

The Effect of Piloting Practices Upon Actual as Opposed to Scheduled Landing Field Performance

Donald L. Wood,¹
Timothy T. Takahashi²
Arizona State University, Tempe, AZ

This fifth paper, in a series, explores the intersection of technical and operational factors that control the “certified” takeoff and landing distances obtainable by modern commercial aircraft. Here, we explore the effects of operational variance on actual (as opposed to scheduled “certified”) aircraft performance. We modelled an aircraft, similar to the A320, to perform trade studies on the different elements affecting landing field performance. The results show little sensitivity to technical factors, such as deviations in approach angle or touchdown weight. The study finds significant impact arising from operational factors such as threshold height, flare time and brake application time. Thus, piloting procedures have very strong effects on landing field performance and operational safety.

Nomenclature

<i>CFR</i>	= Code for Federal Regulations
<i>LDA</i>	= Landing Distance Available (ft) from threshold to end of runway
<i>LDR</i>	= Landing Distance Requirement (ft) from 50-ft obstacle to stop
<i>LGR</i>	= Landing Ground Roll (ft) from touchdown to stop
<i>KIAS</i>	= Knots Indicated Airspeed
<i>V_s, V_{s0}, V_{s1}, V_{sr0}</i>	= Stall Speed (as called out in various parts of the CFR)
<i>VREF</i>	= Final Approach Landing Reference Speed
<i>VMCL</i>	= Minimum Controllable Airspeed (landing flap setting) (one-engine inoperative)

I. Introduction

ON October 27, 2016, during the run-up to the recent presidential election, Vice President Mike Pence’s campaign aircraft, a Boeing 737-700 (N278EA), overran the runway while landing at New York City’s La Guardia Airport (KLGA).¹ Although no one was injured after the “rough touchdown,” passengers were evacuated through the back of the plane.² The incident resulted in the closure of LaGuardia Airport for several hours.¹ The New York Times reported that the event “happened shortly before 8 p.m. as the plane, carrying Mr. Pence and 47 other people, was landing and “overshot” the runway.”³ It was raining at the time of the incident; the aircraft was on the ILS approach to landing runway 22.⁴ The 737’s “main landing gear touched down on the wet runway over 4,000-ft feet beyond the runway threshold.”¹ The “speed brakes were manually engaged about four seconds after touchdown.”¹ The pilots did not engage the thrust reversers until “seven seconds after touchdown.”¹ The pilots “avoided running into approach masts (at the end of the runway) by turning to the right.”⁴ The 737 “traveled through an arrestor bed, a form of crushable concrete used to stop aircraft that overrun a runway, and stopped in a grassy area adjacent to the runway.”⁴ According to the BBC, “The pilot slammed on the brakes and passengers on the aircraft could smell burning rubber.”²

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¹ Aviation Management and Human Factors M.S. Candidate, Ira A. Fulton Schools of Engineering, 7001 E. Williams Field Rd, Mesa, AZ 85212. Member AIAA.

² Professor of Practice, Aerospace and Mechanical Engineering, School for Engineering of Matter, Transport & Energy, P.O. Box 876106, Tempe, AZ, 85287. Associate Fellow AIAA.

Aircraft runway overruns during an otherwise normal landing are an unfortunate occurrence often attributed to pilot error.

14 CFR § 23⁵ and 14 CFR § 25⁶ certified aircraft are expected to be flown according to standard procedures developed by the Federal Aviation Administration (FAA). Before an aircraft dispatches, both all-engines-operating and one-engine-inoperative field and climb performance checks ensure that the aircraft can safely operate from and to designated airports. As aircraft weight increases, so does its required minimum runway length.

If an operator wants to fly an aircraft to an airport with a short runway, its allowable landing weight may be restricted to a value less than its certified maximum. Under many weather conditions, an aircraft might not be able to operate safely at all. Thus, all aircraft include a “certified flight manual” that lists the appropriate temperatures, altitudes, speeds and runway utilization information a pilot needs to make an informed decision.

Using manufacturer provided data, aircraft operators compute the total landing distance required (*LDR*), the distance from a point where the aircraft is 50-ft above the airfield level, through touchdown, until it reaches a complete stop. They also compute the landing ground roll (*LGR*), the distance to stop from the point where the tires first contact the runway. In order to safely land, the landing distance available (*LDA*) must be greater than the landing distance required (*LDR*).

The National Weather Service Weather reported at the time of the incident (the METAR for 23:51Z Oct 27, 2016 at KLGA) indicated winds out of the east-by-southeast (100) at 10 knots, gusting to 15 (see Figure 1).⁴ According to unofficial transcripts from the La Guardia tower air traffic controller, Pence’s 737-700 was “cleared to land (on runway 22), wind 110 at 9 (knots).”⁴ Thus, air traffic control knowingly cleared this flight to land on a runway with ~4 knots of tailwind and ~8 knots of crosswind.

Advisory (unfactored) landing information for a B737-700 for a Flaps 30 approach at an estimated landing weight of 115,000-lbm utilizes 4,690-ft of runway for landing in the wet in the absence of a tail wind to 5,340-ft of runway for landing in the wet with a 10-knot tail wind (see Figure 2).⁷ In both cases, these distances are considerably shorter than La Guardia’s 7,001-ft long runway 22 (see Figure 3). The reader should note that published “advisory” wet weather distances imply that the pilot both applies maximum braking effort commensurate with available traction and uses reverse thrust immediately upon touchdown.

Although Vice President Pence’s 737 was designed and certified for 14 CFR § 121⁸ operations, it was most likely flown under 14 CFR § 135⁹ “On Demand” rules. No matter. The relevant landing runway length requirement rules are functionally identical between 14 CFR § 135.385¹⁰ and identical to 14 CFR § 121.195.¹¹

In addition, 14 CFR § 121.195 requires that scheduled commercial flights may not depart their originating airport if its performance at the intended landing weight “(allowing for normal consumption of fuel ...), would allow a full stop landing at the intended destination airport within 60 percent of the effective length” of the destination runway.¹¹ This rule theoretically requires the pilot to multiply the actual landing distance requirement by a 1.67 factor to determine the minimum acceptable destination runway length ($LDR * 1.67 < LDA$). Thus, an aircraft with $LDR=5,340$ -ft would need to operate from runways longer than 8,917-ft. Note that La Guardia’s runway 22, at 7001-ft, is too short; it does not comply with this regulation.

METAR KLGA 272351Z 10010G15KT 3SM RA BR OVC010
13/12 A3010 RMK AO2 SFC VIS 4 SLP192 P0032 60061 T013
30117 10139 20072 58018

Figure 1 – METAR for KLGA at time of runway overrun

Advisory Information
Landing Distance (0 to 2000 feet pressure altitude)

Landing Weight (1000 lb)	Flaps 30							
	0 Knots				10 Knots Tailwind			
	MIN	MED	MAX	WET	MIN	MED	MAX	WET
150	3280	6440	4650	5580	9430	7950	5140	6300
140	7840	6130	4470	5340	8950	6920	4940	6040
130	7370	5800	4270	5090	8450	6570	4780	5750
125	7150	5640	4180	4950	8200	6390	4630	5610
120	6920	5480	4080	4820	7950	6220	4520	5480
115	6690	5320	3980	4690	7700	6050	4420	5340

Figure 2 – Boeing 737-700 QRH Extract

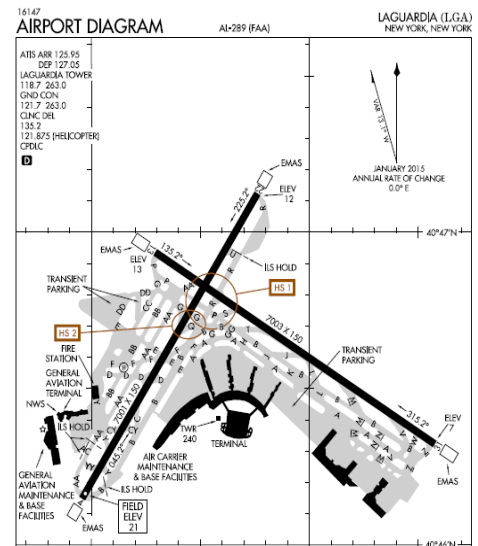


Figure 3 – La Guardia Airport Runway Configuration

However, there is an option in this regulation (14 CFR § 121.195 (e) and 14 CFR § 135.385 (e)) that permits scheduled operations to shorter runways provided that dispatch loads sufficient fuel to fly to an alternate airport that meets all the other requirements of the regulation. We must also pay attention to FAA directive SAFO 06012.¹² This document requests that operators multiply the actual landing distance by a 115% factor ($LDR * 1.15 < LDA$); provided an alternate airport exists where $LDR * 1.67 < LDA$. Thus, an aircraft with $LDR=5,340$ -ft would need to operate from a runway no shorter than 6,140-ft provided the aircraft has reserve fuel to fly to an airport with a runway longer than 8,917-ft. Because La Guardia's runway 22 is longer than 6,140-ft and nearby New York/Kennedy (KJFK) and Newark/Liberty (KEWR) have long runways, this landing was "legal" under this exemption.

There is a second option under 14 CFR § 135.385(f) that permits an "eligible" on-demand operator to fly an on-demand flight to a destination airport where the scheduled performance of the aircraft would result in a full stop landing within 80% of the effective length of the runway.¹⁰ Thus, an aircraft with $LDR=5,340$ -ft could legally fly to an airport with a runway no shorter than 6,675-ft without the need for an alternate airport. Because La Guardia's runway 22 is longer than 6,675-ft, this landing was also "legal" under this exemption.

So what happened to Vice President Pence's aircraft? From publicly available evidence, both dispatch and the pilot in command followed all relevant operational regulations. At the same time, it is obvious that the pilot somehow did not fly the aircraft in a manner where it even approximately performed as well as the "book" would otherwise indicate.

This paper will demonstrate, using numerical simulations, how actual aircraft landing field performance changes with variation in environment and pilot techniques. This paper, the fourth in a series, seeks to document the actual runway utilization during landing for an aircraft flown "off book." Our first paper, AIAA 2017-0007, given at the 2017 AIAA SciTech conference, described the impact of piloting procedure (pitch rate and reaction times) as well as braking traction faced by the engineer when settling upon the "certified distances" for both takeoff and landing.¹³ Here, we look at the actual runway utilization of an aircraft flown using piloting procedures that differ from those used when developing the scheduled performance found in the pilots operating handbook.

II. Background Behind Operations and Relevant Regulations

We must never forget that 14 CFR § 23⁵ and 14 CFR § 25⁶ certified aircraft are expected to be flown according to procedures documented in the airplane flight manual (AFM) and other FAA certified documents; hereafter referred to as the "book." In return, pilots should expect that actual aircraft perform at least as well, if not better, than the published "book performance" guarantees on which the life and livelihood depend.

If an aircraft has insufficient performance to land on the intended runway, the pilot must offload payload in order to restrict its operational weight. This reduction in weight brings the aircraft's landing performance up to the required minimums (for either distance, or climb capability). If the pilot must offload payload to reduce weight, it means that he must leave passengers, luggage and/or cargo behind. If the pilot deviates from published procedure, the aircraft is likely to overrun the runway.

