Improved Safety and Capability via Direct Computation of Takeoff and Landing Performance Data

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Traditionally, physics-based models of takeoff and landing performance, referred to as “first-principles” models, are used to compute the basis data for the performance flight manual. The traditional manual is constructed using curve-fits and approximations of the basis data, and consists of charts that depict performance at baseline conditions, with corrections for non-baseline conditions. The traditional manual employs conservatism in its curve-fits and approximations to ensure that safe results are obtained at all expected takeoff and landing conditions. However, there is no industry standard for establishing the appropriate level of conservatism relative to the physics-based models upon which the traditional manuals are based. The object of this paper is to evaluate the conservatism of a sample flight-manual model under different operational scenarios. The results show that the conservatism inherent in traditional manuals produces an undue penalty in airfield performance. Furthermore, the results show there are conditions where the conservatism in traditional manuals is inadequate. Replacing traditional flight manuals with direct performance calculations from physics-based models not only streamlines the flight-manual development process for manufacturers, but also improves the safety and capability available to operators.

Nomenclature

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tbody>
<tr>
<td>AC</td>
<td>Advisory Circular</td>
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<tr>
<td>AFM</td>
<td>Airplane Flight Manual</td>
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<tr>
<td>AFTEP</td>
<td>Airfield Performance Test Expansion Program</td>
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<tr>
<td>BFL</td>
<td>Balanced Field Length</td>
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<tr>
<td>CAFM</td>
<td>Computerized Airplane Flight Manual</td>
</tr>
<tr>
<td>CFL</td>
<td>Critical Field Length, the greater of BFL and UBFL</td>
</tr>
<tr>
<td>DTOLD</td>
<td>Direct Takeoff and Landing Data</td>
</tr>
<tr>
<td>EFB</td>
<td>Electronic Flight Bag</td>
</tr>
<tr>
<td>FAA</td>
<td>Federal Aviation Administration (United States)</td>
</tr>
<tr>
<td>FMS</td>
<td>Flight Management System</td>
</tr>
<tr>
<td>IATA</td>
<td>International Air Transport Association</td>
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<tr>
<td>ISA</td>
<td>International Standard Atmosphere</td>
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<tr>
<td>OAT</td>
<td>Outside Air Temperature</td>
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<tr>
<td>RCR</td>
<td>Runway Condition Reading</td>
</tr>
<tr>
<td>SCAP</td>
<td>Standardized Computerized Aircraft Performance</td>
</tr>
<tr>
<td>TOF</td>
<td>Takeoff Factor</td>
</tr>
<tr>
<td>TOW</td>
<td>Takeoff Weight</td>
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<tr>
<td>TOLD</td>
<td>Takeoff and Landing Data</td>
</tr>
<tr>
<td>UBFL</td>
<td>Unbalanced Field Length</td>
</tr>
<tr>
<td>$V_{MCG}$</td>
<td>Minimum control speed on the ground</td>
</tr>
<tr>
<td>$V_{ROT}$</td>
<td>Rotation speed</td>
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I. Introduction

Aircraft performance data are necessary for planning safe and efficient operations through all phases of flight, including takeoff, climb-out, cruise, descent, and landing. The ability to accurately predict performance directly impacts the bottom line. Optimal utilization of aircraft lowers operating costs by safely maximizing useful payload and minimizing fuel consumption.

This paper focuses on performance data for civil transport category aircraft and their military equivalents. For these types of aircraft, performance data are traditionally delivered as a section of the aircraft flight manual (AFM), a document that contains comprehensive data and procedures for operation of the certified aircraft. These documents are created by aircraft manufacturers, approved by certification authorities, and provided to aircraft operators.1

Performance data are traditionally presented as charts or data tables covering the certified operating envelope of the aircraft. The presentation format of the data is designed for human readability as a paper or electronic document, as shown in the sample flight-manual chart in Figure 1. The general process for creating performance data for a traditional flight manual starts with the development of physics-based computational models of aircraft behavior using the kinematic equations of motion along with flight-test-derived lift, drag, and thrust parameters. These “first-principles” models are validated with flight-test data and used to derive performance across the certified flight envelope. For presentation in the flight manual, the datasets are simplified into families of lines using various curve-fitting techniques. This results in performance data with varying margins of conservatism that can unnecessarily limit operational capability or yield overly optimistic results. Takeoff and landing data are especially sensitive to this accumulated margin, as runway length restrictions and terminal procedures are often the limiting factors in determining maximum useful payload.

The traditional approach to constructing flight-manual charts is held largely as “tribal knowledge” within manufacturer’s engineering organizations and is not well documented in the open literature. The general workflow for creating flight-manual charts is at least fairly consistent across industry, and the final content of the flight manual is regulated by the certification authority. However, the specific methods at each step are not explicitly governed and appear to differ by manufacturer, and even by airframe, based on the authors’ collective experience. When it comes to defining the basis for the charts, the authors are aware of at least two basic methodologies prevalent in industry that yield significantly different results.

Over the past several years, commercial aircraft operators have begun adopting “paperless cockpit” policies, enabled by the proliferation of portable consumer electronic devices.2 There are many benefits to these policies, from reduced weight afforded by paper reduction in the cockpit, to improved situational awareness through more easily accessible information. However, there is also an opportunity to use the new computing capability to provide direct, on-demand performance calculations using first-principles models, rather than simply displaying electronic versions of traditional flight manuals. Some manufacturers have recognized this opportunity and taken steps to create digital performance calculation solutions. In response, regulatory organizations like the FAA have issued guidance on the hardware and software aspects of “paperless cockpit” policies.3,4 Unfortunately, the regulatory environment does not yet appear to support elimination of traditionally-formatted data in the cockpit for all operators.

For this study, methods for constructing traditional flight manuals were evaluated to quantify the conservatism relative to the direct calculation of performance data using first-principles models. The results show the shortcomings of the traditional methods and the positive impact on flight planning from using first-principles models. Additionally, manufacturers can reduce development time and cost by eliminating the non-value-added task of creating traditional flight manuals and derivative digital performance solutions.

