Discussion of Approaches to Estimate the Aircraft Stopping Distances Under Standard Operating Procedures

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16. Abstract

The Federal Aviation Administration is currently engaged in research of aircraft operational landing performance, aiming to increase the safety and efficiency of aircraft operations in terminal areas. One of the primary research objectives was to identify the operational landing distances achieved in line operations under standard operating procedures. The landing distance is defined as the total distance, from the runway threshold, needed for an aircraft to make a full stop during a landing operation. This distance consists of two components: the touchdown point (i.e., airborne distance) from runway threshold and the stopping distance after touchdown. Although several algorithms have been recently developed to identify aircraft touchdown points via available landing parameters, solutions to adequately determine the aircraft stopping distance are still greatly sought after. This technical note addresses the difficulties of estimating the operational aircraft stopping distance and discusses approaches to resolve the problem. In particular, a new method is proposed to estimate the aircraft stopping distance via studying the deceleration pattern during rollout. The deceleration pattern provides a useful means to estimate the operational stopping distance since it is the realization of a pilot's decision and command under the specific landing conditions, including the piloting techniques, weather conditions, runway situation, air traffic control demands, etc. There are several advantages to this approach. First, the deceleration pattern identified by ground speed information contains relatively little contamination of measurement noise so that a troublesome noise-filtering process is generally not required. Second, this approach is simple and straightforward because it does not depend on the availability of additional information regarding external factors that affect the deceleration performances. Assumptions and investigation results are demonstrated with operational landing examples.

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EXECUTIVE SUMMARY

The Federal Aviation Administration is currently engaged in research of aircraft operational landing performance, aiming to increase the safety and efficiency of aircraft operations in terminal areas. One of the primary research objectives was to identify the operational landing distances achieved in line operations under standard operating procedures. The landing distance is defined as the total distance, from the runway threshold, needed for an aircraft to make a full stop during a landing operation. This distance consists of two components: the touchdown point (i.e., airborne distance) from runway threshold and the stopping distance after touchdown. Although several algorithms have been recently developed to identify aircraft touchdown points via available landing parameters, solutions to adequately determine the aircraft stopping distance are still greatly sought after. This technical note addresses the difficulties of estimating the operational aircraft stopping distance and discusses approaches to resolve the problem. In particular, a new method is proposed to estimate the aircraft stopping distance via studying the deceleration pattern during rollout. The deceleration pattern provides a useful means to estimate the operational stopping distance since it is the realization of a pilot's decision and command under the specific landing conditions, including the piloting techniques, weather conditions, runway situation, air traffic control demands, etc. There are several advantages to this approach. First, the deceleration pattern identified by ground speed information contains relatively little contamination of measurement noise so that a troublesome noise-filtering process is generally not required. Second, this approach is simple and straightforward because it does not depend on the availability of additional information regarding external factors that affect the deceleration performances. Assumptions and investigation results are demonstrated with operational landing examples.

INTRODUCTION

PURPOSE.

The need for improved capacity at airports to accommodate the rapid growth of domestic air traffic in the United States has led to the investigation of safe and feasible means to increase the traffic flow. While the capacity issue becomes important, it is imperative that the increase in capacity should not let safety decline. The Federal Aviation Administration (FAA) is currently engaged in a research project to study the aircraft operational landing performance, aiming to increase the safety of aircraft operations in terminal areas.

One of the primary research objectives was to identify the operational landing distances achieved in line operations under standard operating procedures. The landing distance is defined as the total distance, from the runway threshold, needed for an aircraft to make a full stop during a landing operation. This distance is divided into two components: the touchdown point from runway threshold (resulted from the airborne maneuver) and the stopping distance after touchdown (achieved via ground deceleration). Recently, several algorithms have been developed to identify aircraft touchdown points via available landing parameters [1 and 2]. However, solutions to adequately determine the aircraft stopping distance are still greatly sought after. This technical note addresses the difficulties of estimating the operational stopping distance and discusses approaches to resolve the problem. In particular, a new method is proposed to estimate the stopping distance via studying the aircraft deceleration pattern.

BACKGROUND.