The reason why our new work is important is that existing Federal regulations are vague. A student who first encounters 14 CFR § 25 gets an impression that the regulations explicitly govern pilot procedures. An engineer responsible to code a physics-based simulation for Takeoff and Landing, or reduce flight test data discovers many ambiguities. Some clarification may be found in FAA advisory circular AC-25-7 (in various versions published throughout the years).^{14,15,16,17} However, even the advisory circular leaves many decisions open for interpretation.

Pilots fly aircraft, hopefully, in accordance with established training procedures. Pilots are unlikely to be familiar with AC-25-7C; no regulation demands that the airframe manufacturer document all of the implied assumptions behind certified "book" performance. Indeed, as we noted in AIAA 2017-0007,¹³ many key timing events necessary for a pilot to match the "certified" performance are omitted in the pilots operating handbooks. In many cases, we can only divine the timing implied in a specific aircraft flight

manual by reverse engineering the basis aerodynamic and performance data of an aircraft and comparing it against published performance values.

Thus, the reader can see how complicated “real-world” aircraft operations become. Because pilots often load master an aircraft based upon pro-forma (as opposed to actual) payload weight and predicted fuel economy, aircraft may arrive in the vicinity of the destination airport at an actual flight weight somewhat different from that planned during dispatch. Weather may have changed, resulting in enhanced or diminished braking traction. Finally, pilots may not be trained to fly the aircraft in the same manner as did the test pilots who performed the certification tests incorporated into the AFM. Together, these changes from the ideal scenario used in the flight-manual performance estimations can lead to a significant deviation in the actual field performance of the aircraft compared to the “scheduled performance.”

This paper helps clarify the magnitude of uncertainty during landing.

III. Summary of Scheduled Landing Performance

The reader should always keep in mind that flight manuals provide reference performance data, based upon models that assume that pilots operate aircraft in a specific manner.

The FAA and its predecessor agencies have promulgated many rules and regulations to manage the industry of commercial aerospace (found in Title 14 of the Code of Federal Regulations).^{6,8,9}

Field performance comprises the totality of the following tasks related to takeoff and landing (TOLD): the development of procedures, the setting of key speeds, and the computation of distances and flight paths associated with takeoff and landing.

Aircraft performance engineers compute the total landing distance required (*LDR*), the distance from a point where the aircraft is 50-ft above the airfield level until it reaches a complete stop. They also compute the landing ground roll (*LGR*), the distance to stop from the point where the tires first contact the runway. Deceleration rates must take into account the braking traction afforded by a given runway at the time of landing (see Figure 4). Both MIL-STD-1787¹⁸ and the ICAO¹⁹ provide nomenclature to evaluate available traction. In order to safely land, the landing distance available (*LDA*) must be greater than the landing distance required (*LDR*).

A. Procedural Basics

Officially, the landing distance comprises two sections: 1) the airborne distance from 50-ft to touchdown, and 2) the ground distance from touchdown to stop. “The beginning of the landing distance is referenced to the main gear because it is the lowest point of the airplane when the airplane is 50-ft above the landing surface.”¹⁷ “The end of the landing distance is referenced to the nose gear because it is the most forward part of the airplane in contact with the landing surface, and it should not extend beyond the certified landing distance.”¹⁷ The landing distance comprises two sections: 1) the airborne distance from 50 ft. to touchdown, and 2) the ground distance from touchdown to stop.

Practically, the actual landing distance comprises three distinct elements: 1) pure air phase (aircraft stabilized at a nominal final approach speed and 3-degree flight path angle implied by the VASI lights or localizer RF beam), 2) Transition (where the aircraft “flares” to arrest vertical sink rate before the main tires touch down), 3) Ground phase (where the aircraft derotates, ground spoilers deploy to dump lift and wheel brakes are applied).

RCR	Condition	Rolling resistance (μ)	Braking Capability (w/ anti-skid) (μ)
23	Dry	0.025	0.38
15	Wet	0.050	0.25
11	Wet Snow	0.090	0.18
7	Wet Icy	0.050	0.12

RCR	ICAO Report	Braking Capability (μ)
23	GOOD	> 0.40
	MEDIUM TO GOOD	0.36 to 0.39
12	MEDIUM	0.30 to 0.35
	MEDIUM TO POOR	0.26 to 0.29
5	POOR	< 0.25

Figure 4 – Runway Condition Ratings and associated coefficients of friction (μ).

B. Operational Regulations and Procedure

Landing regulations have been amended many times over the period concerning this study. The earliest applicable rule set for aircraft of interest are found in 14 CFR § 4b;²⁰ this regulation package was later amended and reorganized into the modern 14 CFR § 25 rule set.⁶ In 2007, the FAA amended the regulation controlling the stall speed ratio for the landing reference speed, *VREF*, from 1.3 Vs to 1.23 Vs.²¹ In theory, this change provides an effective reduction in required field length; again, at the expense of a reduction in balked landing climb performance (14 CFR § 25.121(d)²² and 14 CFR § 25.119).²³

We present edited copies of current landing regulations^{24,11} below:

14 CFR § 25.125 Landing.

(a) The horizontal distance necessary to land and to come to a complete stop ... from a point 50 feet above the landing surface must be determined

...

(b) In determining the distance in paragraph (a) of this section:

(1) The airplane must be in the landing configuration.

(2) A stabilized approach, with a calibrated airspeed of not less than *VREF*, must be maintained down to the 50-foot height.

(i) In non-icing conditions, *VREF* may not be less than:

(A) 1.23 VSR0;

(B) VMCL established under §25.149(f); and

(C) A speed that provides the maneuvering capability specified in §25.143(h).

...

(4) The landing must be made without excessive vertical acceleration, tendency to bounce, nose over, ground loop, porpoise, or water loop.

(5) The landings may not require exceptional piloting skill or alertness.

...

(g) If any device is used that depends on the operation of any engine, and if the landing distance would be noticeably increased when a landing is made with that engine inoperative, the landing distance must be determined with that engine inoperative unless the use of compensating means will result in a landing distance not more than that with each engine operating.

[Amdt. 25-121, 72 FR 44666; Aug. 8, 2007; 72 FR 50467, Aug. 31, 2007]

14 CFR § 121.195 - Airplanes: Turbine engine powered: Landing limitations: Destination airports.

(a) No person operating a turbine engine powered airplane may take off that airplane at such a weight that (allowing for normal consumption of fuel and oil in flight to the destination or alternate airport) the weight of the airplane on arrival would exceed the landing weight set forth in the Airplane Flight Manual for the elevation of the destination or alternate airport and the ambient temperature anticipated at the time of landing.

(b) Except as provided in paragraph ... (d) ... of this section, no person operating a turbine engine powered airplane may take off that airplane unless its weight on arrival, allowing for normal consumption of fuel and oil in flight (in accordance with the landing distance set forth in the Airplane Flight Manual for the elevation of the destination airport and the wind conditions anticipated there at the time of landing), would allow a full stop landing at the intended destination airport within 60 percent of the effective length of each runway described below from a point 50 feet above the intersection of the obstruction clearance plane and the runway.

...

(d) A turbojet powered airplane that would be prohibited from being taken off because it could not meet the requirements of paragraph (b)(2) of this section may be taken off if an alternate airport is specified that meets all the requirements of paragraph (b) of this section.

[Doc. No. 6258, 29 FR 19198, Dec. 31, 1964, as amended by Amdt. 121-9, 30 FR 8572, July 7, 1965]

In standard commercial operations, the approach to the airfield precedes that landing phase. As the aircraft descends out of the en route portion of the flight, the aircraft is vectored to the approach side of the airfield with the help of Standard Terminal Arrival Routes (STARs) and through the direction of ATC. The STARs give pilots a standardized terminal approach to plan to and follow, however, ATC can command deviations that aircrews are expected to follow. During this approach phase, the aircraft is slowed with the aircrew performing checks and preparations to ready the aircraft for landing.

When proximate to the airfield, the aircraft will enter the final approach phase. This phase has the aircraft lined up with the appropriate runway, while slowing to final approach speed (VREF) and deploying landing gear and landing flaps. The outer marker commonly identifies the final approach starting point, which is a narrow RF beam that projects from the ground upwards. This point is typically 4-7 nautical miles from the runway threshold; upon crossing the outer marker the aircraft is expected to be in final landing configuration and on a stabilized approach.

As well as identifying the final approach point, or the Final Approach Fix (FAF), the outer marker point also indicates the appropriate distance which the aircraft should have acquired the “localizer.” This narrow RF beam gives the aircraft a path to follow that leads to the runway, should visual cues not be possible due to inclement weather or other visual obstructions. Upon reception of the localizer signal, the Instrument Landing System (ILS) displays steering cues to the pilot in order to achieve the 3° glideslope and runway alignment. Pilots often use the ILS system for IFR approaches.

At about 0.5 nautical miles, the aircraft will cross the middle marker. This marker is often near the minimum IFR approach point of 200-ft, often referred to as “minimums” or Decision Height (DH), where the aircrew must initiate a go around if the runway is unable to be visually acquired. The horizontal distance the aircraft may actually encounter DH would depend on the deviation from the ideal flight path; the middle marker is intended to serve as advisory information of horizontal distance from the airfield. More sophisticated aircraft with “autoland” functionality and high-precision position sensing have the ability to proceed lower than the typical 200-ft, however, this also requires the appropriate support facilities for this on the airfield.

The beginning of the landing phase starts as the aircraft crosses the runway threshold, which is identified by the inner marker. The aircrew is expected to have visually acquired the airfield at this point and be preparing for touchdown. Specific procedures may vary, but as the aircraft enters ground effect, the pilot should hold constant attitude or elevate the nose slightly executing a “flare” maneuver (“there should be no nose depression by use of the longitudinal control”¹⁷). Pilots are allowed to retard thrust to idle during the flare. Once wheels have contacted the runway (touchdown), the pilot may actuate the lift dump system and apply brakes although this is commonly automated upon sensed weight-on-wheels. The aircraft should be “de-rotated at a controlled rate to preclude an excessive nose gear slap-down pitch rate.”¹⁷ Manually applied brakes cannot be applied “before all main gear wheels are firmly on the ground” as overzealous braking action on the pilot’s behalf can result in excessive derotation rates.¹⁸ When calculating the AFM landing distances, the manufacturer may account for the “speed loss from 50 feet to touchdown.”¹⁷ Moreover, “the target rate of descent at touchdown should not exceed 6 feet per second.”¹⁸

Because the FAA recommends a maximum target sink rate at touchdown of 6-ft/sec, simple geometry applied to the 3-degree approach path provides insight to the minimum approach speed that can be flown without a flare maneuver. At $V_{REF} = 68$ -KTAS, flown on a 3-degree path, the vertical velocity component just attains the limiting value of 6-ft/sec. In theory, all approaches flown faster than 68-KTAS, should include some form of flare. For example, an aircraft on a standard approach path with $V_{REF}=137$ KTAS has a basic sink rate of ~12 ft/sec that must be arrested with some form of flare maneuver.

After the aircraft is firmly on the ground, wheel-braking action is maximized depending on runway conditions or length. Slippery runway conditions will limit the maximum braking effort that can be exerted resulting in longer field length requirements. With an excessively long runway, aircrews can elect to reduce wheel-braking effort and rely more on less effective aerodynamic braking. This strategy is commonly employed in an effort to reduce wear and tear on the aircraft.