![Figure 1. A sample paper flight manual chart (Boeing 727-200).](image)
II. Analysis

To evaluate the operational impact of conservatism in traditional flight-manual performance models (and their software equivalents), a typical, first-principles, physics-based, model was constructed. Aerodynamic and propulsion characteristics for the C-130H were reverse-engineered from publicly-available data using classical methods.\textsuperscript{5,6,7} The C-130H is a four-engine turboprop military aircraft first introduced in 1964, which also saw success commercially as the civil-certified L100. Though a dated design, the C-130H possesses all the salient characteristics of a modern transport, including a critical field length that is set at certain combinations of weight, outside air temperature, and pressure altitude by minimum control speeds on the ground ($V_{MCG}$). Published performance data for the C-130H\textsuperscript{8} were used to validate the expansion model.

A subset of the takeoff and landing data was computed using military specifications that are comparable to civilian regulations. Per MIL-STD-3013A,\textsuperscript{9} the critical field length of the C-130H was determined as the greater of the balanced field length (BFL, established without regard to minimum go-speed requirements due to controllability on the ground) and an unbalanced field length (UBFL, established as the distance to accelerate to and stop from the lesser of $V_{MCG}$ or rotation speed ($V_{ROT}$)). The use of $V_{ROT}$ to define the critical unbalanced condition (as opposed to increasing $V_{ROT}$ to $V_{MCG}$) is a unique feature of MIL-STD-3013A that mitigates the effect of $V_{MCG}$ on takeoff distance at certain conditions. For landing, the distance from 50 feet above the runway to the full stop determines the critical distance. Assuming the maximum takeoff or landing gross weight was limited by runway length, the resulting effect on useful payload was also defined.

A. Traditional Approach to Scheduled Performance Data

In a traditional approach, takeoff and landing are scheduled using data from a document-style flight manual (or software that automates the chart-reading process and produces equivalent results). The traditional flight-manual model is developed using data from a physics-based model with flight-test-derived aerodynamic, propulsion, and performance characteristics. This first-principles model is colloquially known as a flight-test expansion model, as it takes the reduced flight-test data obtained at a limited number of test points, and expands the data to compute performance across the airfield performance envelope. The traditional model is a meta-model – a model of the flight-test expansion model, and, because it is simplified for presentation in the limited space of a document-style flight manual, does not exactly reproduce the results of the flight-test expansion model. The traditional model has followed the same general process for several decades. The advent of digital computers moved the equations and data sets from hand-computed spreadsheets to software implementations, but the flow of data and the final product – a presentation suitable for paper – has not changed.

More recently, software-based takeoff and landing data (TOLD) systems have been implemented, but these systems merely read and interpolate computer tables that match the traditional flight-manual charts. These computer-based systems are often subordinate to the paper equivalent, and frequently exist for advisory use only.

Figure 2 shows the traditional approach to creating flight-manual charts and derivative software implementations. The process begins with the development of the physics-based, first-principles expansion model. After the expansion model has been validated and approved by the certification authority, it is used to generate data across the full range of the airfield performance envelope. The resulting data are arranged to depict the parameter of interest (takeoff field length, landing distance, climb gradient, etc.) as a baseline value that is adjusted through a series of non-baseline corrections. Figure 3 depicts the process of converting raw data from the physics-based performance model to curves for traditional flight manual charts. In the figure, charts for balanced field length are developed from data computed by the expansion model, and decomposed into a baseline chart (BFL at zero wind,
runway slope and RCR of 23), followed by corrections for wind, runway slope and RCR. Depending on the philosophy of the OEM, the data at off-baseline conditions may include interactions between the correction of interest and the other corrections, or may incorporate the correction of interest at the baseline conditions only. There does not appear to be an industry standard.

In practice, the data for the corrections are curve-fit according to differing styles. Because the charts are an approximation of the true physical characteristics, they must employ conservatism in their curve fits to ensure the data are safe for scheduling operational performance. Ideally, these conservative approximations are always sufficient, and never excessive to the point of significantly decreasing available aircraft performance capability. The curves in this paper were fit on a most-conservative basis (with curves equal or conservative relative to 100% of the raw points) by an automated script that selected raw points that are most conservative (i.e., greatest in runway distance) over a given span. Such curve fits are shown by the solid black lines in Figure 4. This is one industry practice, but by no means the only practice. Often, curves are hand-faired based on a fit that is conservative for 80% (or some other arbitrary percentage) of the raw data, on the premise that the extreme points are unlikely to occur operationally. Such a curve fits are shown by the dashed red lines in Figure 4. In other cases, outliers are excluded from the curve-fit on a case-by-case basis. These two latter approaches are arbitrary, but less punitive than a fit that accommodates 100% of the data. The application of 100%-conservative fits in this paper avoided variability based on engineering judgment, and provided a most-conservative benchmark.

Similar to the situation for interactions between corrections, there does not appear to be an industry standard for applying conservatism in curve-fits for flight manuals.

B. Direct Approach to Scheduled Performance Data

Ultimately, the first-principles expansion model is an obvious substitute for the traditional flight-manual model, given that it undergoes a significant level of validation before it can produce the source data for the traditional manual. Such an implementation of
the expansion model, which we will call Direct Takeoff and Landing Data, or DTOLD, possesses significant advantages, among them superior accuracy throughout the operating envelope, no excess conservatism beyond that required by the certification authority, and minimal non-conservative data. Additionally, the tasks of developing traditional flight manual charts and digital equivalents—two significant, non-value-added tasks—are eliminated for aircraft manufacturers, as shown in Figure 2.

