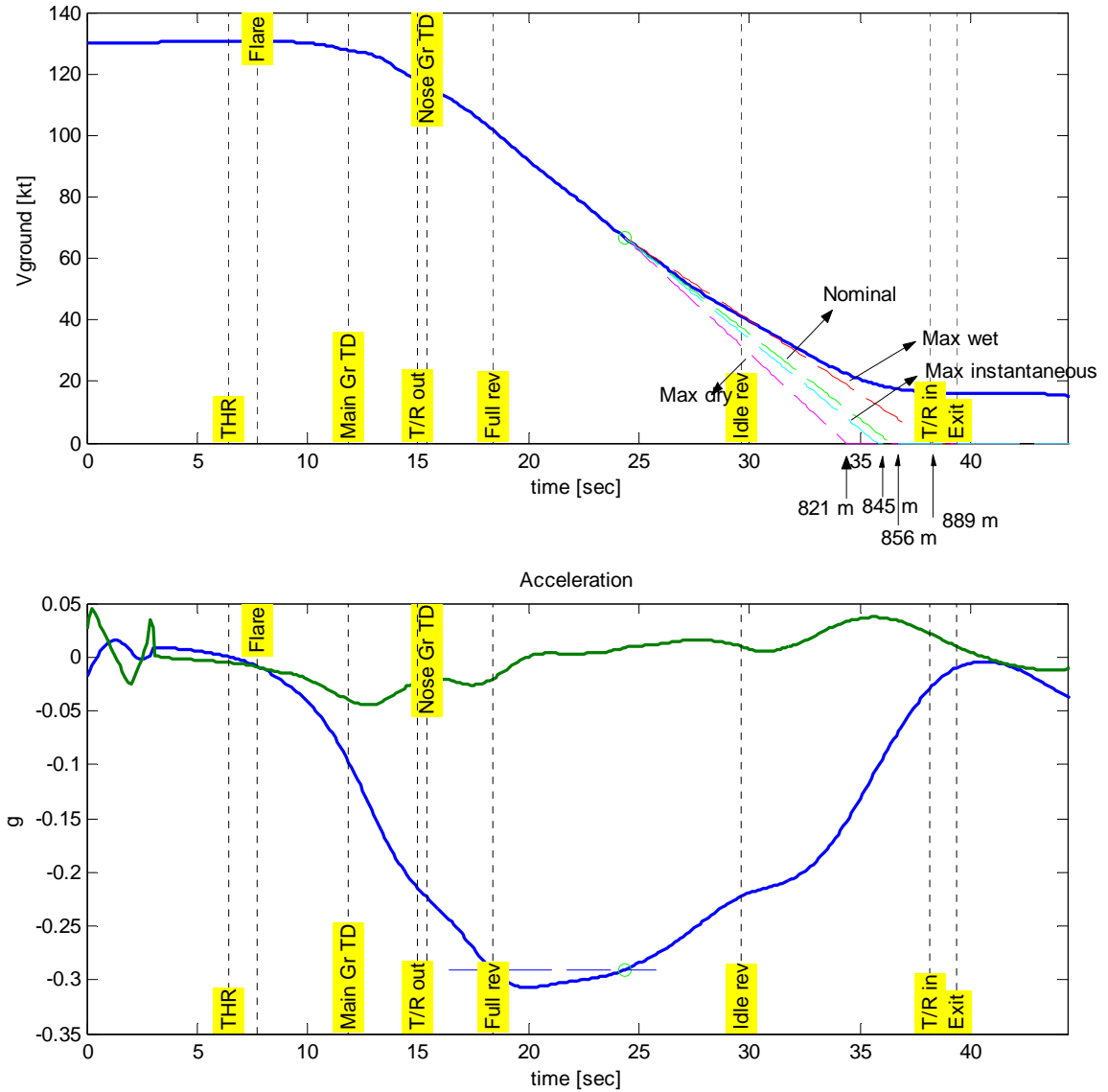- Nominal: 856 m
- Maximum wet: 889 m

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Figure 5. Example 2—Effects of Various Deceleration Profiles on Calculated Ground Distances

One could question also why the spread in the various ground distances can vary so much between two examples, and why, for instance, the maximum dry distance in the first example is 1002 m and 821 m in the second. A contributing factor is that there may be differences in the deceleration profile from main gear touchdown to nose gear touchdown.

Another reason for this is the fact that, in all cases, the extrapolation starts at the tangential speed. Based on the definition of tangential speed (i.e., the velocity where actual deceleration equals nominal deceleration), the value of this speed may vary substantially from case to case (in practice, it may range from approximately 100 to 60 kt). The calculation of the nominal ground distance is very insensitive for the actual value of the tangential speed, because the nominal deceleration is equal to the average deceleration in the initial part of the landing run. This means that if a higher speed was selected from which to extrapolate the deceleration profile (e.g.,