Many engineers claim that the FAA regulations state that reverse thrust credit cannot be used in determining landing distance requirements. However, the use of thrust reversing during landing is common in day-to-day operations in the United States. Formally, 14 CFR § 25.125 (g) only disallows credit for a deceleration device “that depends on the operation of any engine.”²⁴ This, conceivably would allow for credit for the reverse thrust developed by at least one engine of a twin engine aircraft, provided

that a stop with asymmetric reverse thrust would “not require exceptional piloting skill.”²⁴ AC-25-7C specifically calls out (for takeoff) that “Section 25.109(f) was added to permit credit for the use of reverse thrust in determining wet runway accelerate-stop distances ... and to explicitly deny reverse thrust credit for determining dry runway accelerate-stop distances.”¹⁷ However, AC-25-7C is very vague regarding jet engine reverse thrust credit for landing.¹⁷

C. Real World Experiences

Because regulation 14 CFR § 25.125 requires the engineer to determine the landing performance under normal operating conditions but does not allow credit for systems that would be inoperative in the event of an engine failure, we can easily compute the total distance covered by the aircraft from “a point 50 feet above the landing surface,” through touchdown, and deceleration to “come to a complete stop.”¹⁷ (see Figure 5)

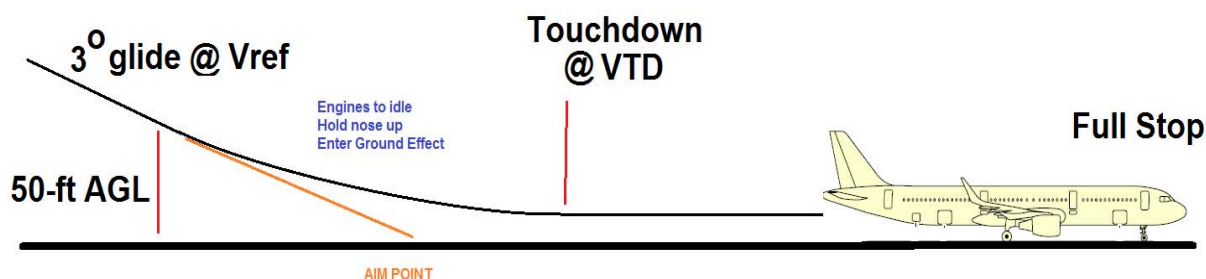


Figure 5 – Schematic of Aircraft Approach, Flare, Touchdown and Landing Roll Out

The simulation must begin with stabilized, descending flight at the landing reference, V_{REF} , at an altitude 50-ft above the airfield and a descent flight path angle of -3° . We compute the first portion of distance covered in the air phase of landing using simple geometry. The second portion accounts for the transition phase before the wheels contact the ground. Between crossing the threshold and touchdown, the pilot retards the engine thrust to idle, and elevates the nose to arrest the sink rate as the aircraft enters ground effect. The pilot may not exceed the tail strike pitch angle in this procedure. This simulation reflects the verbiage of 14 CFR § 25.125(b)(5) that states that “landings may not require exceptional piloting skill or alertness.”²⁴

The nominal air phase comprises the time to cover flight to the “aim point,” which is governed by simple geometry. On a standard approach, the aim point is $50\text{-ft} / \sin(3^\circ) = 955\text{ ft}$ down range from the 50-ft point.



Figure 6 - Runway Markings at KPHX (7R – long runway)

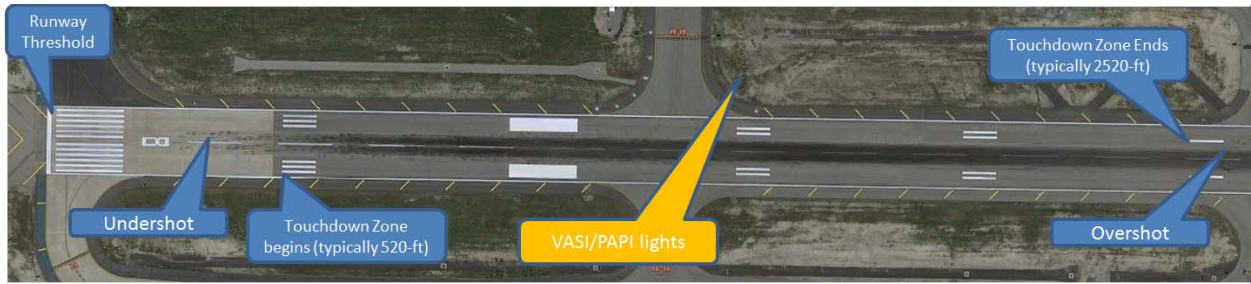


Figure 7 - Runway Markings at KBUR (8 – short runway)

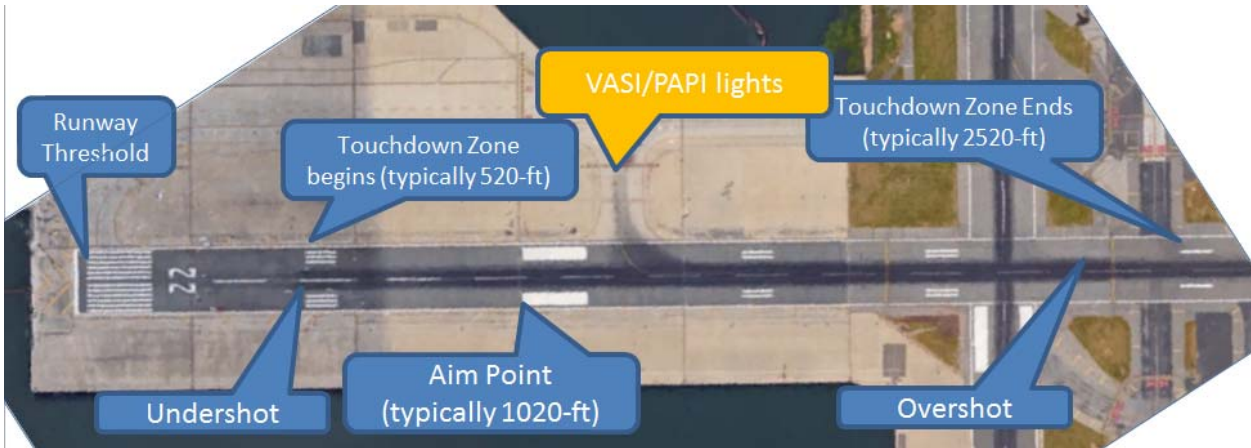


Figure 8 - Runway Markings at KLGA (22 – short runway)

Following FAA AC-150/5340-1L, which governs runway markings, the typical touchdown aim point begins 1,020-ft beyond the threshold (see Figures 6, 7 and 8) with visual cues every subsequent 500-ft.²⁵ It is interesting to note that the visual approach slope indicator (VASI) lights at KPHX are located approximately 200-ft down runway (~1300-ft beyond the threshold) from the nominal aim point. Thus, the VASI lights guide a pilot landing a small aircraft on runway 7R at KPHX to touchdown beyond the nominal aim point. Conversely, due to visual parallax the VASI lights will guide a pilot landing a large aircraft (~100-ft wheelbase) with a nose-high touch down attitude to touchdown on the aim point markers. Due to the location of a taxiway (see Figure 7), the VASI lights at KBUR are located a further 200-ft down runway (~1,500-ft beyond the threshold), and will likely guide pilots to longer air phase distances. The VASI lights at KLGA (see Figure 8), like those at KPHX, are located ~1,300-ft from the threshold.

The authors maintain careful logs regarding the air phase distance they personally observe while flying on commercial 14 CFR § 25 jets (see Table 1, overleaf). This dataset comprises operations flown only in good weather, with dry runways; most likely the landing was performed under visual flight rules.

Of the 31 observed landings, in only three instances did the aircraft actually touch down on the painted aim-point (or slightly ahead); the remaining 90% of landings resulted in a touchdown point beyond the formal aim point. In our dataset, the mean touchdown point was ~1,675-ft downrange with a +/- 565-ft standard deviation. Three observed landings ended with a prolonged flare that resulted in more than 2,500-ft air phase distance. None was overshoot by the ~4200-ft air phase of the ill-fated Pence flight

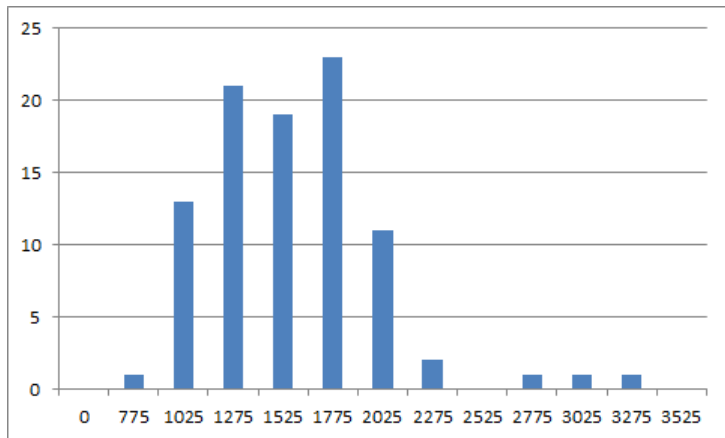


Figure 9 – Histogram of Air Phase distances

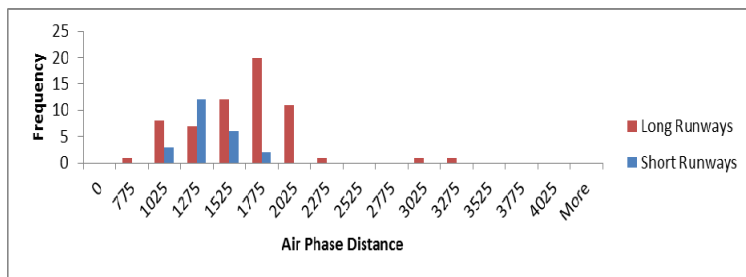


Figure 10 – Histogram of Air Phase distances data sets separated between operations onto a long runway vs. operation into known “challenging airports” KLGA, KBUR, KHPN and KDCA.

Table 1 – personal observation air phase distances Observed Air Phase Distance from Commercial Carriers (visual estimate from on-board passenger - accurate to ~200/ft).