Ideally, for operational flight planning, DTOLD is implemented as both an on-board and off-board solution. Within the certified avionics architecture, the Flight Management System (FMS) is employed to determine optimal flight paths by combining navigation and performance calculation functions. The performance function of the FMS typically relies on a first-principles model to compute airborne performance, but frequently relies on predefined data tables that match the paper manual for takeoff and landing performance. Separately, the electronic flight bag (EFB) has become an indispensable component of paperless operations, and can be approved to meet the regulations that require flight crews to have access to an approved Airplane Flight Manual (AFM) on the aircraft, per Advisory Circular (AC) 120-76. The FAA also issued AC 25.1581 to address the use the digital versions of the AFM, referred to as the “computerized” AFM (CAFM). Some manufacturers have already created CAFMs to directly calculate performance data using first-principles models. The CAFM can be used to generate approved performance data, but does not satisfy the operational requirement for flight-crew access to the AFM. The evolutionary next-step is the implementation of DTOLD for both on-board and off-board computations.

C. Case Study

The two different philosophies for developing corrections (both with and without interactions with other corrections) were applied using the estimated C-130 expansion model. The results for the two approaches were compared to results from the expansion model for two different operational scenarios.

The reverse-engineered aerodynamic and propulsion data for the C-130 were loaded into the general-purpose Airfield Flight Test Expansion Program (AFTEP). The software incorporated modifications to support the C-130 model. After establishing the input data sets and modifying the AFTEP program, an extensive set of test cases were validated using Ref. 8.

Table 1 shows the ranges of all input parameters used to generate the sample flight manual charts. Additional, less-common parameters, such as brake pressure and anti-skid status could have been used in the analysis, but the selected parameters were deemed sufficient to illustrate the effects of conservatism in the typical flight-manual.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Step</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weights</td>
<td>lb</td>
<td>80,000</td>
<td>175,000</td>
<td>5,000</td>
</tr>
<tr>
<td>Pressure Altitude</td>
<td>feet</td>
<td>0</td>
<td>16,000</td>
<td>1,000</td>
</tr>
<tr>
<td>ISA Deviation</td>
<td>°C</td>
<td>-50 (Limited to OAT ≥ -50°C)</td>
<td>40</td>
<td>10</td>
</tr>
<tr>
<td>Runway Winds</td>
<td>knots</td>
<td>-20</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>Runway Slopes</td>
<td>%</td>
<td>-4</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>RCR</td>
<td>NA</td>
<td>5</td>
<td>23</td>
<td>Irregular values: 23, 12, and 5</td>
</tr>
</tbody>
</table>

1. Takeoff Factor

In accordance with MIL-DTL-7700G, a “takeoff factor” was developed as a correlation parameter for the flight manual charts. Takeoff factor is presented as a separate flight manual chart that combines air temperature, pressure altitude, and engine thrust. Takeoff factor is determined once, and then used repeatedly as an entry to other flight manual charts, thereby simplifying the charts. Figure 9 shows takeoff factor as traditionally defined as a function of four-engine take-off ground roll on a standard (ISA) day and a fixed gross weight (selected here as 120,000 lb). Figure 10 displays the takeoff factor as presented in the flight manual, expanded across the range of outside air temperature and pressure altitude.

This paper is based on an estimated expansion model and generalized methods. The results are not an assessment of the conservatism or operational suitability of any historical or current C-130 or L100 performance manuals.

American Institute of Aeronautics and Astronautics
2. Balanced Field Length

Figure 11 through Figure 16 show substantiating data for balanced field length (BFL) charts. The order of the substantiating charts reflects the order in which they appear in the flight manual chart: baseline, followed by corrections for slope, wind, and RCR. Figure 11 shows the basic BFL as a function of all weights, as well as all temperatures and altitudes via the correlation parameter, TOF. Reference slope, wind, and RCR conditions apply to the baseline conditions of Figure 11. The raw data computed from the flight-test expansion model appear as symbols, and conservative curves have been faired through the data at each take-off gross weight to form corrections for the flight manual chart. The curves are based on a most-conservative, 100%-fit of the data obtained via the automated script.

Figure 12 shows the runway slope correction for BFL at all weights, temperatures, and altitudes. Reference wind (zero) and RCR (23) conditions apply. Data computed from the flight-test expansion model appear as symbols, with conservative curves faired through the data, again via the automated script on a most-conservative basis, at each runway slope to form curves for the flight manual.

Figure 13 shows the wind correction for BFL at all weights, temperatures, and altitudes. Here again, the reference slope and RCR conditions apply. Data computed from the flight-test expansion model appear as symbols, with conservative curves faired through the data at each wind. Because the perturbations in the wind correction due to the preceding runway slope correction are not included in the raw data of Figure 13, the interactions between slope and wind are not captured by the faired curves, and the resulting corrections are categorized as “BASE ONLY.”

Like Figure 13, Figure 14 shows the BFL wind correction at all weights, temperatures, and altitudes. However, wind data at non-zero (non-baseline) slopes are included in order to capture interactions between wind and slope in determining BFL, as the slope correction appears before the wind correction in the order of the flight-manual chart. Reference RCR conditions are applicable, as the RCR correction occurs after the wind correction in the flight-manual chart. Because the interactions between wind and all preceding corrections are included in the formulation of the faired curves, the resulting corrections are categorized as “FULL.”

Figure 15 shows the RCR correction data at all weights, temperatures, and altitudes, but at reference slope and wind conditions. Conservative curves have been faired through the data at each RCR to form “BASE ONLY” curves for the flight manual. Similarly, Figure 16 shows RCR correction at all weights, temperatures, and altitudes, but includes the effects of slopes and winds, to form a “FULL” set of conservative curves for the flight manual.

3. Unbalanced Field Length

Figure 17 through Figure 23 provide the substantiating data used in the creation of the unbalanced field length (UBFL) charts. The order of the substantiating charts reflects the order in which they appear in the flight manual chart: a baseline at a nominal weight, followed by corrections for weight, RCR, slope, and wind. Figure 17 shows the baseline UBFL as a function of deviation from ISA conditions. The chart captures the effects of temperature and pressure altitude via the correlation parameter takeoff factor. Reference conditions for gross weight (120,000 lb), runway slope (zero), wind (zero), and RCR (23) apply. Again, conservative curves were faired through the data at each ISA deviation to form flight-manual curves.