A major difficulty for determining aircraft stopping distance is that aircraft usually do not make a full stop on rollout (i.e., keeping the aircraft on the centerline of the runway). During a landing roll, the pilot uses various braking mechanisms, including speed brakes, spoilers, thrust reversers, and aircraft braking systems, to decelerate the aircraft to an acceptable ground taxi speed. Hence, no direct information could be obtained for the operational stopping distance—it can only be estimated based on the aircraft landing roll performance. Figure 1 presents the speed-time profile of an operational landing roll of a Boeing-737-400 aircraft landing onto a 7000-foot runway. This profile shows the aircraft's time-dependent speed information from the touchdown until exiting the runway. Though the traveling distance information is usually not recorded, it can be yielded by the integral of velocity function, which will be discussed in the Approach C section.

It is worth noting that the selection of the turnoff point depends on a number of factors, including aircraft touchdown location and speed due to piloting techniques, aircraft landing weight, runway condition, weather condition, airport traffic demands, and the destination terminal and gate location. Since the aircraft usually does not stop until it taxies to the destination gate, studying the operational stopping distance requires estimating the time to stop without taxiing under standard operating procedures. Moreover, it is arguable that the choice of turnoff location is significantly dependent on the decisive destination of gate assignment. If the aircraft heads for a destination gate close to the end of the runway, it is likely that the pilot would intend to turnoff the aircraft at the last exit and adapt a lower deceleration rate to prolong the rollout. As illustrated in figure 1, a coasting period during which an aircraft travels without significant deceleration might even occur. Thus, it is a great challenge to estimate the reasonably shortest time to stop, as if the pilot were to make an immediate full stop after touchdown following standard operating procedures, based on available operational landing roll data. The goal is to provide an adequate means to estimate the optimal stopping distance under various weather and runway conditions based on actual landing data recorded in line operations. In particular, a method is desired to differentiate the deceleration effort that is taken to stop the aircraft or that is merely tailored for turning off at a farther location. The estimation, however, should follow all safety and operational concerns under the standard operating procedures and should not be confused with the much more aggressive practice of the maximum performance landing.

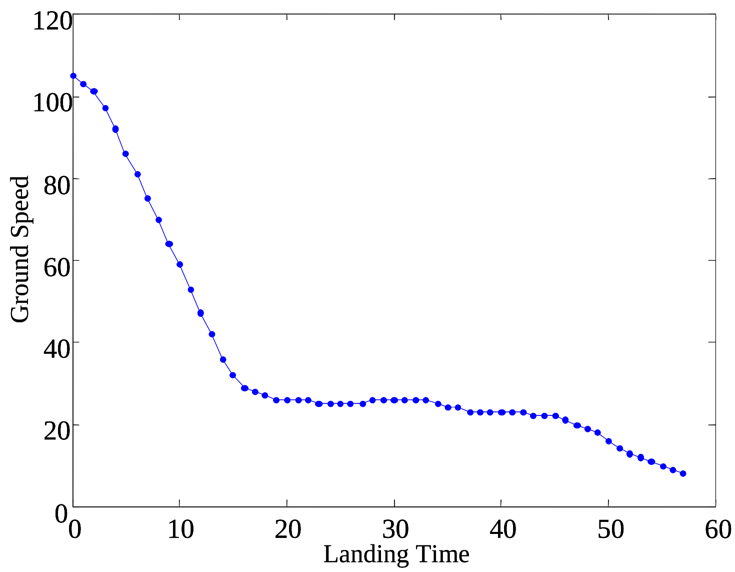

Figure 1. Speed-Time Profile of a Typical Landing Roll

APPROACH A: STUDY OF LANDINGS ON SHORT-LENGTH RUNWAYS

This approach focuses on investigating operational flights landing on short-length runways where the pilot has to concentrate on decelerating the aircraft during the landing roll. Attempts of applying this approach have been currently pursued by a joint study by the FAA and National Aerospace Laboratory (NLR). However, the operational performance of landings at short runways (typically shorter than 7000 feet) still shows noticeable variations. Therefore, additional efforts have to be taken to further filter out the “coasting-like” period for better estimating the operational stopping distance.