Date	Airport	Aircraft	Est Dist
6/9/2017	KPHX	E175	2600
6/9/2017	KLAX	B777200	900
6/6/2017	KPHX	B737900	1100
6/4/2017	KDEN	B737800	2200
3/6/2017	KDEN	B737	1700
3/3/2017	KDEN	B737	1200
3/3/2017	KLGA	B737	1500
1/21/2017	KPHX	CRJ700	1750
1/21/2017	KBUR	CRJ900	1250
1/13/2017	KIAH	A320	2000
1/11/2017	KPHX	A321	1750
1/8/2017	KDFW	A321	1000
1/8/2017	KDFW	E170	1750
1/8/2017	KIAH	B737900	2000
12/21/2016	KEWR	A320	1250
9/5/2016	KPHX	B737900	1500
9/2/2016	KEWR	B737900	1750
8/13/2016	KPHX	A320	3200
8/13/2016	KORD	B767300	1500
7/1/2016	HAI	A319	900
6/30/2016	EGLL	B757200	1200
6/29/2016	KIAD	B737900	2000
6/29/2016	KDEN	B737800	3000
6/26/2016	KPHX	A320	1800
6/5/2016	KPHX	A320	2000
5/12/2016	KEWR	B737	1500
4/18/2016	KPHX	CRJ700	900
4/18/2016	KDEN	E175	1750
4/14/2016	KDEN	B737900	1700
4/14/2016	KICT	A320	1400

In most of our observations, we witnessed a throttle chop during flare. Typically, pilots retard the throttles shortly after the aircraft passes the threshold. Some approaches were flown with a fully stabilized airspeed all way to touchdown. On a few flights, particularly those involving the B737-900, we observed the pilot applying a throttle bump during flare to help arrest sink rates. According to the flight-monitor display in the cabin, touch down occurred 2 or 3 knots faster than *VREF*.

In addition to the personal dataset, the authors with additional student help, reviewed a diverse collection of posted “You-Tube” videos. With an augmented data set of 84 observed landings, we found a mean touchdown point was ~1505-ft downrange with a +/- 435-ft standard deviation. We plotted this data in histogram form as Figure 9; the data set clearly does not form a classical “normal distribution.” We then re-sorted the data to look at the distribution for flights into known “challenging airports” with short runways (LaGuardia, Burbank, White Plains and Washington/National) (see Figure 10). After we teased apart the data, we see a more classical normal distribution forming only when pilots fly into challenging airports (an average air-phase of 1250-ft with a standard deviation of +/- 204-ft). We believe that when pilots fly onto a typical long runway, they intentionally “grease” the touchdown. This results in air phase distances that are both much longer than expected and from a statistical perspective “all over the place.”

IV. Numerical Simulations

In order to build a numerical model of the aircraft landing procedure, engineers must identify relevant “cue speeds” as well as relevant procedure and timing.

Key aircraft speeds during both ground and flight phases of landing are annotated in terms of KIAS. This exists because flight is a function of the dynamic pressure, q that the airplane experiences rather than its physical speed on the ground. On the other hand, the kinetic energy of an aircraft is proportional to its true airspeed, KTAS. Therefore, numerical simulations must simultaneously track aircraft speeds in terms of KIAS (for procedural control) as well as KTAS (to satisfy the equations of motion).

A. Nominal Stabilized Final Approach and Touchdown Speed

Transport category aircraft may have many different flap settings. At minimum, aircraft have three flap settings representing cruise, takeoff and landing. The Airbus A320, for example, has five settings: **UP** (used for en-route flight), **CONF 1+F** (deploy the takeoff leading edge slats and minimally deploy the trailing edge flaps), **CONF 2** (further deploy the trailing flaps), **CONF 3** (extend the landing leading edge slats and fully extend the trailing edge flaps), **FULL** (maximum deflection of the trailing edge flaps).²⁶ Each successive flap setting increases both the maximum lift coefficient (CL_{max}) and zero-lift-drag (CDO).

The landing reference speed, V_{ref} , is the lowest scheduled stabilized airspeed flown during the landing sequence. It represents the airspeed that the aircraft maintains on its final approach until it just begins to enter ground effect, 50-ft above the runway surface. Regulation 14 CFR § 25.125²⁴ holds that V_{REF} must be the greater of either 123% of the stall speed in the landing configuration or the minimum control speed in landing, $VMCL$.

$$V_{ref} = \max(1.23 V_{s_{landing}}, VMCL) \quad (1)$$

Where V_s is the stall speed with the flaps in the landing (**FULL**) setting.

The minimum control landing airspeed, $VMCL$, represents the lowest airspeed during flight where “when the critical engine is suddenly made inoperative, it is possible to maintain control of the airplane ... and maintain straight flight with an angle of bank of not more than 5 degrees” with the flaps in the touchdown setting, the remaining engines brought to full (“TO/GA”) power and the landing gear deployed.²⁷

While our simulation fully models the air phase, please note that FAA advisory circular AC-25-7C states that “experience shows an upper bound to the part 25 zero-wind airborne distances achieved in past certifications and, similarly, a minimum speed loss.”¹⁷ Thus, some manufacturers may use the following supplied FAA distances in lieu of a physics based (or flight test) model:

$$\text{Air Distance (feet)} = 1.55 (V_{REF}-80)^{1.35} + 800 \text{ where } V_{REF} \text{ is in knots TAS} \quad (2)$$

$$\text{Touchdown Speed} = V_{REF} - 3 \text{ knots} \quad (3)$$

For this work, we do not follow the FAA guideline. We go beyond the “pro-forma” distance by allowing our simulation to model an aircraft flying above or below the scheduled V_{ref} speed. In this paper, we will call this speed V_{REF} (the all caps version being “actual” as opposed to “scheduled” speed). There are two mechanisms that lead to $V_{REF} \neq V_{ref}$: the first being the fact that the actual final approach aircraft weight differs from the pro-forma value the pilot uses to set his cue speed, the second being a case where the pilot does not successfully stabilize final approach at the intended speed (due, for example, to wind shear).

Figure 11 depicts the weight dependent V_{REF} schedule for the Airbus A320 with **FULL** landing flaps.²⁶ For this aircraft, the reference speed varies by about 1 knot per 2,000-lbm in aircraft mass. Thus a 10,000-lbm discrepancy between pro-forma and actual landing weight will result in the aircraft flying $V_{REF} \sim V_{REF} + 5KIAS$ if the aircraft is lighter than expected (i.e. additional stall speed margin) and $V_{REF} \sim V_{REF} - 5KIAS$ if the aircraft is heavier than expected (i.e. reduced stall speed margin).

The touchdown speed, V_{TD} , is the speed the aircraft is flying at the moment the main landing gear contacts the runway. Because the AFM does not necessarily call out a specific flight procedure used to develop the certified landing distances, pilots are likely to improvise their own procedure.

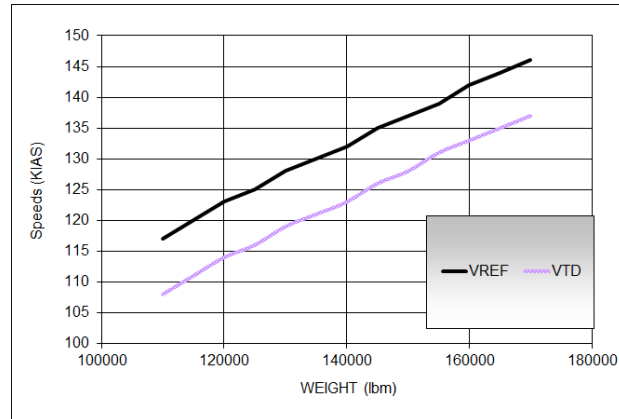


Figure 11 – Weight dependence of V_{REF} – A320 FULL Flaps (after A320 FCOM)

The actual touchdown speed may vary significantly from the stabilized approach speed. In our simulation, we include a “throttle cut” to idle during the flare maneuver. In all cases, the aircraft crosses the threshold at a stabilized airspeed with throttles advanced enough to maintain the sink rate and constant indicated airspeed. Our simulation has the option of holding stabilized airspeed all the way to touchdown; in other words having touchdown (V_{TD}) at our actual V_{REF} ; or retarding throttles to idle during the flare.

Procedural variation may result in V_{TD} being faster, slower or equal to the landing reference speed. Many autoland systems typically apply autothrottle to maintain constant airspeed through the entire final approach including landing flare; this procedure results in $V_{TD} \sim V_{REF}$. A common landing procedure will have the pilot reduce power just as the aircraft crosses the threshold (nominally 50-ft above ground level). The aircraft will settle as it decelerates and fully enters ground effect during the landing flare maneuver and touchdown a few seconds later. This procedure results in $V_{TD} < V_{REF}$. Conversely, a throttle “push” to help soften touchdown can increase airspeed so that $V_{TD} > V_{REF}$ by several knots. Certified distances typically take into account throttle retardation during flare, and hence a touchdown speed lower than V_{REF} and a corresponding reduction in braking distance.

If the pilot chooses to select either idle or significant thrust during flare, we may estimate the difference between V_{REF} and V_{TD} from the implied imbalance between aerodynamic and propulsive forces. To compute this, we must first compute dimensional drag for the aircraft in ground effect at the flight speed. We can approximate this by assuming that the deceleration is small, so we just compute the dimensional drag at V_{REF} from the drag coefficient with landing flaps deployed in ground effect at the landing angle-of-attack with any increments for extended landing gear:

$$D = (C_{D_{REF}}(\alpha_{Landing}) + \Delta C_{D_{gear}}) \cdot \left(1481 \cdot \left(\frac{V_{REF}}{1000} \right)^2 \right) \cdot S_{ref} \quad (4)$$

Then, we may infer the touchdown speed based upon application of any given thrust imbalance over a particular flare time:

$$V_{TD_{FTSEC}} = V_{REF_{FTSEC}} - \frac{mg(T_{idle} - T)}{W} \cdot 32.2 \Delta t_{FLARE} \quad (5)$$

Returning to Figure 11, we can see an estimate of the touchdown speed of an Airbus A320 provided full “throttle cut” to idle is made just as the aircraft crosses the threshold. Our simulation shows a level of thrust imbalance the results in an aircraft that loses ~10 KIAS airspeed over the 5-seconds between threshold and touchdown.

For our parametric simulation, which allows us to arrive at the threshold either above or below the standard 50-ft altitude, we may vary the altitude where the throttles retard. Recall, our calibration work leads us to believe that the official Airbus procedure (when arriving over the threshold at 50-ft AGL) begins a throttle cut early in the flare. In our simulation, we can vary the throttle cut from 50-ft AGL

down the 25-ft AGL or even hold our threshold speed all the way to touchdown. Combined with a parametric variation in threshold altitude, our simulations capture a wide dispersion in possible touch down speeds.

B. Geometric Modelling of Air Phase Distance from Threshold to Aim Point

The simplest estimate of the air phase distance derives from the simple geometry found in Figure 5 (above). The down range location of the aim point is a function of the aircraft altitude at the threshold (the screen height, H_{OBS}) and the stabilized final approach flight path angle, γ :

$$D_{AIMPOINT} = H_{OBS} / \sin(\gamma) \quad (6)$$

The nominal air phase distance varies widely based upon geometry; this may be graphically represented in Figure 12. If the pilot crosses the threshold 50-ft above the nominal altitude (i.e. at 100-ft), the air phase distance is doubled. If the pilot flattens out his approach trajectory (either continuing to follow a shallow visually approach or by flattening the trajectory due to an early flare) that results in the air phase being flown at a 2-degree sink rate, the air phase distance extends roughly 500-ft. Combining these two effects can easily extend the air phase distance to nearly 3000-ft.