Figure 18 shows the weight correction at all temperatures and altitudes for the UBFL. Reference conditions for slope, wind, and RCR apply. Figure 19 provides the RCR correction for UBFL at all temperatures, altitudes, and weights. Reference slope and wind conditions apply.

Figure 20 provides the UBFL runway slope correction at all temperatures, altitudes, and weights. Reference RCR and wind conditions apply, making a BASE ONLY correction. Similarly, Figure 21 shows the UBFL runway slope correction at all temperatures, altitudes, and weights, but includes the effect of non-baseline RCR values, making a FULL correction. Reference conditions for wind, which follows the slope correction, apply. Note the significant difference between the FULL and BASE corrections at negative runway slopes, suggesting a strong interaction between RCR and runway slope for UBFL.

Figure 22 gives the UBFL wind correction at all temperatures, altitudes and weights. Reference RCR and runway slope conditions apply, making a BASE ONLY correction. Figure 23 provides the wind correction for UBFL at all values of temperature, altitude, weight, RCR, and runway slope, making this a FULL correction.

4. Landing Distance

Figure 24 through Figure 31 provide substantiating data for the flight manual charts for landing distance to 50
feet. The order of the substantiating charts reflects the order in which they appear in the flight manual chart: a baseline, followed by corrections for temperature, slope, wind, and RCR. Figure 24 provides the basic landing distance chart at all aircraft gross weights and pressure altitudes. Reference values of runway slope, wind, and RCR conditions apply, as do ISA atmospheric conditions. Data computed from the expansion model appear as symbols and form exact curves for the flight-manual chart (no conservative fairings of data were required for the computed data of Figure 24).

Figure 25 shows the ISA deviation correction to landing distance at all weights and altitudes. Reference slope, wind, and RCR apply. Figure 26 gives the runway slope correction to landing distance at all weights and altitudes. Reference conditions for temperature (ISA deviation of zero), wind (zero), and RCR (23) apply, resulting in a BASE ONLY correction. Similarly, Figure 27 provides the slope corrections to landing distance at all weights and altitudes, but adds the effects of varying temperatures, resulting in a FULL correction. Reference conditions for wind and RCR apply.

Figure 28 provides wind corrections to landing distance at all weights, altitudes, and temperatures. Reference temperature, slope, and RCR conditions apply, resulting in a BASE ONLY correction. Similarly, Figure 29 shows wind corrections at all weights, altitudes, temperatures, and runway slopes, to form a FULL correction. Reference conditions for the one subsequent correction (RCR) still apply.

Figure 30 provides RCR corrections to landing distance at all weights and altitudes. Reference temperature, slope, and wind conditions apply to form a BASE ONLY correction. Figure 31 gives RCR corrections at all weights, altitudes, temperatures, slopes, and winds to form a FULL correction.

5. Final Flight Manual Charts

Using the conservative curves faired through the raw data, flight manual charts were prepared. The corrections were cross-plotted to create equivalent charts, known colloquially as “barber poles” or “sliders,” which were arranged with baseline data and other corrections to form flight-manual “chase-around” charts.

Figure 32 and Figure 33 depict the flight-manual charts for balanced field length, created using the faired curves of Figure 11 through Figure 16. Corrections based on perturbations of all preceding corrections (i.e., the FULL corrections) are shown in solid black lines on the charts, while corrections based on reference conditions only (i.e., the BASE ONLY corrections) are shown by dashed red lines. As seen in Figure 33, there is only one set of curves for the slope correction, which is based on the reference conditions of baseline wind and RCR. This is acceptable because the preceding data (the first BFL chart, shown as Figure 32) are based on reference conditions only. Thus, the FULL and BASE corrections diverge only after the first perturbation from those baseline conditions, which in this case is the slope correction on Figure 33. This is seen by the differing FULL (solid black) and BASE (dashed red) curves for the wind and RCR corrections.

Figure 34, Figure 35, and Figure 36 depict the flight-manual charts for unbalanced field length that derive from the faired curves of Figure 17 through Figure 23. Like the BFL charts, a separate set of curves appear for the BASE and FULL cases after the first correction, which in this case is RCR.

Figure 37, Figure 38, and Figure 39 depict the flight manual charts for landing distance that result from the faired curves of Figure 24 through Figure 31. Like the BFL and UBFL charts, a separate set of curves appear for the BASE and FULL cases after the first correction, which in this case is a correction for ISA deviation.

III. Results

A. Comparison of Traditional and Direct Approaches

1. Full Source Expansion Matrix

As shown by the difference between the red and black curves on the flight-manual charts, the conditions used to construct a correction, particularly whether the correction addresses only reference conditions or perturbations of all preceding corrections, affects the shape and magnitude of the corrections. To assess the relative accuracy of the two approaches, results from the flight-manual charts were compared to the results from the expansion model for the full source expansion matrix of 199,200 points that formed the basis for the charts. An automated script linearly interpolated tabular data sets that were equivalent to the flight manual charts to obtain flight manual results. The full source matrix reflects points distributed evenly across all the input parameters of the airfield performance envelope. This evaluation made no attempt to bias the comparisons to conditions away from the corners of the envelope that are unlikely to occur operationally.
Figure 40 compares CFL from the expansion model to CFL from the flight-manual model. Some of the extreme conditions in the run matrix result in CFL values that are greater than practically all available runways. Therefore, points where the CFL from the expansion model was greater than 20,000 ft were removed (leaving the sample at 193,815 points). The 1:1 slope line superimposed on Figure 40 corresponds to perfect correlation. Points below the line are conditions where the flight manual is non-conservative, and points above the line are conditions where the flight manual is conservative. The chart shows that the BASE case results in a significant number of flight manual points that are non-conservative. In contrast, the FULL case results in points that are on or above the line, indicating the flight-manual results are equivalent or conservative. As a whole, the FULL points diverge farther from the 1:1 line.