APPROACH B: DYNAMICS STUDY OF DECELERATION FORCES AND MECHANISMS

Several studies, including the research collaborators of the NLR and University of Dayton Research Institute through a separate FAA agreement and grant, proposed to estimate the time to stop by investigating the braking devices used for deceleration and applying brake-energy analysis on the available flight parameters recorded during landing rolls. This kinetics approach aims to develop an algorithm to predict the time to stop by estimating the braking energy based on an optimal combination of braking devices operating under various weather and runway conditions. In addition, given that configuration information of most braking devices is available in operational flight data, a filtering scheme would be established to identify the segments when the pilot commanded active inputs to decelerate the aircraft.

Since the kinetic problem is highly nonlinear, approximate solutions may require appropriate segmentation of separate brake roll performances. Furthermore, some key information, such as the longitudinal acceleration, is usually contaminated with significant measurement noise when the aircraft is traveling on the ground. To properly smooth out the embedded measurement noise would introduce another challenge to the analysis. Note that several environmental factors contribute to decelerating an aircraft, including aerodynamic drag and the friction force between the tires and runway surface. Availability of accurate information of weather and environmental conditions for determining appropriate contribution of external factors to the braking performance is critical to this approach.

APPROACH C: STUDY OF DECELERATION PATTERN

Another approach was proposed to estimate the time to stop after the aircraft touchdown by studying the deceleration pattern. As indicated in figure 2, a typical landing roll can generally be characterized by the following deceleration phases: initial braking, nominal deceleration, coasting, and adjusted deceleration for exit/taxi speed. The first initial braking phase accounts for the possible time lag observed in the activation of thrust reverser and other braking devices (e.g., speed brake and autobrake system). When the commanded braking configurations are fully activated, the aircraft will roll out at a constant deceleration rate (i.e., the nominal rate) during the nominal deceleration phase. The coasting phase, in which no active deceleration inputs are commanded, occasionally exists after the aircraft slows down to the desired speed on rollout. The adjusted deceleration phase usually takes place within a certain range prior to the turnoff location. In this phase, the pilot adjusts the deceleration rate to reach the target exit/taxi speed, depending on the exit type (e.g., regular or high-speed exit) and the connection to taxiway (e.g., at a sharp angle or with graduate transition). This deceleration pattern provides a useful means to estimate the operational stopping distance since it is the realization of a pilot's decision and command under the specific landing conditions, including the piloting techniques, weather conditions, runway situation, ATC demands, etc.

Let $\Delta x(t_1, t_2)$ denote the traveling distance between t_1 and t_2. It can be obtained by the following integration:

$$\Delta x(t_1, t_2) = \int_{t_1}^{t_2} v(t) \cdot dt \text{ ; } v(t) \text{ is the velocity function at time } t. \qquad (1)$$

Since the ground speed is usually updated every second, the displacement (ft) within the second can be obtained by liner approximation of the average of two consecutive ground speed records (ft/sec). Therefore, $\Delta x(t_1, t_2)$ is approximated as follows:

$$\Delta x(t_1, t_2) = \sum_{t_1+1}^{t_2} \left(\frac{v(t) + v(t-1)}{2} \right); \; v(t) \text{ is the velocity value at time } t \tag{2}$$