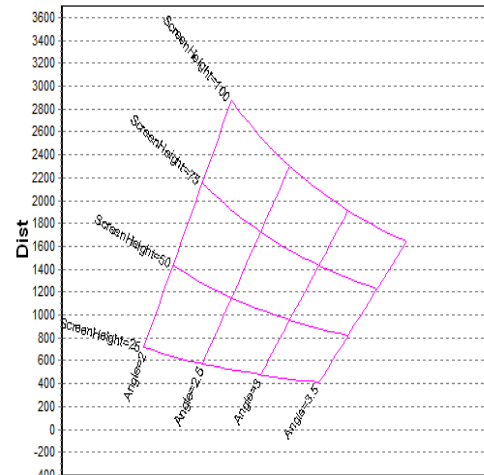


Figure 12 – Aim Point geometry

C. Geometric Modelling of Total Air Phase Distance from Threshold to Touchdown

Finally, we may calculate the total air phase distance for a normal approach by summing the distance to the nominal touchdown point with the additional distance that aircraft travels in landing flare (approximated by multiplying the time to flare by the average flight speed).

Our simulation time step integrates the motion of the aircraft during this maneuver. It allows for trades based upon a minimum air phase time (nominally 6 seconds) between 50-ft and touch down as well as one controlled by the actual time needed to traverse the distance from the threshold to the aim-point.

D. Flare, Touchdown and Transition to Ground Roll Simulation

Once the wheels touch down, the plane needs to de-rotate so that all wheels are firmly in contact with the runway. On an aggressive landing, performed to the letter of regulation 14 CFR § 25.125, which requires distances to be computed for procedures that do “not require exceptional skill or alertness,” this maneuver is likely to take 2 or 3 seconds.²⁴

In the absence of a functioning auto-braking system, the pilot is expected to de-rotate, then dump lift and apply brakes. With an automatic braking assistance system, the aircraft may automatically dump lift and apply brakes upon contact of the main landing gear. The pilot will de-rotate during the braking phase.

Our simulation time step integrates the motion of the aircraft during this maneuver. It allows for trades based upon minimal reaction times (nominally 4 seconds) for lift dump deployment and maximum braking effort application upon transitioning to ground roll.

E. Rollout, Braking to Stop

After the aircraft has transitioned to ground roll, maximum braking effort is applied along with aerodynamic braking. For certification distances, no credit for reverse thrust is allowed. The idle thrust of the engines continues to oppose the braking action of the tires.

Our simulation time step integrates the motion of the aircraft during this maneuver. Runway conditions are simulated as dry; however, allowances have been made to vary the braking traction effectiveness for trade studies.

V. Trade Studies

This paper will consider the effects of various aerodynamic, propulsive, mass-properties and human factors uncertainties upon the landing distances of a notional narrow-body twin-engine commercial airliner, reminiscent of an Airbus A320. It will compare and contrast these new results with effects of timing and operational parameters published in AIAA 2017-0007.¹³

While AIAA 2017-0007 examined timing and braking effects upon both takeoff and landing, in this new paper, we examine the effects of operational variation upon speeds and distances during landing for an aircraft flown against a specific “book.” Thus, we seek to understand:

- What are the effects of small changes in flight weight to the actual landing distance? Consider aircraft arriving at the threshold at a speed scheduled for an incorrect weight.
- What are the effects of small changes in flight path to the actual landing distance? We consider aircraft arriving at the threshold both above and below their intended altitude (flight paths from 25 to 200-ft AGL at the threshold as deviation from the nominal 50-ft).
- What are the effects of small changes in approach speed to the actual landing distance? We consider aircraft arriving at the outer marker both above and below its intended reference speeds
- What are the effects of throttle chop during flare? We consider how this procedure impacts touchdown speeds and landing distances
- What are the effects of prolonged flare?
- What are the effects of slow/fast derotation rates?
- What are the effects of delayed lift dump and braking action for landing?
- What are the impacts of changes in tire traction to the actual landing distance? We will consider a variety of braking traction coefficient cases.

While we expect some of these trades to have greater impact than others, we keep all variance within a reasonable window in order to understand the impact of subtle changes in speeds, flight paths and weights that pilots encounter in day-to-day operations of a typical commercial airliner. Extreme changes that have very low probabilities of occurrence are outside the scope of this analysis.

The takeaways from these trades let us examine the impact of pilot training and timing on critical field length.

A. Baseline Aircraft

The nominal aircraft configuration employed here is reminiscent of an Airbus A320. Our best estimate at reverse engineering published field performance values for an A320 with IAE V2527-A5 engines is shown below in Table 2.

We find excellent agreement between certified performance and our analytical model based upon the following assumptions. It features an aspect ratio 8.5 wing of $S_{ref}=1319$ ft². Gear up zero-lift drag for “FULL” landing flaps is $CD_0=0.0550$. Extended landing gear adds an additional $\Delta CD_0=0.0100$. Lift dump spoilers add an additional $\Delta CD_0=0.0250$ and reduce lift $\Delta CL=-0.4$ for landing. Windmill drag of an inoperative engine adds $\Delta CD_0=0.0050$. Setting **FULL** landing flaps produces $CL_{max}=2.7$ with zero incidence $CL_0=0.7$. The notional ground incidence is $\alpha=-1^\circ$. Maximum ground incidence at tail strike is $\alpha_{max}=18^\circ$. Cue speeds, controlled by lateral-directional control power, are limited by $VMCL=110$ KIAS. We model a 27,000-lbf static thrust engine with speed dependent thrust lapse commensurate with a BPR=6 engine; there is no thrust push upon sensed engine failure.

Table 2 – Baseline Aero Data

CD0 t/o & approach flaps	0.0225
CD0 landing	0.0550
dCDgear	0.0070
dCDspoilersLanding	0.0250
dCLspoilersLanding	-0.4000
CL0 landing	0.7000
CLmax_LD	2.7
VMCL	110 kias

Table 3 - Baseline Timing

LANDING	
Time in Flare	6 sec
Derotate / Lift Dump / Brake Applicat	4 sec

Table 4 - Baseline Field Performance Estimates (reverse engineered A320)
Performance computed using $\mu=0.5$ braking traction

Wt (lbm)	Alt(ft)	FAA factored LDR (ft)	LDR no rev T (ft)	LGR no rev T (ft)	PLA in flare	AOA @ Vref	Horizon attitude @ Vref (normal)	Vapp (kias)	Vref (kias)	Vtd (kias)
170000	0	5650	3400	2150	IDLE	11.8	8.80143	173	146	137
165000	0	5500	3300	2100	IDLE	11.8	8.80143	170	144	135
160000	0	5350	3200	2050	IDLE	11.8	8.80143	167	142	133
155000	0	5250	3150	1950	IDLE	11.8	8.80143	165	139	131
150000	0	5100	3050	1900	IDLE	11.8	8.80143	162	137	128
145000	0	4950	2950	1850	IDLE	11.8	8.80143	159	135	126
140000	0	4800	2900	1750	IDLE	11.8	8.80143	157	132	123
135000	0	4650	2800	1700	IDLE	11.8	8.80143	154	130	121
130000	0	4550	2700	1650	IDLE	11.8	8.80143	151	128	119
125000	0	4400	2650	1550	IDLE	11.8	8.80143	148	125	116
120000	0	4250	2550	1500	IDLE	11.8	8.80143	145	123	114
115000	0	4100	2450	1450	IDLE	11.8	8.80143	142	120	111
110000	0	3950	2350	1400	IDLE	11.8	8.80143	139	117	108

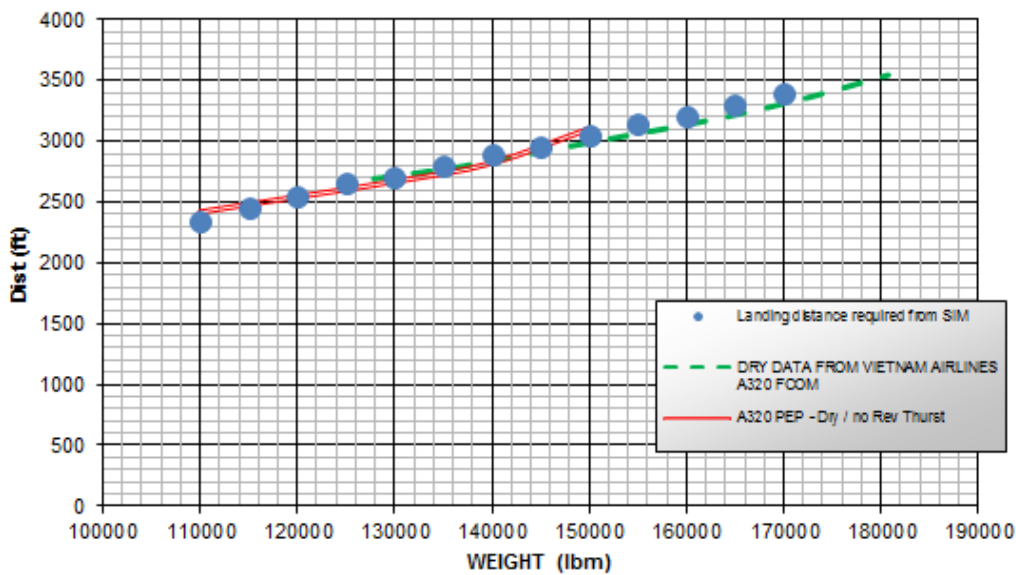


Figure 13 – Baseline Field Performance Results (comparison with A320 flight manual)

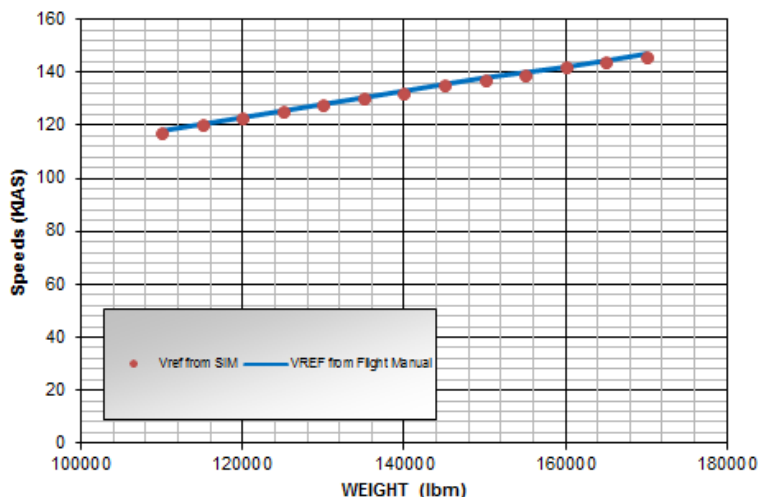


Figure 14 – Landing Final Approach Speeds (comparison with A320 flight manual)

Following our best guess at the baseline reaction times for landing (see Table 3, above), we attempted to calibrate our simulation against published field performance data. To reasonably match published data, we had to employ (for the baseline model), very aggressive landing timing following the A320 flight manual procedures. Lift dump and braking commence immediately upon the mains contacting the runway. Derotation occurs after brake application. Braking effectiveness is quite strong, with a dry runway braking traction $\mu=0.5$.

Comparing the approach speeds and landing field length requirements found in A320 manuals and performance calculation software to the outputs from our numerical simulation, we find very good calibration. The numerical simulation trends follow the AFM data extremely well, with increases in approach speed and landing distance as expected.