groundspeed just after nosewheel touchdown), this would hardly affect the calculated nominal distance. However, if the deceleration for maximum dry or maximum wet deviates significantly from the nominal deceleration profile, there will be a clearly significant effect of the groundspeed from which the deceleration profile is extrapolated on the computed ground distance. This effect is shown in figure 6.
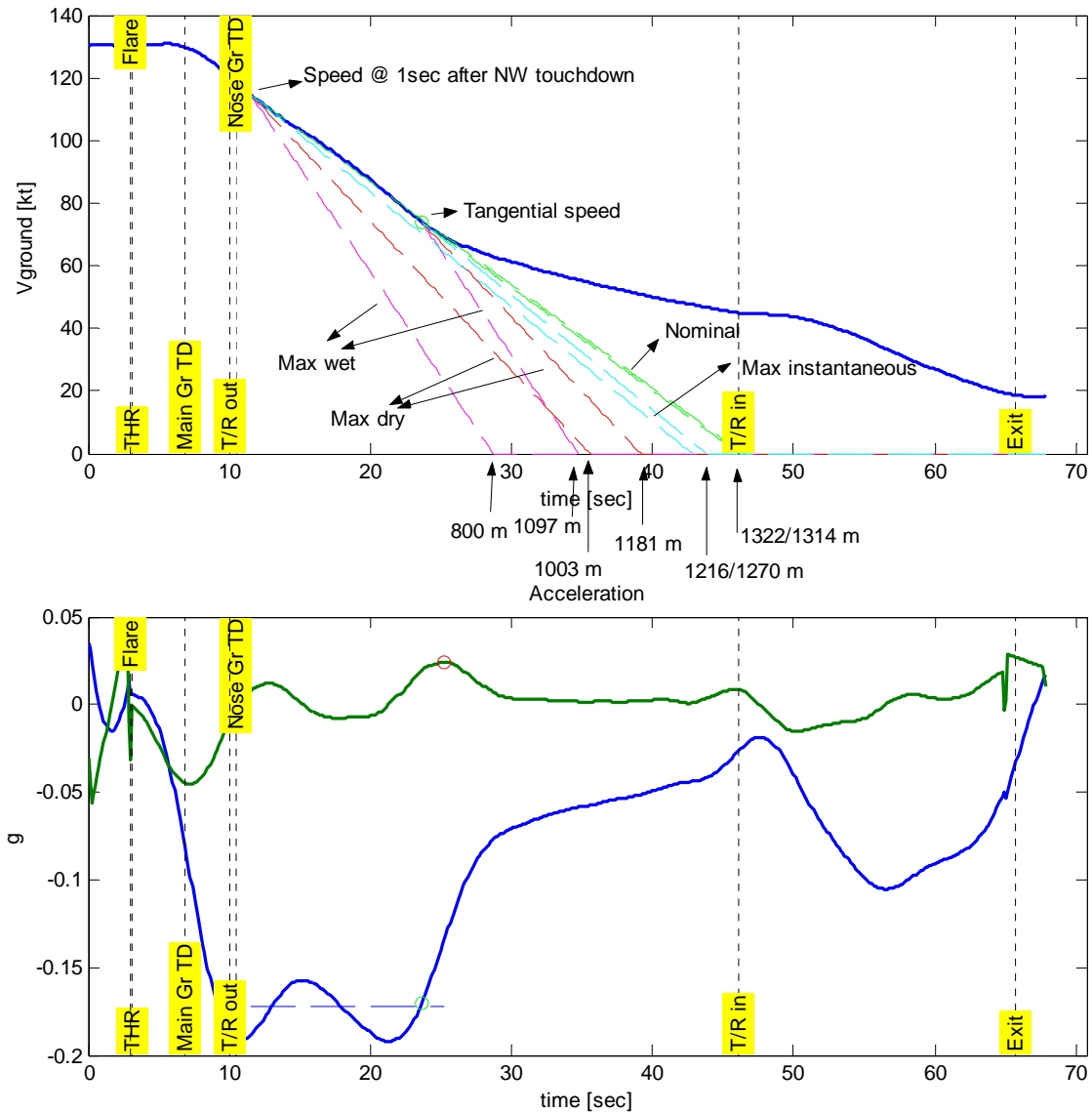

Figure 6. Example 3—Effects of Various Deceleration Profiles on Calculated Ground Distances

In this particular case, the nominal deceleration has a fairly average value (~ -0.18 g), while the tangential speed is relatively low (~ 74 kt). This example shows the effect of the selection of a higher velocity than the tangential speed, to start the extrapolation, on the computed ground distances.

The results of the ground distance computation are summarized in table 1.

Table 1. Ground Distance Computation Results

Ground Distance	Integrated From Tangential Speed	Integrated From V @ 1 sec After Nosewheel Touchdown
Nominal	1314 m ~ 4311 ft	1322 m ~ 4337 ft
Maximum instantaneous	1270 m ~ 4167 ft	1216 m ~ 3990 ft
Maximum dry	1097 m ~ 3599 ft	800 m ~ 2625 ft
Maximum wet	1181 m ~ 3875 ft	1003 m ~ 3291 ft

As shown, there is a substantial range in the resulting ground distances, depending on the applied method.