To better understand the distribution of error associated with the FULL and BASE approaches, Figure 41 shows the cumulative probability distribution for error in the flight-manual model for CFL from the same sample (with CFL from the expansion model greater than 20,000 feet removed). The results show that the FULL flight-manual model is never non-conservative, but accrues greater than 487 ft in excess conservatism for 50% of the conditions, and greater than 1,020 ft in excess conservatism for 20% of the conditions. In contrast, the BASE flight-manual model carries less excess conservatism, accruing greater than 162 ft in excess conservatism for 50% of cases, and greater than 611 ft for the worst 20% of the cases. However, the BASE model is non-conservative for about 20% of the cases. The results for takeoff distance for the full source matrix are summarized in Table 2 and Figure 7.

By making certain assumptions, the excess conservatism was converted to payload out of a given field-length-limited airfield. Taking the CFL data from the expansion model for all weights at ISA conditions, and baseline corrections (zero wind and slope, and RCR of 23), results in an average change in takeoff weight of 16.6 lb per foot of required field length, as illustrated in Figure 5. This is a rough approximation, with a true value that varies significantly, as evident in the figure. This average will tend to underestimatethe effect on weight at lower weights, altitudes, and temperatures, and over-estimate the effect at greater weights, altitudes, and temperatures. Assuming field-length-limited conditions, and applying the average of 16.6 lb/ft, the FULL case results in a payload reduction greater than 8,110 lb for 50% of the cases, and greater than 16,980 lb for 20% of the cases. The BASE case results in greater than 2,700 lb for 50% of cases, and greater than 10,170 lb for 20% of cases. To put these values in perspective, consider the average takeoff weight in the analysis of 127,500 lb. For the FULL case, the reduction in available takeoff weight is greater than 6% of the average takeoff weight for 50% of cases, and greater than 13% for 20% of cases. For the BASE case, the reduction is greater than 2% of the average weight for 50% of cases, and greater than 8% for 20% of cases. The results for field-length-limited takeoff weight for the full source matrix are summarized in Table 2, Figure 7, and Figure 8.

The exclusion of cases with CFL values greater than 20,000 feet was somewhat arbitrary. Arguably, a more realistic scenario restricts the analysis to even lesser values of CFL. To evaluate the effect of different cut-off values of CFL, the above study was repeated with CFL values greater than 10,000 ft removed. The results changed very little, with the payload reductions within 1% of the values obtained using the 20,000 ft cut-off.

In a similar manner, the landing distance results were evaluated for the full matrix (N=199,200). Figure 42 compares landing distance from the expansion and flight-manual models. No landing distances at these conditions exceeded 20,000 ft, and hence no points were removed for landing. Figure 43 provides the cumulative probability distribution for error in the flight-manual model for landing distance for the run matrix. The FULL flight-manual model is never non-conservative, but accrues greater than 344
ft in excess conservatism for 50% of the cases, and greater than 776 ft for 20% of the cases. In contrast, the BASE flight-manual model is less conservative, with greater than 75 ft excess conservatism for 50% of cases, and greater than 240 ft for 20% of the cases, but is non-conservative for about 19% of the conditions. The results for landing distance for the full source matrix are summarized in Table 2 and Figure 7.

The effect of excess conservatism on field-length-limited landing weight was estimated using the same approach as used for takeoff. Using the baseline landing data (ISA, all weights, baseline corrections), a change in weight of 23.4 lb per foot of required landing distance was determined, as illustrated in Figure 6. Applying this average, and assuming the nominal landing weight for the run matrix (127,500 lb), the FULL case yields a reduction in landing weight greater than 8,040 lb (6% of nominal landing weight) for 50% of the cases, and greater than 18,140 lb (14% of nominal landing weight) for 20% of cases. In comparison, the BASE case yields reductions greater than 1,750 lb (1% of nominal landing weight) for 50% of cases, and greater than 5,610 lb (4% of nominal landing weight) for 20% of cases. The results for field-length-limited landing weight for the full source matrix are summarized in Table 2, Figure 7, and Figure 8.

2. Operational Scenarios

The assumption that all points from the source run matrix are equally likely to occur is unrealistic operationally. Therefore, to better assess the occurrence of non-conservative and excessively-conservative results from the flight-manual model, two hypothetical operational data sets were constructed for Monte Carlo analysis. In the absence of actual operational data, these data sets are purely conjectural, but generally move the inputs conditions closer to sea-level altitude, standard-day temperature, and nominal correction values.

Figure 44 shows hypothetical frequency and cumulative probability distributions for operational takeoff weights. Part (i) of Figure 44 corresponds to operational set #1, and part (ii) corresponds to operational set #2. Similarly, Figure 45 shows distributions for landing weights; Figure 46 shows distributions for airfield pressure altitudes; Figure 47 shows distributions for temperature deviations from standard day (ISA); Figure 48 shows distributions for runway slopes; Figure 49 shows distributions for winds; and Figure 50 shows distributions for RCR values. Note that there is a subtle difference between part (i) and part (ii) of Figure 50. Part (i) of Figure 50 defines a continuous range of operational RCR values, while part (ii) assumes operational RCR values take on the discrete values of 5 (icy), 12 (wet), and 23 (dry) only. A review of the operational sets shows that set #2 tends to be more benign, with conditions more likely to occur at lower altitudes and closer-to-nominal corrections.

3. Operational Set #1

Figure 51 through Figure 54 show results from the Monte Carlo analysis of operational set #1. Figure 51 compares CFL from the expansion and flight-manual models for the set. For the BASE case, the points below the 1:1 line are non-conservative. The sample is based on a Monte Carlo simulation of set #1 of size N=50,000. Points where the CFL from the expansion model was greater than 20,000 feet were removed.