Table 4 (prior page) shows field length requirements and approach speed for the baseline aircraft at varying weights. All field length calculations are done without reverse thrust credit, per 14 CFR § 25.125(c)(3).²⁴ The Landing Distance Required (*LDR*), which includes the air phase distance from 50-ft, is calculated along with the Landing Ground Roll (*LGR*). The *LGR* is calculated at the point the main landing gear touches the ground, through derotation and roll out. Approach speeds are also calculated for the varying weights on a 3° approach glideslope.

Figure 13 (prior page) shows a graphical representation of the certified landing distances from the numerical simulation compared to the outputs from the A320 performance estimation program and the performance estimates from the Vietnam Airlines FCOM.²⁶ The numerical sim follows the increasing landing distance with higher weight trends from both calibration sources very closely. The numerical simulation is very well calibrated for landing distance calculations.

Figure 14 shows a graphical representation of the final approach speed (*VREF*) output from the numerical simulation compared to the *Vref* speeds listed in the A320 manual. The numerical sim follows the published increasing approach speeds trend with higher weight very closely. The numerical simulation is very well calibrated for approach speed calculations.

B. Effect of Operational Variance – Height at Threshold

Figure 15 displays the effects on actual landing distance from varying threshold height. The field length requirements are evaluated with the aircraft crossing the runway threshold on a 3° glideslope at the lowest height of 25-ft with a maximum height of 200-ft, in 25-ft increments.

The baseline for the threshold height is 50-ft. Approach speed, time in flare, and derotation timing are held constant for all scenarios, as well as aircraft payload with a landing weight of 135,000-lbm. Reverse thrust is not used in any simulation.

We see an enormous variation in actual landing distance here. The trend shows a non-linear response at low deviations (due to the presence of the required flare maneuver). At 75-ft+ deviations the response is linear with increasing runway usage. We can see that the 14 CFR § 121.195¹¹ 167% factored landing distance value recommended by the FAA can safely accommodate a large error in threshold crossing height. However, the 115% SaFO factored distance¹² can only absorb a small, 25-ft, deviation in threshold crossing altitude.

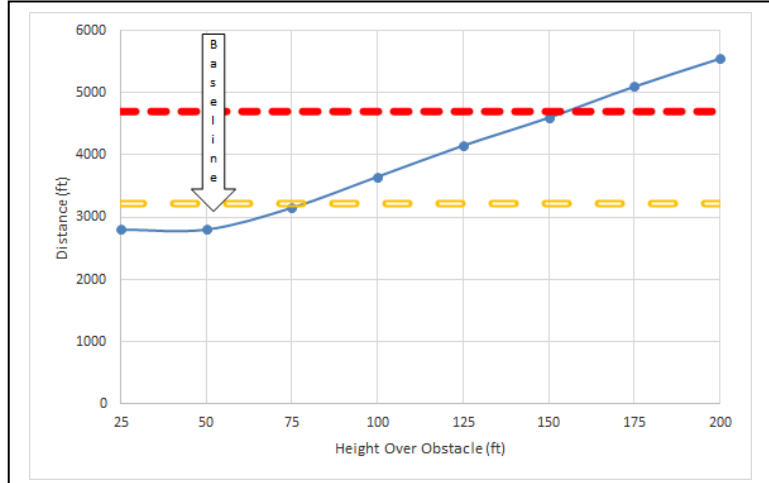


Figure 15 – Effect of Varying Runway Threshold Height on 1 Landing Distance. Solid line: Simulation. Thick Dashed line: 14 CFR § 121 Factored Distance. Compound Dashed line: 115% SaFO Factored Distance.

C. Effect of Operational Variance – Flight Weight

Figure 16 displays the effects on actual landing distance from deviations in aircraft dispatch weight. Landing configuration and V-speeds are determined from a dispatch provided arrival weight of 135,000-lbm, with the aircraft actual weight deviating from 10,000-lbm under to 20,000-lbm over. The field length requirements are evaluated with the aircraft crossing the runway threshold on a 3° glideslope at a height of 50-ft. Approach speed, time in flare, and derotation timing are held constant for all scenarios. The trend shows negligible effects on landing performance due to actual landing weight deviations.

Our results should not be surprising upon further consideration. Recall that fundamental geometry governs the actual landing air phase distance. Similarly, the braking distance is controlled by the deceleration capabilities of the brakes applied to a given touchdown speed. Thus, an error in actual landing weight that is not recognized by the pilot will not cause the aircraft to deviate from either its stabilized *VREF* speed or its touchdown speed. While an overweight aircraft will fly with reduced stall speed margin (and hence acquire additional air-phase flight risk), this sort of error does not substantially affect landing distance. Both the SaFO¹² and 14 CFR § 121¹¹ factored distances fully cover this error.

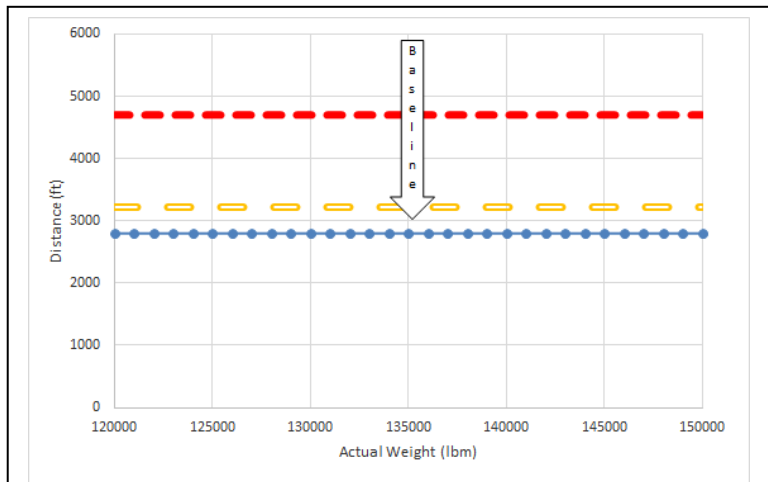


Figure 16 – Effect of Varying Deviation in Aircraft Dispatch Weight on Landing Distance. Solid line: Simulation. Thick Dashed line: 14 CFR § 121 Factored Distance. Compound Dashed line: 115% SaFO Factored Distance.

D. Effect of Operational Variance – Approach angle

Figure 17 displays the effects on actual landing distance from varying glideslope angles. We evaluate the field length requirements with the aircraft crossing the runway threshold on a 2.5°, 3°, and 3.5° approach path angle at a height of 50-ft AGL. Approach speed, time in flare, and derotation timing are held constant for all scenarios, as well as aircraft payload with a landing weight of 135,000-lbm. The trend shows a negligible response in landing performance with the varying glideslope angles.

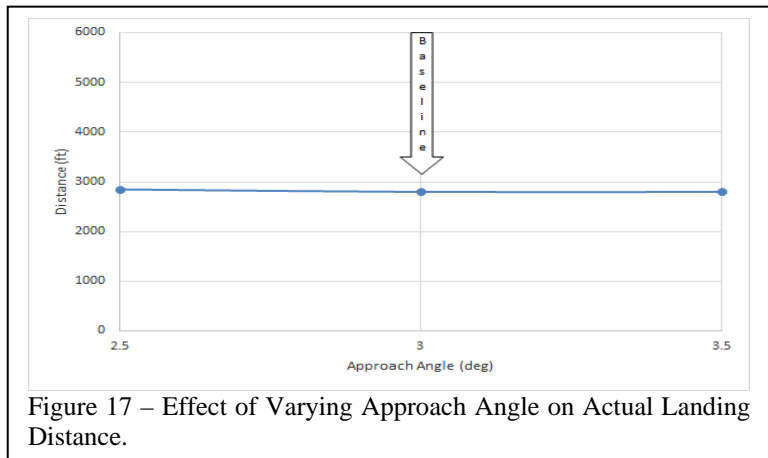


Figure 17 – Effect of Varying Approach Angle on Actual Landing Distance.

This trend is, perhaps, an artifact of our simulation. The choice of approach angle does not appreciably influence the air phase distance or the touchdown speed, so long as the pilot maintains a consistent time in flare.

E. Effect of Operational Variance – Changes in actual V_{REF} at 50-ft

Figure 18 displays the effect on actual landing distance from varying final approach speed (V_{REF}). The field length requirements are evaluated with the aircraft crossing the runway threshold at 50-ft on a 3° glideslope with the approach speed ± 10 KIAS from the baseline. Time in flare and derotation timing are held constant for all scenarios, as well as aircraft payload with a landing weight of 135,000-lbm. The trend shows a linear decrease in field length requirements with a lower approach speed and, conversely, an increase in runway usage for a higher approach speed. Large deviations in V_{REF} show significant response to landing distance requirements.

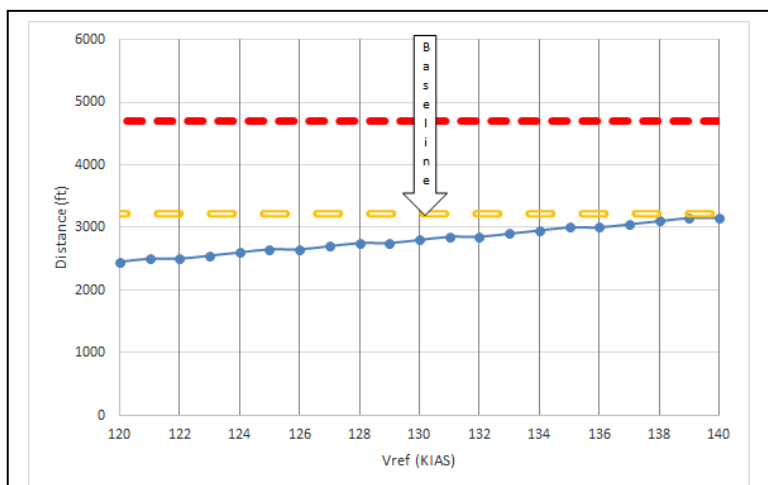


Figure 18 – Effect of Varying Final Approach Speed on Landing Distance. Solid line: Simulation. Thick Dashed line: 14 CFR § 121 Factored Distance. Compound Dashed line: 115% SaFO Factored Distance.

We can see that the 167% factored landing distance value recommended by the FAA¹¹ can safely accommodate a large error in actual final approach and, hence, touchdown speed. However, the 115% SaFO factored distance¹² can only absorb a small, 10-knot deviation in final approach and touchdown speed.

F. Effect of Operational Variance – Throttle Retard in Flare

Figure 19 (overleaf) displays the effect on actual landing distance from varying throttle “chop” altitudes. The field length requirements are evaluated with the aircraft crossing the runway threshold at 50-ft, however, the throttles are retarded at the 50-ft (baseline), 25-ft and 0-ft (touchdown) altitudes. Time in flare and derotation timing are held constant for all scenarios, as well as aircraft payload with a landing

weight of 135,000-lbm. The trend shows a linear response in field length requirements with an increase in landing distance with a lower throttle chop altitude.

We can see that the 167% factored landing distance value recommended by the FAA¹¹ can safely accommodate a large variation in throttle retard procedure. However, the 115% SaFO factored distance¹² can only absorb a small change in procedure. Recall, a throttle cut at 50-ft leads to a 10-knot speed loss between *VREF* and *VTD*. Thus, we should expect (and we do see) the same variation in distance impact as we see from a 10-knot deviation in final approach and touchdown speed.