One could argue that the nominal and maximum instantaneous distances, integrated from tangential speed, are good indicators of what the airplane could achieve, given the present conditions and associated braking characteristics; while the maximum dry and maximum wet distances, integrated from V @ 1 sec after nosewheel touchdown, can be considered representative of the maximum performance theoretically achievable under given conditions.

3. APPLICATION OF THE DIFFERENT METHODS FOR ESTIMATING LANDING STOPPING DISTANCES.

The different methods discussed in section 2 are applied to the full set of flight data that are available for the B-737-400 and the A319/A320/A321. The results obtained with these different methods are discussed in this section.

3.1 DERIVED STOPPING DISTANCES USING DIFFERENT APPROACHES.

The stopping distance derived from the available landing data, based on the different approaches, are shown in figures 7 to 11. In figures 10 and 11, only those cases are considered in which the runway was estimated to be dry or wet, respectively, from the available Aviation Routine Weather Report (METAR) data. Most of the results shown in figures 7 to 11 are normally distributed. The different approaches considered clearly give different results in the ground stopping distances, as shown in figures 7 to 11. This is also clear from the statistical data listed in table 2. Stopping distances based on maximum dry or wet runway deceleration also show significant differences in the results based on either the tangential speed or the speed 1 second after nosewheel touchdown. For the other approaches, this difference is much less or nonexistent. Results based on the nominal deceleration approach give higher stopping distances than results obtained with the maximum instantaneous approach (see table 2). There is also a larger spread in the results obtained with the nominal deceleration approach (see standard deviations listed in table 2). The shortest stopping distances are obtained using the maximum dry or wet runway deceleration approach. These results should be considered as theoretical optimum stopping results that could be achieved during day-to-day landings.
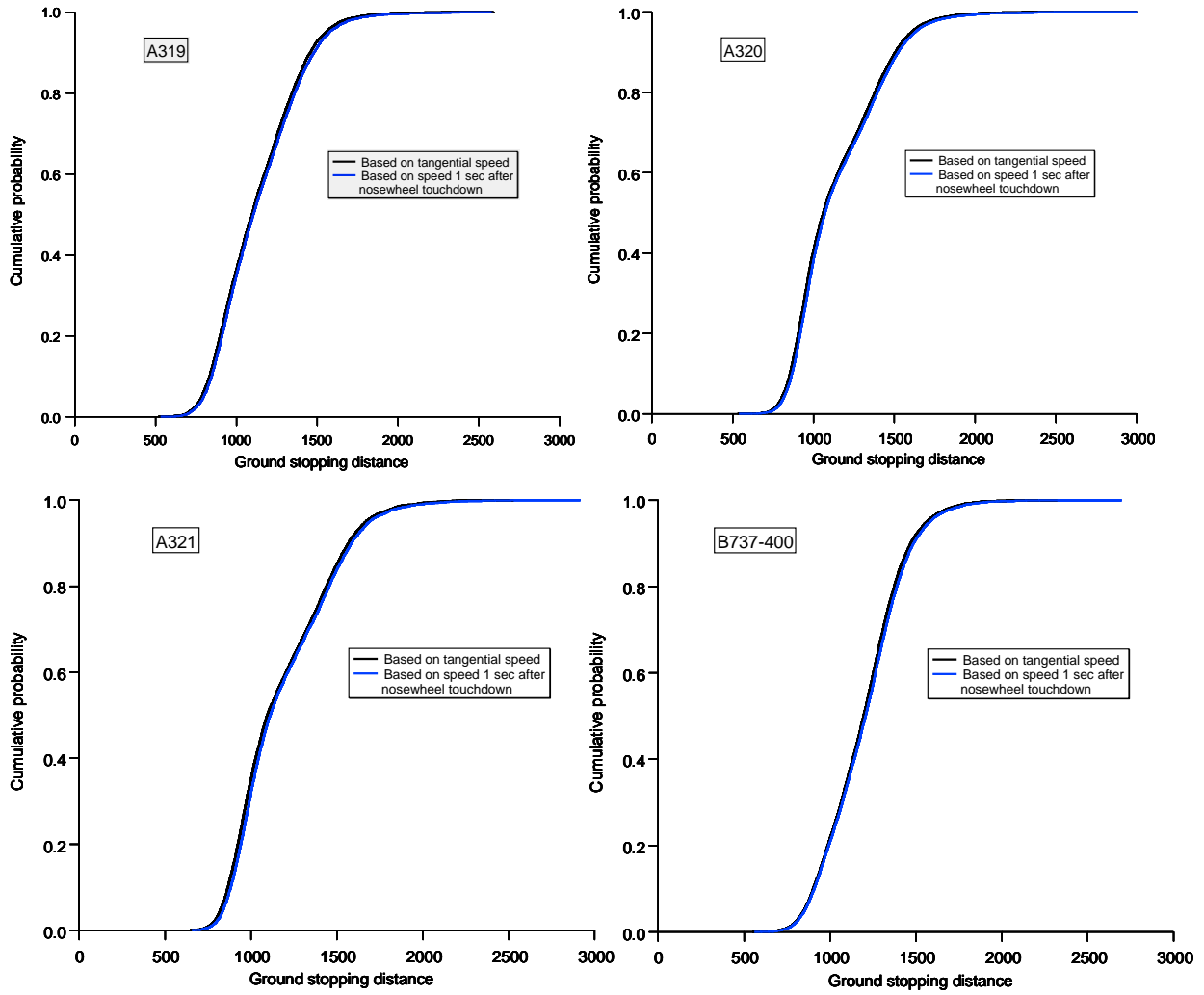
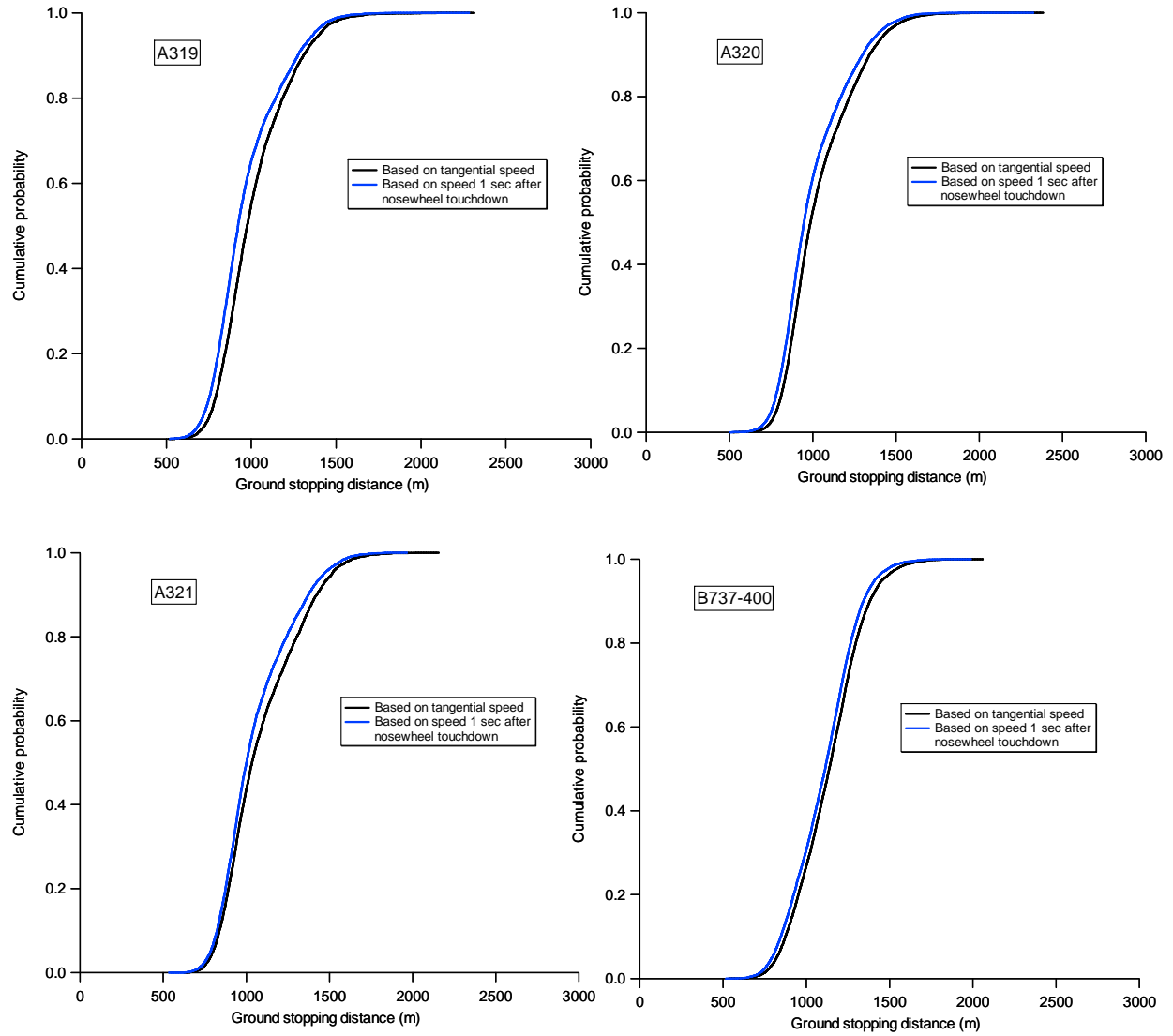Figure 7. Stopping Distances Based on a Nominal Deceleration