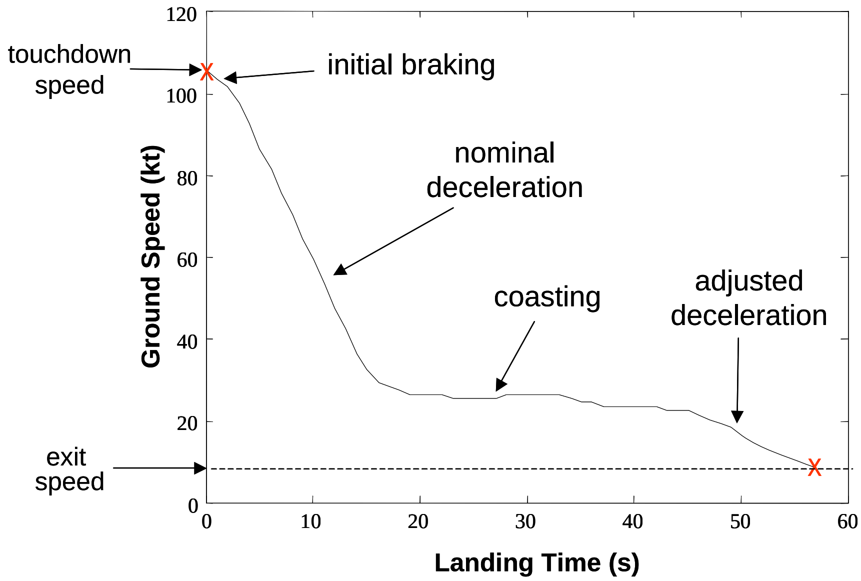

Figure 2. Deceleration Pattern of a Typical Landing Roll

More sophisticated nonlinear methods, such as cubic spline fitting, will improve the simple linear approximation for traveling distance information [3]; however, it is beyond the scope of discussions in this technical note. After the time-dependent distance, information is obtained, the time domain velocity profile can be converted to the location domain profile as displayed in figure 3. It shows that after touchdown, the aircraft travels roughly 3500 feet before it leaves the exit in approximately 58 seconds. Clearly, during the coasting period, the aircraft just maintains the desired speed for traveling to the target exit location. Therefore, it is concluded that the distance achieved during the coasting period gives no significance to estimating the operational stopping distance. Also, the distance achieved if the aircraft ever accelerates to attain a higher speed during the landing roll also gives no significance to estimating the operational stopping distance. Taking these circumstances into account, two methods that are discussed in the following sections that estimate the possible stopping distance based on the operational deceleration performance during the landing roll.

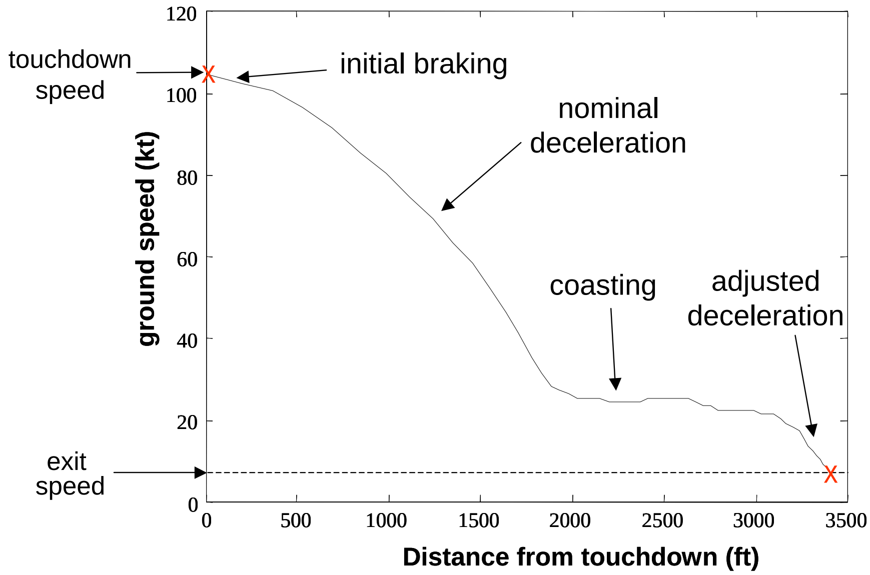

Figure 3. Speed-Location Profile During a Typical Landing Roll

CONTINUOUS DECELERATION AT NOMINAL RATE UNTIL STOP.

The first method assumes that the aircraft would continue decelerating at the nominal rate (i.e., the constant deceleration rate obtained via fully activated braking configurations) until it comes to a full stop. As indicated in figure 4, the nominal deceleration rate is computed by the average speed change during the straight-line segment (e.g., between points A and B) identified after initial braking in the speed-time profile. The speed change at time t, $\Delta v(t)$, is defined by $v(t) - v(t\text{-}1)$. An iterative search for the series of $\Delta v(t)$ during the landing roll performance would eventually identify a particular phase after initial braking, where $\Delta v(t)$ remains a constant value. Assuming that the aircraft continues decreasing its speed at such a constant Δv until it comes to a full stop, an estimated speed profile is generated, as shown by the blue dotted line in figure 4. This generated speed profile is then used to estimate the operational time to stop, as well as the stopping distance. By applying the approximation of equation 2, a speed-location profile for continuous deceleration toward a complete stop is generated and displayed in figure 5. It shows that the aircraft would be able to stop in 21 seconds at roughly 2000 feet after touchdown if it continues to decrease speed at the nominal deceleration rate.