G. Effect of Operational Variance— Changes in flare time

Figure 20 displays the effect on actual landing distance from varying the time in flare. The field length requirements are evaluated with the aircraft crossing the runway threshold at 50-ft on a 3° glideslope with the time in flare varied from four to eight seconds in one second intervals. Approach speed and derotation timing are held constant for all scenarios, as well as aircraft payload with a landing weight of 135,000-lbm.

The trend shows a decrease in field length usage for the low time in flare and an increase in the high time in flare.

The time in flare directly affects the air phase during the transition from the approach flight path to the ground roll; the longer flare times result in the aircraft traveling farther down the runway at speed before the wheels contact the ground and braking can be applied, and vice versa for the short flare timings. The four-second time in flare results in a 300-ft shorter landing distance, while the eight-second flare timing results in a 450-ft increase in landing distance over baseline.

The non-linear response is due to the fact that our simulation models a throttle chop at flare initiation. For a given *VREF*, a reduced time in flare translates to a higher touchdown speed than a longer flare would lead to a shorter airphase but longer groundphase distance.

The effect of variation in flare time has a moderate effect with deviation around ~7% on the certified landing distance with higher sensitivity to an extended flare. As before, the 167% factored landing distance¹¹ safely accommodates a large variation in flare timing. However, the 115% SaFO factored distance¹² can only absorb a small change in procedure.

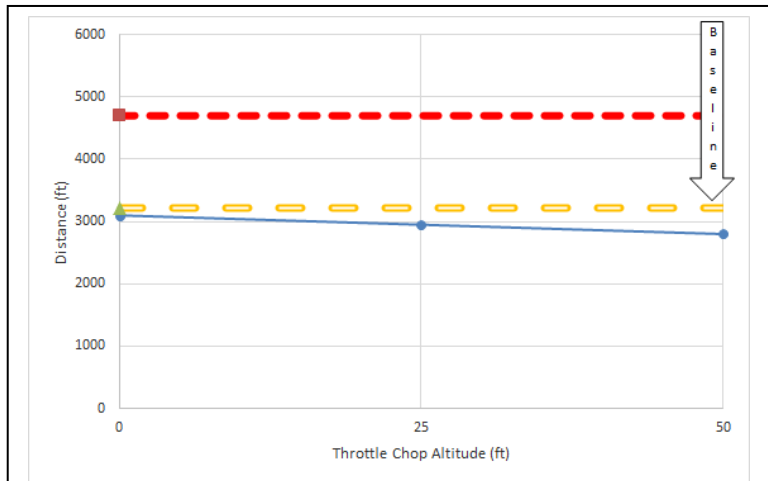


Figure 19 – Effect of Varying Altitude of Throttle Retard in Flare on Landing Distance. Solid line: Simulation. Thick Dashed line: 14 CFR § 121 Factored Distance. Compound Dashed line: 115% SaFO Factored Distance.

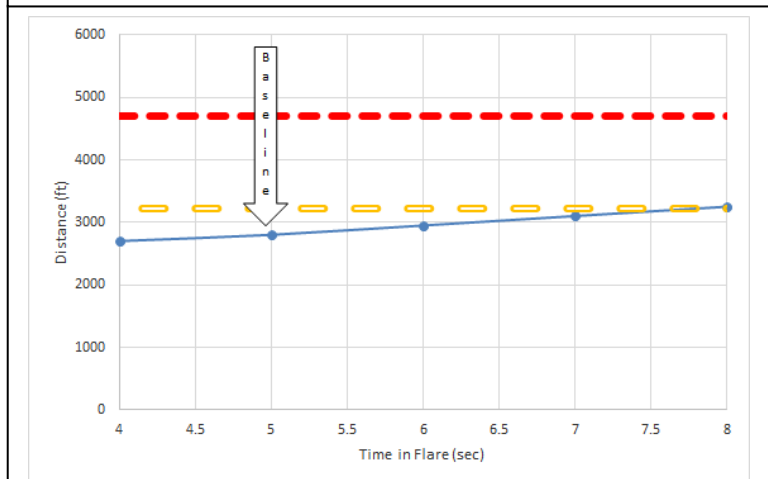


Figure 20 – Effect of Varying Time in Flare on Landing Distance. Solid line: Simulation. Thick Dashed line: 14 CFR § 121 Factored Distance. Compound Dashed line: 115% SaFO Factored Distance

H. Effect of Operational Variance - Lift Dump / Derotation Rate

Figure 21 displays the effect on actual landing distance from varying derotation time. The field length requirements are evaluated with the aircraft crossing the runway threshold at 50-ft on a 3° glideslope with the derotation timing varied from one to five seconds in one second intervals. Approach speed and time in flare are held constant for all scenarios, as well as aircraft payload with a landing weight of 135,000-lbm.

The trend shows a linear decrease in field length requirement for a lower derotation time, and longer runway usage for longer derotation times. The reader should recall, that maximum effort braking does not take effect until the aircraft has fully derotated. This results in quicker brake applications for the shorter derotate times, and delayed brake applications for the longer derotation times. This deviation in brake application timing accounts for the variation in runway usage of about ±450-ft, resulting in ~8% deviation from baseline.

The effect of derotation timing has moderate effect on certified field length. As before, the 167% factored landing distance¹¹ safely accommodates a large variation in lift-dump / derotation timing. However, the 115% SaFO factored distance¹² can only absorb a small change in procedure; an additional two seconds will result in the aircraft using up the entire SaFO distance margin.

I. Effect of Operational Variance – Reverse Thrust Brake Application Time

Figure 22 displays the effects on certified landing distance from deviations in wheel braking and reverse thrust application. We may trigger braking action immediately upon full derotation (nosewheel touchdown) or delay it by up to six-seconds. The field length requirements are evaluated with the aircraft crossing the runway threshold on a 3° glideslope at a height of 50-ft. Approach speed, time in flare, and derotation timing are held constant for all scenarios, as well as aircraft payload with a landing weight of 135,000-lbs. The trend shows a linear response to landing distance with an increase of 300-ft for every second of delay in braking action.

Once again, we see that the 167% factored landing distance¹¹ safely

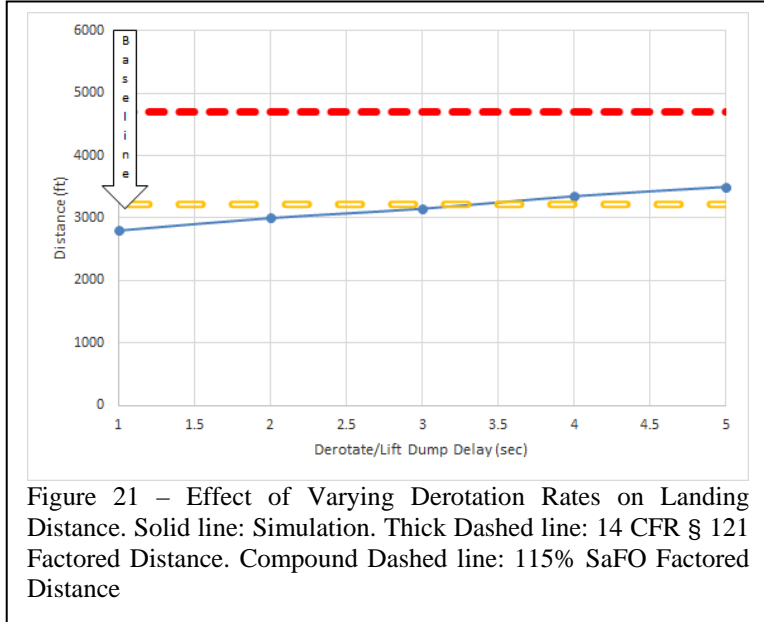


Figure 21 – Effect of Varying Derotation Rates on Landing Distance. Solid line: Simulation. Thick Dashed line: 14 CFR § 121 Factored Distance. Compound Dashed line: 115% SaFO Factored Distance

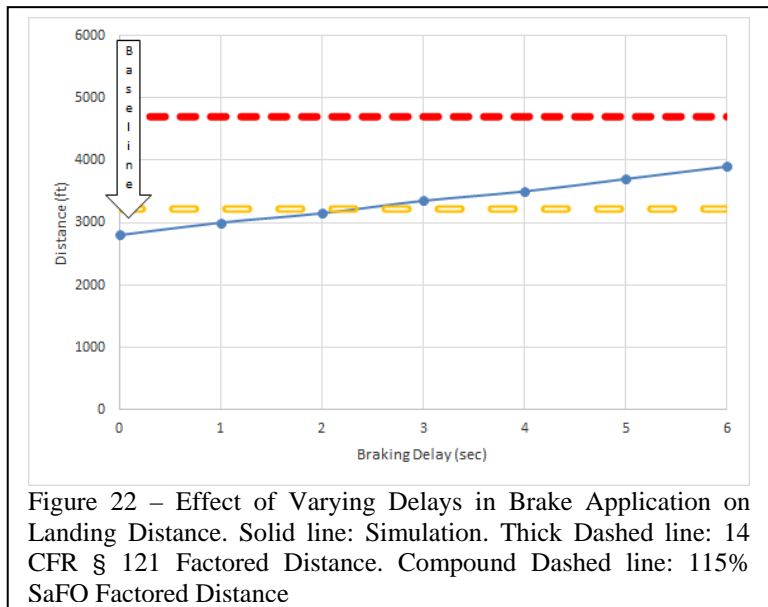


Figure 22 – Effect of Varying Delays in Brake Application on Landing Distance. Solid line: Simulation. Thick Dashed line: 14 CFR § 121 Factored Distance. Compound Dashed line: 115% SaFO Factored Distance

accommodates a large variation in lift-dump / derotation timing. However, the 115% SaFO factored distance¹² can only absorb a small change in procedure; an additional two seconds will result in the aircraft using up the entire SaFO distance margin.

J. Effect of Operational Variance – Braking Traction

Figure 23 displays the effects on certified landing distance from deviations in wheel braking traction. The wheel traction coefficient (μ) is varied from 0.1 to 0.6, in 0.1 intervals, with the baseline occurring at $\mu=0.5$. The field length requirements are evaluated with the aircraft crossing the runway threshold on a 3° glideslope at a height of 50-ft. Approach speed, time in flare, and derotation timing are held constant for all scenarios, as well as aircraft payload with a landing weight of 135,000-lbm.

The trend shows a non-linear response to changes in braking effectiveness with the most significant increases in landing distances at $\mu=0.3$ and below.

Here, absent any other variation, the 167% factored landing distance safely accommodates a large variation in braking traction. Recall, a nominal $\mu=0.25$ represents ICAO “poor” braking traction. However, the 115% SaFO factored distance¹² can only absorb a small change in traction; the distance margin is entirely consumed when the actual braking falls off from $\mu=0.50$ to $\mu=0.40$; recall that $\mu=0.40$ still lies within the boundaries of ICAO “good” traction.