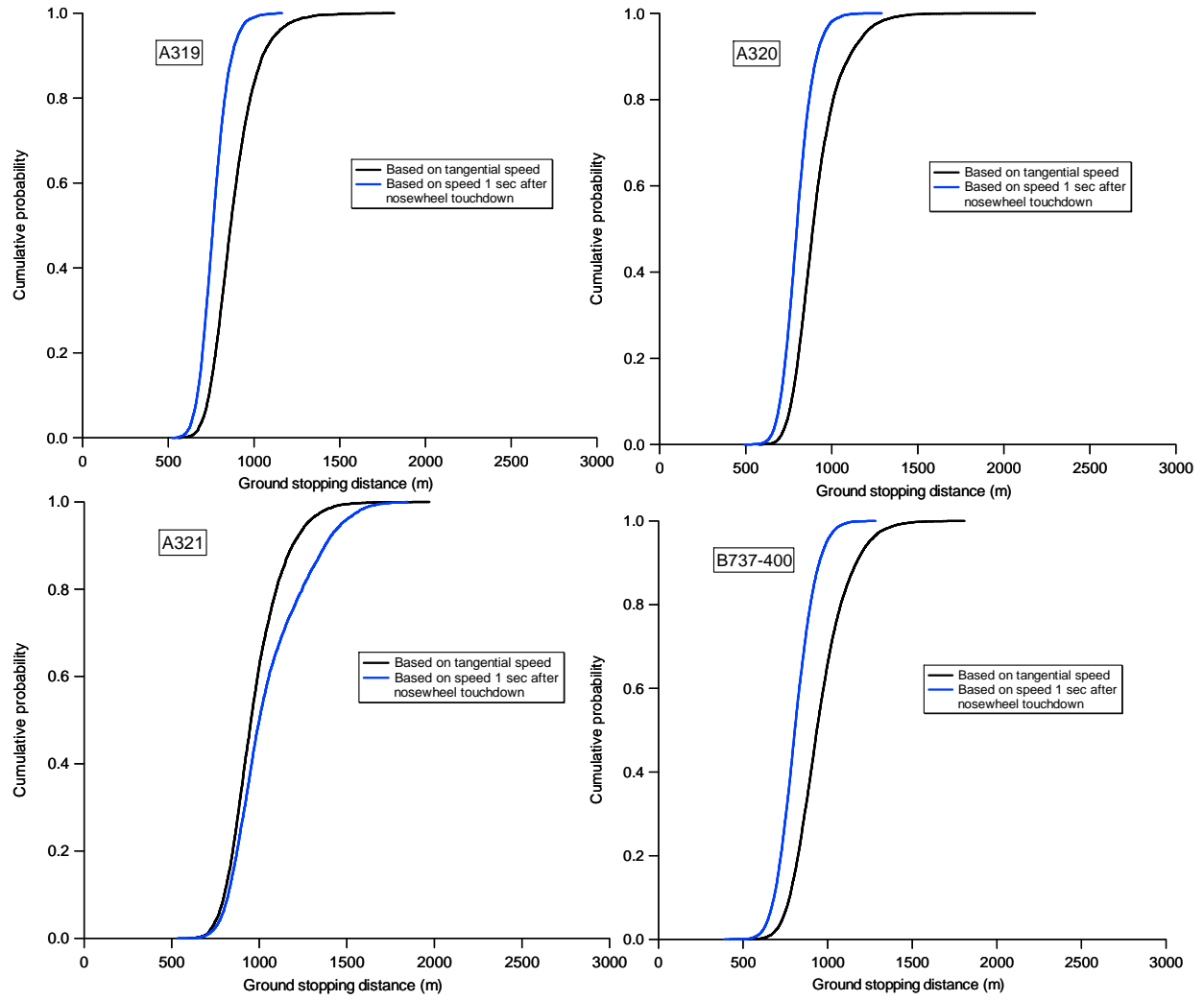Figure 8. Stopping Distances Based on a Maximum Instantaneous Deceleration