Figure 52 shows the cumulative probability distribution for error in CFL for the flight-manual model for the Monte Carlo analysis of operational set #1. The FULL flight-manual model is always conservative, but accrates greater than 329 ft in excess conservatism for 50% of the cases, and greater than 573 ft for 20% of the cases. The BASE flight-manual model carries less average conservatism, but accrates greater than 144 ft in excess conservatism.

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for 50% of the cases, and greater than 315 ft for 20% of the cases. The BASE case is also non-conservative for about 5% of the conditions.

The excess conservatism was converted to a change in takeoff weight using the previous value of 16.6 lb/ft. For the FULL case, the result is greater than 5,480 lb (4% of the nominal TOW of 127,500 lb from the full source matrix) for 50% of the cases, and greater than 9,540 lb (7% of nominal TOW) for 20% of the cases. For the BASE case, the result is greater than 2,400 lb (2% of the nominal TOW) for 50% of the cases, and greater than 5,240 lb (4% of the nominal TOW) for 20% of the cases.

Figure 53 compares the landing distances from the flight-test expansion model and the flight-manual model as obtained from the Monte Carlo analysis of operational set #1. Figure 54 shows the cumulative probability distribution for error in landing distance for the flight-manual model for the same sample. Again, the FULL flight-manual model is always conservative, but accrues greater than 120 ft (2,810 lb, or 2% of the nominal landing weight of 127,500 lb from the full source matrix) in excess conservatism for 50% of the cases, and greater than 319 ft (7,460 lb, or 6% of nominal landing weight) for 20% of the cases. The BASE flight manual is less conservative, with greater than 66 ft (1,540 lb, or 1% of nominal landing weight) for 50% of the cases, and greater than 131 ft (3,060 lb, or 2% of the nominal landing weight) for 20% of the cases, and is non-conservative for nearly 1% of the conditions. The takeoff and landing results for operational set #1 are summarized in Table 2, Figure 7, and Figure 8.

Using the average takeoff weight (134,279 lb) and average landing weight (115,976 lb) for operational set #1 instead of the nominal value of 127,500 lb for the full source matrix has little effect on the percentages computed for changes to takeoff and landing weight.

4. Operational Set #2

Figure 55 through Figure 58 show results from the Monte Carlo analysis of operational set #2. Figure 55 compares CFL from the expansion and flight-manual models for the set. Sample size is N=50,000, with CFL values greater than 20,000 feet removed. Figure 56 shows the cumulative probability distribution for error in CFL for the sample. The FULL flight-manual model is always conservative, but accrues greater than 160 ft (2,660 lb or 2% of the nominal TOW) in excess conservatism for 50% of the cases, and greater than 302 ft (5,030 lb or 4% of the nominal TOW of 127,500 lb from the full source matrix) for 20% of the cases. The BASE flight-manual model is less conservative, but accrues greater than 78 ft (1,300 lb or 1% of the nominal TOW) in excess conservatism for 50% of the cases, and greater than 163 ft (2,710 lb or 2% of nominal TOW) for 20% of the cases. The BASE case is non-conservative for about 3% of the conditions.

Figure 57 compares the landing distances from the flight-test expansion model and the flight-manual model as obtained from the Monte Carlo analysis of operational set #2. Figure 58 shows the associated cumulative probability distribution for error in landing distance for the flight-manual model. The FULL flight-manual model is always conservative, but accrues greater than 53 ft (1,240 lb or approximately 1% of the nominal landing weight of 127,500 lb from the full source matrix) in excess conservatism for 50% of the cases, and greater than 164 ft (3,830 lb or 3% of nominal landing weight) for 20% of the cases. The BASE flight-manual model is less conservative, but accrues greater than 30 ft (700 lb or approximately 1% of nominal landing weight) in excess conservatism for 50% of the cases, and greater than 73 ft (1,710 lb or approximately 1% of the nominal landing weight) for 20% of the cases. The BASE case is non-conservative for between 1% and 2% of the cases. The takeoff and landing results for operational set #2 are summarized in Table 2, Figure 7, and Figure 8.

Using the average takeoff weight (127,716 lb) and average landing weight (113,139 lb) for operational set #2 instead of the nominal value of 127,500 lb for the full source matrix has a negligible effect on the computed changes to takeoff and landing weight.
Table 2. Summary of excess conservatism for flight manual model compared to expansion model as determined from source run matrix and two hypothetical operational scenarios. Minimum differences for worst 50% and 20% of cases. Average weight of 127,500 lb used for all percent weight computations.

<table>
<thead>
<tr>
<th>SOURCE RUN MATRIX</th>
<th>50%</th>
<th>Δ DISTANCE (ft)</th>
<th>FULL</th>
<th>BASE</th>
<th>Δ WEIGHT (lb)</th>
<th>FULL</th>
<th>BASE</th>
<th>% AVG WT</th>
<th>FULL</th>
<th>BASE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>487</td>
<td>162</td>
<td>344</td>
<td>75</td>
<td></td>
<td>6%</td>
<td>2%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8,110</td>
<td>2,700</td>
<td>8,040</td>
<td>1,750</td>
<td></td>
<td>6%</td>
<td>1%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20%</td>
<td>Δ DISTANCE (ft)</td>
<td>1020</td>
<td>611</td>
<td>776</td>
<td>240</td>
<td></td>
<td>13%</td>
<td>8%</td>
<td>14%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Δ WEIGHT (lb)</td>
<td>16,980</td>
<td>10,170</td>
<td>18,140</td>
<td>5,610</td>
<td></td>
<td>13%</td>
<td>8%</td>
<td>14%</td>
</tr>
</tbody>
</table>