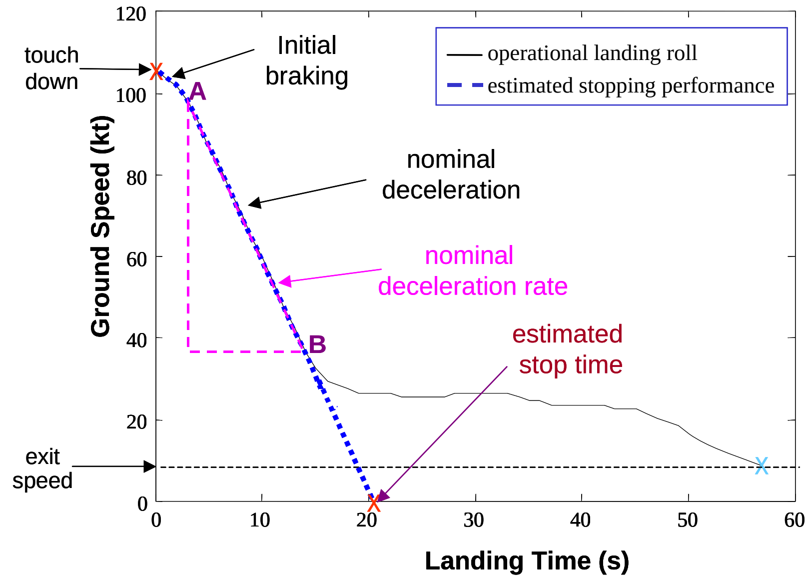

Figure 4. Estimated Speed-Time Profile for Continuous Deceleration

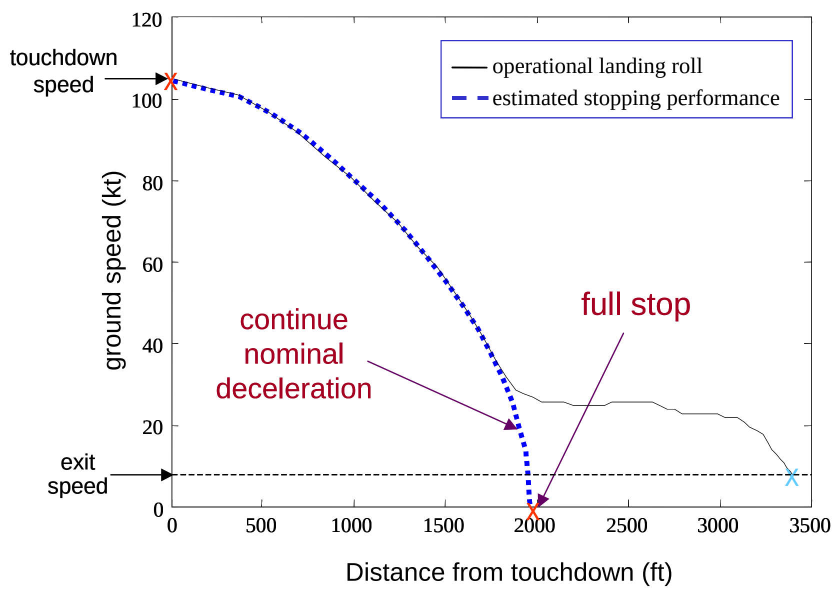

Figure 5. Estimated Speed-Location Profile for Continuous Deceleration

It is arguable that this assumption is not totally realistic. Although the nominal deceleration rate is practically attainable during the specific landing roll, continuation to decrease the speed with such a deceleration rate until the aircraft comes to a full stop might not always be desirable when considering the comfort of the passengers. Furthermore, the nominal deceleration rate is usually the largest deceleration during the entire landing roll performance. This deceleration rate is generally obtained by applying a combination of deceleration devices, including thrust reversers, aerodynamic braking, wheel braking, etc. Nevertheless, such a deceleration rate might not be easily achieved when the aircraft moves at a lower speed, especially when the aircraft is about to stop. Therefore, the next section discusses another method that will address these considerations.

CONTINUOUS DECELERATION WITHOUT UNNECESSARY COASTING AND ACCELERATION.