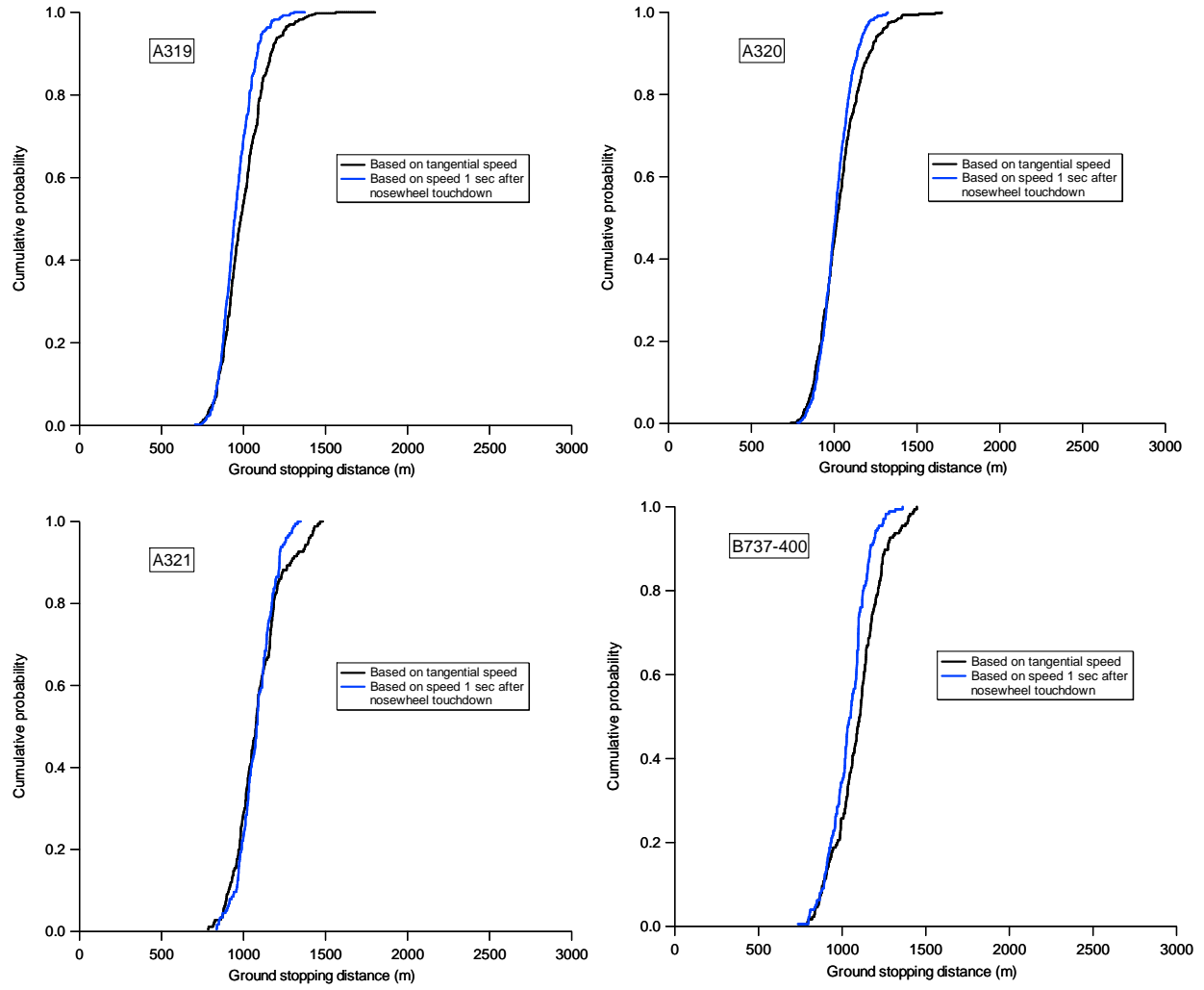Figure 9. Stopping Distances Based on Maximum Dry Runway Deceleration