| OP SET #1         | 50% |  Δ DISTANCE (ft) | 329  | 144  | 120           | 66   |      | 4%       | 2%   | 1%   |
|                   |     |  Δ WEIGHT (lb)   | 5,480 | 2,400| 2,810         | 1,540|      | 4%       | 2%   | 1%   |
|                   | 20% |  Δ DISTANCE (ft) | 573  | 315  | 319           | 131  |      | 7%       | 4%   | 6%   |
|                   |     |  Δ WEIGHT (lb)   | 9,540 | 5,240| 7,460         | 3,060|      | 7%       | 4%   | 6%   |

| OP SET #2         | 50% |  Δ DISTANCE (ft) | 160  | 78   | 53            | 30   |      | 2%       | 1%   | 1%   |
|                   |     |  Δ WEIGHT (lb)   | 2,660 | 1,300| 1,240         | 700  |      | 2%       | 1%   | 1%   |
|                   | 20% |  Δ DISTANCE (ft) | 302  | 163  | 164           | 73   |      | 4%       | 2%   | 3%   |
|                   |     |  Δ WEIGHT (lb)   | 5,030 | 2,710| 3,830         | 1,710|      | 4%       | 2%   | 3%   |

Figure 7. Error between flight-manual model and expansion model for takeoff and landing distances. Minimum error for worst 50% and 20% of cases shown. Results for the source run matrix and two hypothetical operational scenarios.
Figure 8. Error between flight-manual model and expansion model for estimated field-length-limited takeoff and landing weight. Minimum errors for worst 50% and 20% of cases shown. Results for the source run matrix and two hypothetical operational scenarios. Average weight of 127,500 lb used for all percent weight computations.

5. Barriers to Implementation of DTOLD

The primary barrier to full implementation of DTOLD solutions lies in the current regulatory regime, which still relies on the traditional flight manual to satisfy operational requirements on the flight deck. In order to supplant the traditional paper flight manual, a DTOLD solution must be established as the primary source of on-board airfield performance data. This requires the definition of necessary testing, validation, and regulatory approval processes. The widespread adoption of “paperless cockpit” policies and associated regulatory guidance provide a starting framework. Under the EFB guidance, DTOLD would likely fall under the Type C application category and require software development under the RTCA DO-178 guidelines and require dedicated Class 3 EFB hardware to host the software to create a certification process similar to embedded avionics and software. While this would complicate the DTOLD development and approval process for manufacturers, the additional effort would be offset by eliminating the construction of a traditional flight manual. The additional cost of installing and certifying Class 3 EFBs for operators would be offset by the elimination of weight from paper back-ups and the effort required to support and update them.

For off-board planning purposes, several manufacturers, particularly OEM’s for airliners, have been moving toward first-principles models for several years. In one case, Embraer was able to take advantage of more-accurate first-principles models to certify operations at an airport that was previously unreachable due to the performance limitations in the traditional flight manual. There is less apparent movement toward DTOLD among the general aviation and military communities.
Another barrier to implementation is the reluctance of manufacturers to release proprietary first-principles data and models outside of their organizations. This is a valid concern, so a channel to deliver secure first-principles data and models is necessary. To help establish uniform standards for computerized performance data supplied to operators, the International Air Transport Association (IATA) formed the Standardized Computerized Aircraft Performance (SCAP) Task Force. The goal of the task force is to develop specifications that define the interface for performance analysis software created by manufacturers and provided to operators. A common interface prevents operators, who often utilize several aircraft types, from having to develop custom software for each aircraft type, and it also standardizes the type of performance data produced by software. Once again, each of these SCAP “modules” are developed using various methods, from table look-up routines to first-principles calculations, and they are not approved by the FAA. Nevertheless, SCAP presents an existing channel to securely deliver DTOLD solutions that could be further refined to cover approved, first-principles data sources.

IV. Conclusion

This study demonstrates two significant shortcomings of traditional, paper-based flight manuals (and their electronic equivalents). First, the traditional manual results in a degree of conservatism that diminishes the available performance of the aircraft. This reduces the maximum aircraft weight for operation at a given airfield, or in conditions where performance is not limiting, forces the use of procedures that maximize performance capability (for example, the use of higher-power settings on takeoff when lower settings would be sufficient). The result is an inefficient use of available resources: the available payload and range are reduced, and the life of components (and interval between maintenance) is shortened. Arguably, the excess conservatism in a traditional model is beneficial as an additional margin of safety, but the existing regulations provide explicit margins in the calculations from the first-principles expansion model (in the form of factors on landing distance, the use of minimum-engine performance on takeoff, etc.).

A second shortcoming exposed by this study is that certain commonly-applied methods for the creation of traditional flight manuals routinely produce non-conservative results. The takeoff and landing distance in a traditional manual is obtained as a baseline value that is adjusted using corrections for non-baseline conditions. Corrections that are based on baseline conditions for all parameters and do not account for interactions with other corrections provide insufficient conservatism for a significant percentage of cases. The exposure to these non-conservative results will vary. Operators that routinely fly at extremes of the envelope will be more exposed to non-conservative effects in manuals built on baseline-only corrections. This non-conservatism will be exacerbated if the constituent corrections are based on curve-fits that employ subjective “engineering judgment” to account for less than 100% of the data. While calculations from the expansion model are explicitly governed by the regulations, it is the authors’ experience that the procedures for constructing flight-manual correction curves from expansion-model data are not standardized across industry. It seems reasonable that any traditional flight-manual model should be subjected to a comprehensive validation versus the expansion model, similar to the evaluation in this paper, in order to ensure adequate conservatism across the envelope. This does not seem to be the norm.

It is worth noting that this is a single study based on two subtle variations of a traditional flight-manual model. Changes to the order for the corrections, the inclusion of other corrections, or the use of a correlation parameter other than takeoff factor would likely perturb the results. In fact, it is incumbent on the performance engineer to evaluate different configurations of the charts to minimize conservatism and maximize capability. However, it seems reasonable to conclude that any chart constructed on the traditional model of baseline-plus-corrections will incur a penalty to performance due to excess conservatism. This would apply to factors that limit airfield performance other than field length, such as obstacle-clearance, climb-gradient, and brake-energy.