To relax the stringent assumption that the aircraft continues decelerating at the nominal rate until it stops, another method was proposed to estimate the time to stop by studying the meaningful deceleration phases only. This method will identify and eliminate the unnecessary coasting or acceleration phases since the traveling distance achieved during these two phases gives no significance to the estimate of operational stopping distance.

The speed change, Δv, is used as the indicator to identify the coasting or accelerating period. The algorithm listed below summarizes the procedures to estimate the time to stop and stopping distance:

1. Identify the aircraft coasting or acceleration phases by $\Delta v \geq 0$.

2. Eliminate data points belonging to the coasting or acceleration phases identified by step 1.

3. Construct a new speed-time profile by parallelly shifting the disconnected segments to form a continuous deceleration curve.

4. Compute the final deceleration rate by averaging the speed change during the ending segment (e.g., the last five observations) of the new deceleration curve produced in step 3.

5. Assume that the aircraft continues decelerating at the final deceleration rate obtained in step 4 until it comes to a full stop.

6. Estimate the operational time to stop and stopping distance while the ground speed reaches 0.

The identified coasting phase is highlighted by the pink circle shown in figure 6. By eliminating the coasting period and computing the final deceleration rate, an estimated speed-time profile was constructed and is presented by the blue-dotted line. Again, distance information is obtained by the approximation of equation 2, yielding the estimated speed-distance profile displayed in figure 7 for continuous deceleration without coasting. It shows that this specific landing aircraft would be able to stop in 43 seconds at approximately 2500 feet after touchdown if progressing without coasting or acceleration. Relaxation of the assumptions discussed in the previous section yields roughly an additional 500 feet in the estimate of stopping distance, which results from decelerating at a lower than nominal rate while traveling at slow speed.