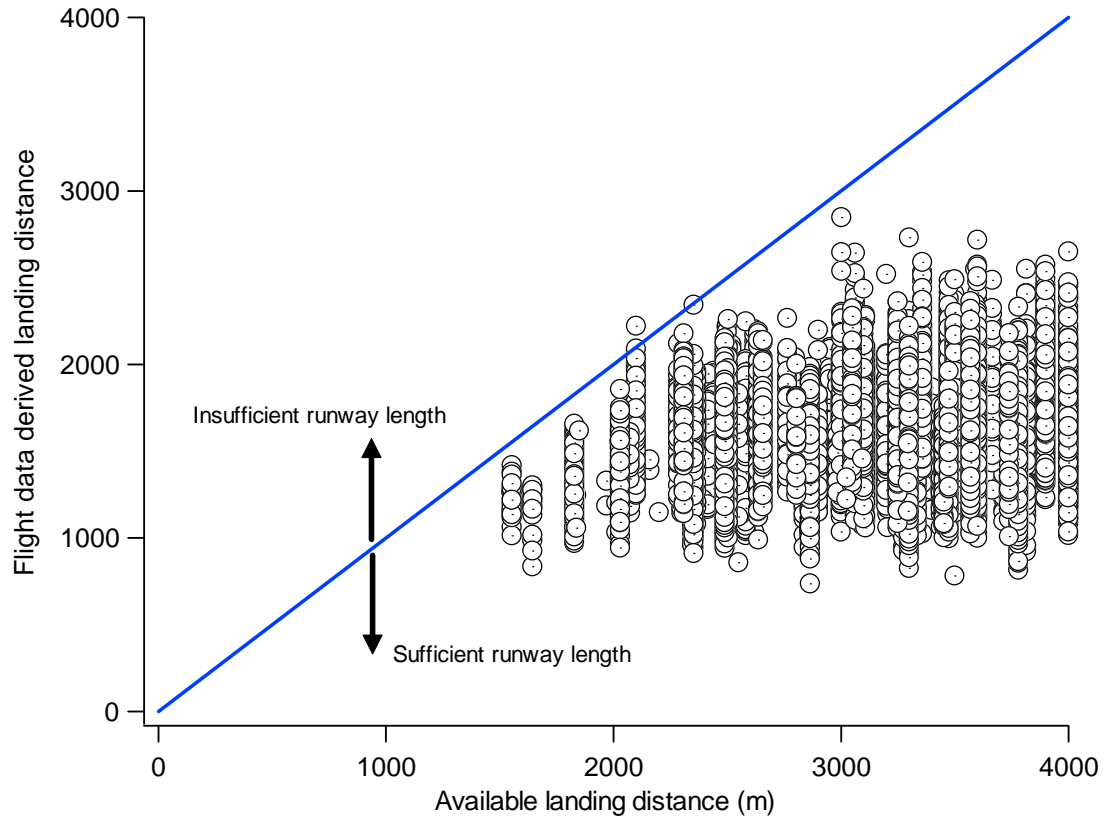Figure 10. Stopping Distances Based on Maximum Wet Runway Deceleration