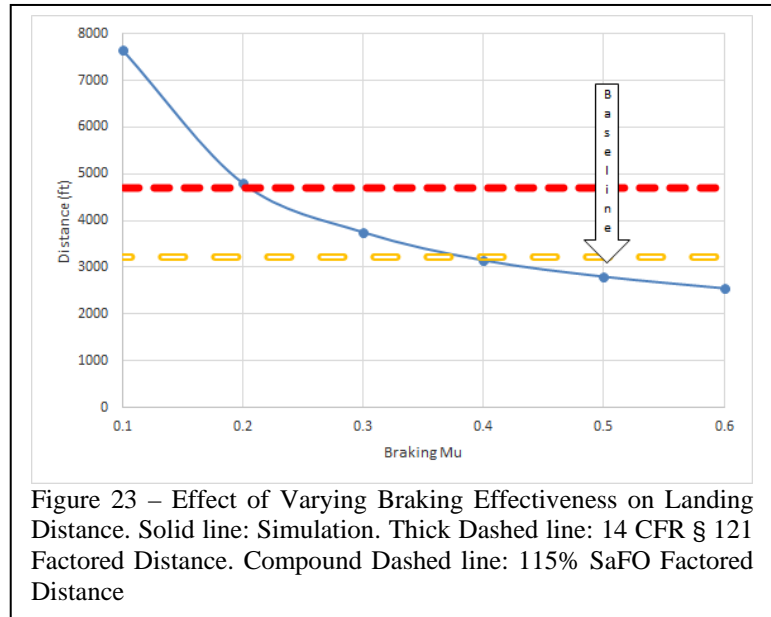


Figure 23 – Effect of Varying Braking Effectiveness on Landing Distance. Solid line: Simulation. Thick Dashed line: 14 CFR § 121 Factored Distance. Compound Dashed line: 115% SaFO Factored Distance

VI. NTSB Report on Pence Incident

On September 21, 2017, the NTSB released the final report on the runway excursion experienced by the 737-700 carrying soon-to-be Vice President Mike Pence and his entourage.²⁸ The report details the flight events that took place on the night of October 26, 2016 from takeoff to landing, with additional detail paid to the landing events. The findings reported by the NTSB show that pilot error in procedures and go-around decision making resulting in the mishap.

Eastern Airlines flight 3452 originated from (KFOD) Fort Dodge, Iowa having departed at 1623 local time operating under 14 CFR 121 (non-scheduled air carrier), rules. The flight to (KLG) La Guardia International airport was uneventful throughout the climb, cruise and initial descent.

At approximately 1902, local time, the aircrew had completed the approach briefing and followed a standard terminal arrival route for KLG runway 22. The briefed weather conditions at the airfield were three statute miles visibility with rain, winds were from 120° at 9 knots. A broken cloud base was reported at 900-ft AGL with a solid overcast layer at 1500-ft AGL. The standard operating procedures for this Eastern Airlines 737-700, was to disengage autopilot and autothrottle at 300-ft AGL and fly the remainder of the final approach manually. The weather conditions reported showed no signs of intruding into the minimums for this aircrew, although they would be landing with a slightly quartering tailwind.

During the approach briefing, the Captain was designated as the “pilot observing” (PO) while the first officer was designated as the “pilot flying” (PF). The aircrew was advised before departure that the ground spoiler “auto-deploy” system was not operational and that manual deployment of the spoilers was

required upon touchdown. Since the first officer was to be acting as the PF, the captain was tasked with manually deploying the spoilers upon touchdown at a selected *VREF* of 137 KIAS.

At 1938, local time, the aircraft was under autopilot and autothrottle control while established on the glideslope and localizer. The final approach configuration was set with flaps at 30° and auto-brake at 3. At this point, the aircraft was flying through rain and clouds with the airport fully obscured. One minute later, the aircraft broke out of the clouds and the aircrew was able to spot the airfield approach lights, well above minimums. At 300-ft the first officer disconnected the autopilot and autothrottle systems to manually fly the rest of the approach.

Just before disconnect of the automated flight systems, the aircraft was well established on the runway centerline and glideslope. When the first officer took manual control of the aircraft, FDR data showed the aircraft deviating above the glideslope approach beam and following the Visual Glide Slope Indicator (VGSI) lights. This minor deviation is to be expected as the VGSI and glideslope beam are not coincident, however, the VGSI approach angle is at 3° with a threshold crossing altitude of 67-ft.

The first officer followed the VGSI, crossing the runway threshold at 66-ft on glideslope. At 50-ft, the enhanced ground proximity warning system began giving aural altitude alerts to the aircrew, with a height call out every 10-ft. The first officer began initiating the flare maneuver at 38-ft, presumably just after the 40-ft call and well above the 20-ft recommended by the Boeing flight crew training manual. At the 20-ft call, the captain made a remark to the first officer to get the plane on the ground. At the 10-ft call, the captain stated in a much more panicked tone, to get the airplane on the ground as they were quickly running out of runway. The wheels finally touched down 4,242-ft beyond the threshold at a groundspeed of *VTD* 130 knots, leaving just 2,759-ft of the 7,001-ft runway to bring the 737 to a stop.

As soon as the main wheels had contacted the runway, the aircrew had applied maximum manual braking which overrode the autobrake system. The aircraft derotated two seconds after main landing gear contact, but the nose “bounced” due to large nose-up control inputs, presumably fighting the torque effects from the braking action without the nosewheel firmly planted on the runway. The nose wheel finally settled onto the runway three seconds after the first contact with the captain deploying the ground spoilers half a second before. The activation of the lift dump spoilers occurred 4.5 seconds after touchdown, in which the aircraft traveled another 1,250-ft down the runway. Approximately 3.5 seconds after the ground spoilers were deployed, maximum reverse thrust was commanded.

By the time the aircraft was settled onto the runway, with full braking action established, there was only 1,109-ft left to bring the aircraft to a full stop. The situation began to look grim, and wanting to avoid an overrun onto the road just past the end of the runway, the captain steered the aircraft to the right. The aircraft encountered an arresting bed at the end of the runway, having slowed to about 35 knots. Full stop was finally achieved, after passing through a portion of the arrestor bed, 172-ft past the end and to the right of the runway.

The investigation determined that if the aircrew had set the aircraft down in the designated landing zones, 2,500-ft past the threshold, full stop would have been achieved even with the lengthy delays in ground spoiler and maximum reverse thrust deployment. Upon post-accident interviews, both aircrew were interviewed saying they **should have initiated a go-around** after “floating” the aircraft so far down the runway. Neither aircrew initiated the go-around because their training never included a scenario in which the aircrew must decide to go-around, they had only been instructed to execute a go-around or not.

In all, the aircraft was not on a destabilized approach, which might require a missed approach initiation at a higher altitude, rather once the aircrew disabled flight control automation and executed the flare maneuver, the descent rate was arrested and the aircraft continued to fly instead of settling onto the runway. It is not uncommon for pilots to attempt landing an aircraft with as little descent rate as possible and “grease the landing.” While this may be impressive to passengers and other on-lookers, the reality is that valuable runway is consumed in the abnormally long flare that is needed to bring the aircraft to a stop. It is hard to say if this was the case in this scenario, however, this aircrew became so focused on landing the aircraft, in spite of clear indications that they should have executed a go-around, that the aircrew landed and attempted to stop the 737 in an impossibly short distance. Lack of training and overly optimistic pilots led to a situation that narrowly avoided disaster.

VII. Conclusions

This paper seeks to examine the safety impacts of actual field performance, previously introduced in AIAA-2017-0007, from the distances given in a pilots handbook. We examined the effects of procedural and dispatch parameter variability, oversight and error in detail. We varied parameters in a manner that would be seen on a regular basis. For example, weight error due to slight inconsistencies in cargo weight or reduced fuel burn in flight. For this paper, we evaluated the impact of these effects in contrast to a baseline field performance model analyzed at a typical landing weight.

Because there is no Federal requirement for manufacturers to document a “standardized procedure” for operations, the aircraft flight manual may be quite vague. We find that this lack of clarity may have drastic effects on the actual landing distances an aircraft requires during operations: slight deviations in approach and landing procedures along with reduced braking effectiveness create significant extensions to field length requirements.

This indicates that the pilot’s ability to control the aircraft in a manner highly consistent with the approved flight manual is critical to achieve the critical field length requirements; **any** deviation in these procedures result in a large departure over the predicted landing distances required.

In general, we find that the 167% factored landing distance found in 14 CFR § 121 provides ample reserve distance to cover compounding errors in the landing procedure. Conversely, we find that the 115% factored landing distance as prescribed by SaFO 06012²⁹ provides only limited protection against pilot variance.

Modern aviation is safe because aircraft typically fly from or to long runways. Thus, these errors, which lead to a longer than projected landing distance, do not result in an accident. When multiple errors compound, as was the case in the Pence 737 incident, an aircraft can easily overrun a short runway.

As stated in the NTSB report,²⁸ the 737 could have been stopped if the aircrew had landed in the appropriate touchdown zone and still had delays in executing braking action. Given that the aircrew had “floated the flare,” so excessively would the aircraft have been able to stop in the short distance remaining? While reverse thrust braking was not evaluated in this paper, we can examine the effects from other delays and compound them.

The NTSB report stated that the aircraft had an extended time in flare of 16 seconds from initiation to touchdown. This extends well past the delays our simulation evaluated; however, since we observe a linear response, extrapolating the effects on field length requirements is reasonable. We see an increase in the landing distance requirements of approximately 150-ft per second of extended time in flare. Our simulation observes a five second time in flare as a baseline, and when compared to this case, the extended time in flare of 11 seconds over baseline yields a landing distance extension of 1,650-ft. The actual observed touchdown of the Pence 737 occurred 1,742-ft after the threshold, showing close agreement to our simulation despite the differing aircraft. If we add the extended landing distance the baseline landing distance requirement, the FAA factored landing distance exceeds the 7,001-ft landing distance at La Guardia, however, this excludes any reverse thrust credit. Given the deployment of the reverse thrust in this case, it is likely aircraft could have stopped in the available runway had no other procedural delays occurred.

The delay of the lift dump by 4.5 seconds after touchdown has significant impact in this case. The NTSB report states an average reaction timing for other pilots, gathered from other flight FDRs, to be around 0.5 seconds, although the report grants a 1 second reaction time, which is also the reaction timing given for pilot initiated actions in AC-25-7C. This also follows with the baseline used in our simulation. Since this delay falls within the bounds of our examination of delays in lift dump deployment, we can see a 500-600-ft increase in field length requirements for the 4.5 seconds of delay case. Given that the aircraft overran the runway by 172-ft, it is safe to assume the aircraft would have come to a full stop in the available amount of runway had the aircrew deployed the ground spoilers within a second of touchdown, which is in agreement of the NTSB landing analysis. In fact, our simulation shows that the aircraft will experience a 150-ft per second delay increase in landing distance requirements, so if the pilots had deployed the ground spoilers at 3.5 seconds after touchdown instead of 4.5, the aircraft may have been able to stop without a runway excursion.

Given the compounding effects of the delayed lift dump and extended time in flare for this incident, our simulation why an aircraft with an ~5,000-ft “handbook” landing distance would overrun the 7,001-ft runway at La Guardia. This is exactly what happened. Individually, the effects on field length requirements appear to be covered by the full 167% FAA factored landing distance¹¹ but not so well covered by the SaFO 115% factor.¹²

In the end, pilot error remains a problem. Compounding effects of multiple “off-handbook” operational procedures can drastically increase the landing distance required outside of any reasonable safety margins.

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²⁶ Airbus A320 FCOM

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