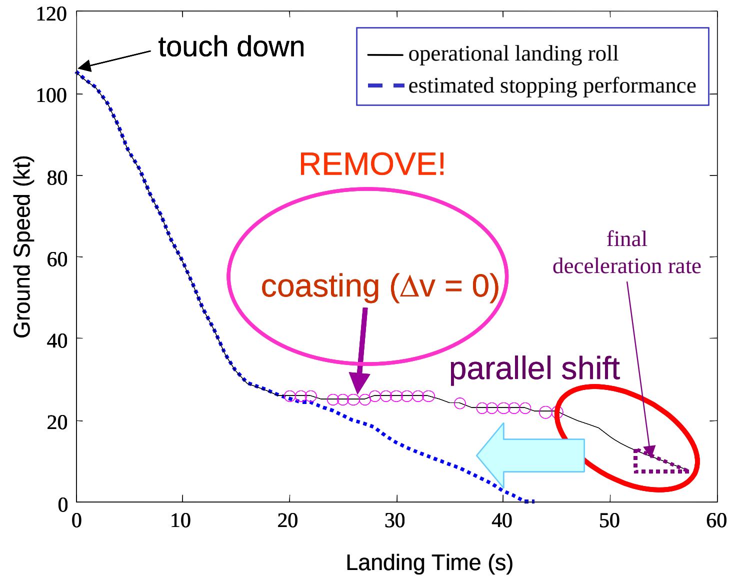

Figure 6. Estimated Speed-Time Profile for Traveling Without Coasting Period

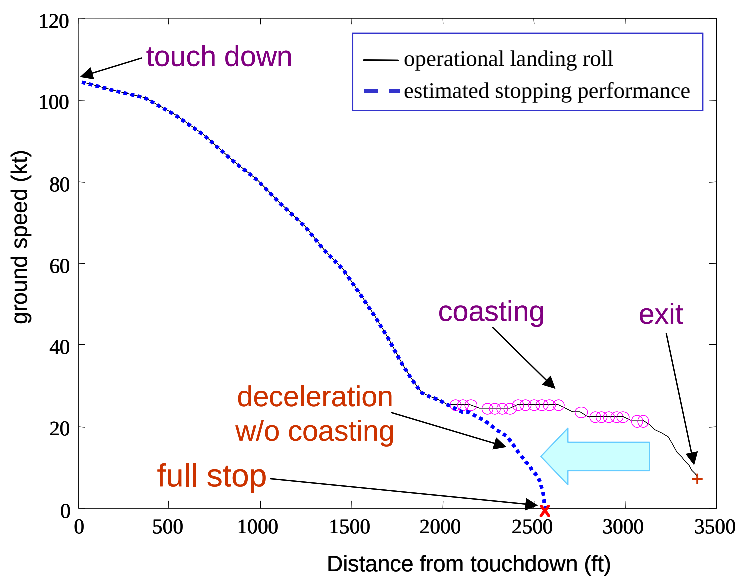

Figure 7. Estimated Speed-Distance Profile for Traveling Without Coasting Period

Implementation of this method involves adequate selection of the deceleration phases and appropriate estimation of the final deceleration rate. The deceleration patterns would be very different for turning off at regular or high-speed exits. The adjusted deceleration phase is generally easy to observe on rollout when the aircraft turns off at regular exits. However, when turning off at high-speed exits, the pilot might conduct such an adjustment to decelerate the aircraft just before reaching the end of exit. Therefore, the turnoff point where the heading information starts showing significant deviation from runway direction is usually not a good choice for the cutoff point of selecting landing roll decelerations. Furthermore, significant variation of exit speed was noticed in the preliminary analysis. It is recommended to carefully screen the landing roll performance for selecting representative deceleration patterns. A general guideline follows:

1. Include all continuous deceleration (monotonic decreasing values).

2. Select velocity profile until the ground speed is regained after turning off. That is to select the velocity profile until the first bounce-back (nondecreasing value) of ground speed observations after the magnetic heading showing significant deviation from the landing runway direction. This guideline applies to both turning off at regular or high-speed exits.

Moreover, the estimation of the final deceleration rate is not clearly defined in this technical note. A preliminary analysis of a limited number of operational landings indicates that averaging speed change during the final 5 seconds of the decelerating velocity profile would yield satisfactory results. Nevertheless, it should be tested against a larger set of operational data to establish a practical guideline or an algorithm for properly estimating the final deceleration rate for this method.

SUMMARY

It was proposed to use the speed change, Δv, to study the deceleration pattern during the operational landing roll for estimating the operational aircraft stopping distance. There are several advantages of this approach: First, Δv is a robust measure during aircraft movement on the ground. Although Δv is not as sensitive as other measures, such as longitudinal acceleration for indicating the aircraft's movement, it has much less contamination of measurement noises especially while aircraft moving on the ground. Second, this approach is simple and straightforward since the deceleration pattern reflects the pilot's decisive commands under the specific landing condition. Moreover, this approach is less dependent on the availability of additional information regarding external factors affecting the landing performance because the aircraft deceleration is the sum of commanded deceleration (braking, flaps, thrust reversers, etc.) and deceleration caused by various forms of external retardation forces. Therefore, this approach does not need to estimate the friction under the specific runway condition and to compute the braking contribution to aircraft deceleration, which is crucial to the dynamics study of deceleration forces.

Table 1 summarizes the results of estimation by studying the deceleration pattern. In routine line operation, the aircraft travels 3470 feet after touchdown to leave the runway exit with exiting speed $\cong$ 4 knots. Note that the distance to runway exits is fixed so that the pilot has to adjust the speed for traveling to the desired exit. Assuming the aircraft continues decelerating at the nominal rate, it is estimated that the aircraft would stop in 1998 feet after touchdown. A more relaxed assumption adds approximately 500 feet to the estimated stopping distance by allowing the aircraft to decelerate at a lower rate when traveling at slow speed. It is arguable that these estimates indicate the upper and lower bounds of the possible stopping distance under the specific landing condition. Despite the landing technique, aircraft gross weight, weather condition, runway situation, and airport traffic demands, the stopping distance obtained by this approach indicates a general estimate according to the specific circumstance. Consequently, to attain meaningful stopping distance, it is essential to select representative operational landings that follow standard operating procedures under adequate landing conditions.

Table 1. Summary of Operational Turnoff and Estimated Stopping Distances

Category \ Estimation Method	Taxiing to Terminal	Decelerating at Nominal Rate	Decelerating Without Coasting
Time to exit\stop (seconds)	58	20.6	43.2
Distance to exit\stop (feet)	3470	1998	2506
Exit\stop speed (knots)	4	0	0

Most technical details were not thoroughly discussed in this technical note since only limited operational samples were available for the preliminary analysis. Further analysis is highly recommended to test against a large size of operational data to fine tune these methods and to complete the estimation algorithm.

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