Figure 11. Comparison Between Flight-Derived Landing Distance and Landing Distance
Available, Based on Maximum Instantaneous Deceleration and Tangential Speed

Table 2. Overview of Statistical Data of the Stopping Distance for Different Approaches to
Estimate Full-Stopping Ground Roll Distances

Airplane Type	Nominal Deceleration (@Vtan) (m)	Maximum Instantaneous Deceleration (@Vtan) (m)	Maximum Dry Deceleration (@Vtan) (m)	Maximum Wet Deceleration (@Vtan) (m)	Nominal Deceleration (@Vnw+1) (m)	Maximum Instantaneous Deceleration (@Vnw+1) (m)	Maximum Dry Deceleration (@Vnw+1) (m)	Maximum Wet Deceleration (@Vnw+1) (m)
Average								
A319	1124	1015	884	995	1139	969	766	958
A320	1128	1033	912	1025	1143	992	800	1002
A321	1167	1085	973	1090	1184	1048	865	1077
B-737-400	1200	1142	966	1083	1212	1111	820	1026
Standard Deviation								
A319	247	203	134	135	254	201	82	96
A320	259	205	137	140	265	198	84	100
A321	280	226	156	159	283	212	96	114
B-737-400	219	195	158	156	224	190	105	123

3.2 TOTAL LANDING DISTANCE.

With the ground roll stopping distance available, it is possible to derive a value of the total landing distance by summing the stopping distance with the airborne distance for each landing. This flight-derived landing distance is compared to the landing distance available (LDA) shown in figures 12 and 13, assuming the maximum instantaneous and nominal deceleration approaches, respectively. The results obtained using the maximum instantaneous deceleration show that all landings (with the exception for one case) can be stopped with the LDA. The one landing that exceeded the LDA was caused by the fact that, in this case, the airplane used a taxi exit at the end of the runway. The last part of this runway was not defined as to be used for landing performance calculations. The results based on the nominal deceleration show that a small number of landings would not be able to stop on the runway. Again, in one case, the airplane used a taxi exit at the end of the runway. As shown in figure 13, the results obtained with the nominal declaration show slightly longer landings (e.g., less margin) than the results obtained with the maximum instantaneous deceleration approach.
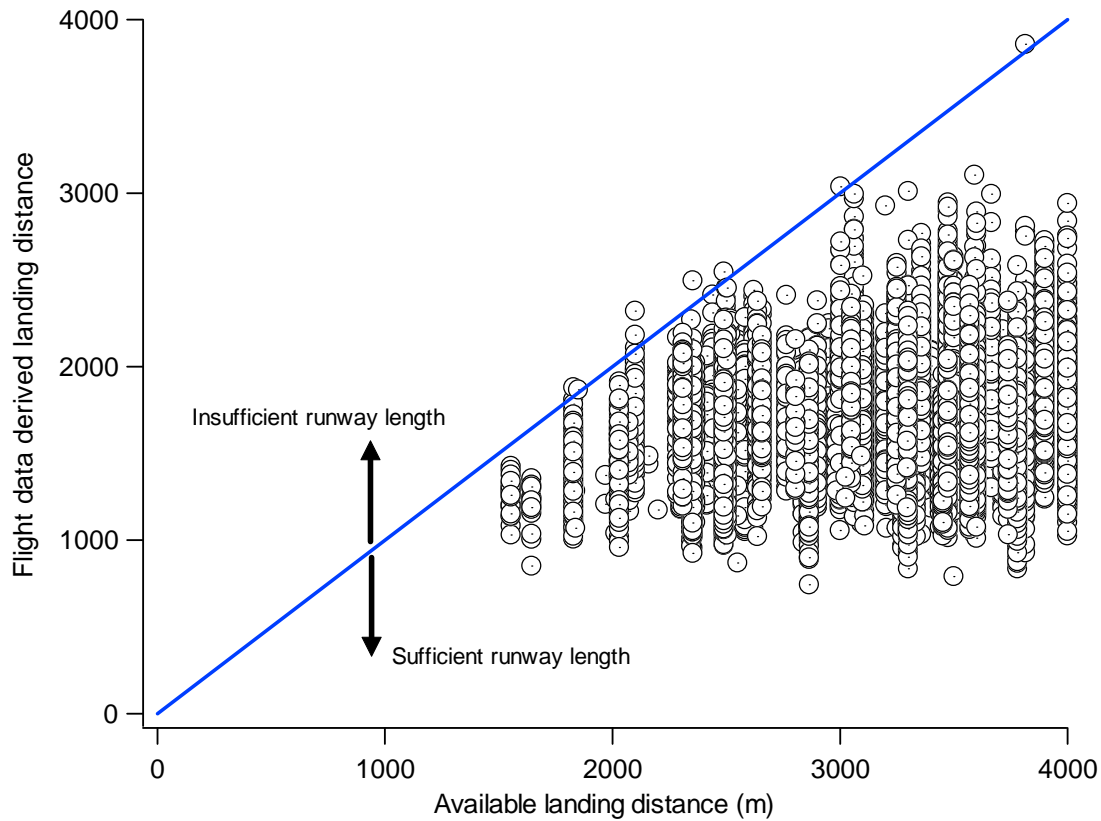

Figure 12. Comparison Between Flight-Derived Landing Distance and LDA, Based on Nominal Deceleration and Tangential Speed
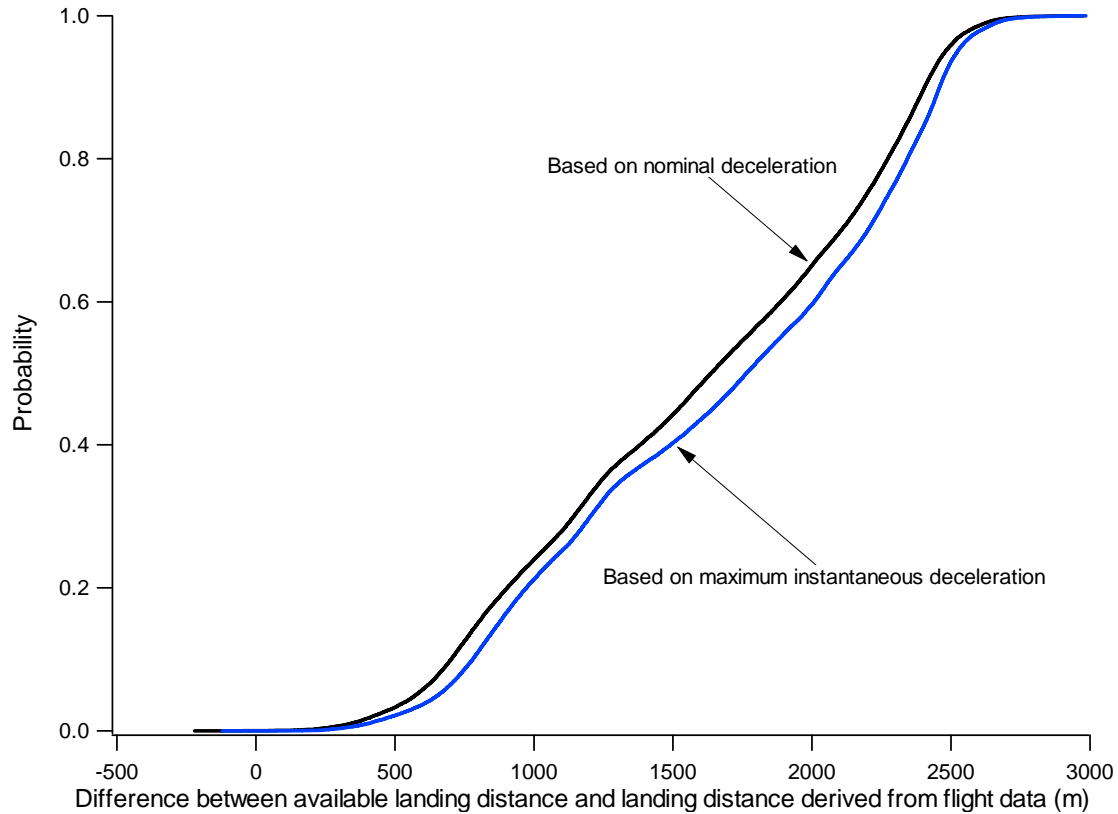
Figure 13. Comparison of Remaining Runway During Landing

4. CONCLUSIONS AND RECOMMENDATIONS.

This report described various methods used to calculate the ground distance from actual landing data. In total, eight variants were defined. All the variants were implemented in the current processing software. After reprocessing all available cases, the statistical properties and possible correlations of each variant were investigated. Based on these results, it was concluded that ground stopping distances obtained with the maximum instantaneous deceleration approach may be considered the most useful or realistic candidate to serve as an indicator for the actual airplane landing performance. Results based on the nominal deceleration approach gave a higher stopping distance than results obtained with the maximum instantaneous approach. There was also a larger spread in the results obtained with the nominal deceleration approach.

It is recommended to further analyze the braking characteristics during ground roll by considering the use of autobrake settings, pedal input, brake pressure, etc., correlated with other variables, such as weather and runway characteristics.

5. REFERENCES.

1.   van Es, G.W.H. and van der Geest, P.J., "A Study of Normal Operational Landing Performance on Subsonic Civil Narrow-Body Jet Aircraft During ILS Approaches," NLR-CR-2006-049, 2006.

2.   van Es, G.W.H., van der Geest, P.J., Cheng, A., Hackler, L., and Dillard, A.E., "A Study of Normal Operational Landing Performance on Subsonic, Civil, Narrow-Body Jet Aircraft During Instrument Landing System Approaches," FAA report DOT/FAA/AR-07/7, March 2007.

3.   Cheng, A., "Discussion of Approaches to Estimate the Aircraft Stopping Distances Under Standard Operating Procedures," FAA report DOT/FAA/AR-TN07/21, May 2007.

4.   van der Geest, P.J., "Determination of Aircraft Stopping Distance," NLR-TN-ATSI-0702, 2007.