Ultimately, the study demonstrates that the traditional flight manual is an anachronism. Simplifying airfield performance data to a few human-readable charts results in a model that at best defines an overly-conservative performance envelope, and at worst yields non-conservative results at the edges of the envelope. Ironically, once the traditional charts are created, they are rarely used. Software that interpolates matching data tables is much faster and more accurate than a human reading the charts. Unfortunately, these software equivalents incur the same problems and penalties with conservatism as their paper source. Direct, first-principles models enable safer, more efficient aircraft operations, and are already being implemented in some sectors of the industry. As technology and regulations evolve, the direct model will replace the traditional model across all segments of the industry, both as an on-board and off-board solution.
Figure 9. Take-off factor as defined as a function of four-engine take-off ground roll on a standard (ISA) day, gross weight 120,000 lb.

Figure 10. Takeoff factor expanded across temperature and altitude using computed values of four-engine take-off ground roll from the expansion model. Take-off factor in this form is used as a correlation factor in place of temperature and altitude on flight manual charts.
Figure 11. Balanced field length (BFL) at all weights, temperatures, and altitudes. Reference slope, wind, and RCR conditions apply. Temperature and altitude effects correlated to take-off factor. Data computed from the flight-test expansion model appear as symbols. Conservative curves have been faired through the data at each take-off gross weight to form curves for the flight manual chart.

Figure 12. Balanced field length (BFL) runway slope correction at all weights, temperatures, and altitudes. Reference wind and RCR apply. Data computed from the flight-test expansion model appear as symbols. Conservative curves have been faired through the data at each slope to form curves for the flight manual.
Figure 13. Balanced field length (BFL) wind correction at all weights, temperatures, and altitudes. Reference slope and RCR conditions apply. Data computed from the flight-test expansion model appear as symbols. Conservative curves have been faired through the data at each wind to form curves for the flight manual.

Figure 14. Balanced field length (BFL) wind correction at all weights, temperatures, altitudes, and slopes. Reference RCR conditions apply. Data computed from the flight-test expansion model appear as symbols. Conservative curves have been faired through the data at each wind to form curves for the flight manual.
Figure 15. Balanced field length (BFL) RCR correction at all weights, temperatures, and altitudes. Reference slope and wind conditions apply. Data computed from the flight-test expansion model appear as symbols. Conservative curves have been faired through the data at each RCR to form curves for the flight manual.

Figure 16. Balanced field length (BFL) RCR correction at all weights, temperatures, altitudes, slopes, and winds. Data computed from the flight-test expansion model appear as symbols. Conservative curves have been faired through the data at each RCR to form curves for the flight manual.
Figure 17. Unbalanced field length (UBFL) ISA deviation correction at all temperatures and altitudes. Reference weight (120,000 lb), slope, wind, and RCR conditions apply. Data computed from the flight-test expansion model appear as symbols. Conservative curves have been faired through the data at each ISA deviation to form curves for the flight manual.

Figure 18. Unbalanced field length (UBFL) weight correction at all temperatures and altitudes. Reference slope, wind, and RCR apply. Data computed from the flight-test expansion model appear as symbols. Conservative curves have been faired through the data at each weight to form curves for the flight manual.
Figure 19. Unbalanced field length (UBFL) RCR correction at all temperatures, altitudes, and weights. Reference slope and wind apply. Data computed from the flight-test expansion model appear as symbols. Conservative curves have been faired through the data at each RCR to form curves for the flight manual.

Figure 20. Unbalanced field length (UBFL) runway slope correction at all temperatures, altitudes, and weights. Reference RCR and wind conditions apply. Data computed from the flight-test expansion model appear as symbols. Conservative curves have been faired through the data at each slope to form curves for the flight manual.
Figure 21. Unbalanced field length (UBFL) runway slope correction at all temperatures, altitudes, weights, and RCR values. Reference winds apply. Data computed from the flight-test expansion model appear as symbols. Conservative curves have been faired through the data at each slope to form curves for the manual.

Figure 22. Unbalanced field length (UBFL) wind correction at all temperatures, altitudes, and weights. Reference RCR and runway slope apply. Data computed from the flight-test expansion model appear as symbols. Conservative curves have been faired through the data at each wind to form curves for the manual.
Figure 23. Unbalanced field length (UBFL) wind correction at all temperatures, altitudes, weights, RCR values, and runway slopes. Data computed from the flight-test expansion model appear as symbols. Conservative curves have been faired through the data at each wind to form curves for the flight manual.

Figure 24. Landing Distance to 50 feet at all weights and altitudes. Reference slope, wind, RCR, and ISA atmosphere apply. Data computed from the flight-test expansion model appear as symbols form exact curves for the flight manual chart (no conservative fairing of data required for this case).
Figure 25. ISA deviation correction to landing distance to 50 feet at all weights and altitudes. Reference slope, wind, and RCR apply. Data computed from the flight-test expansion model appear as symbols. Conservative curves have been faired through the data at each ISA deviation to form curves for the flight manual.

Figure 26. Runway slope correction to landing distance to 50 feet at all weights and altitudes. Reference temperature, wind, and RCR apply. Data computed from the flight-test expansion model appear as symbols. Conservative curves have been faired through the data at each slope to form curves for the flight manual.
Figure 27. Runway slope correction to landing distance to 50 feet at all weights, altitudes, and temperatures. Reference wind and RCR apply. Data computed from the flight-test expansion model appear as symbols. Conservative curves have been faired through the data at each slope to form curves for the flight manual.

Figure 28. Wind correction to landing distance to 50 feet at all weights, altitudes, and temperatures. Reference temperature, slope and RCR apply. Data computed from the flight-test expansion model appear as symbols. Conservative curves have been faired through the data at each wind to form curves for the manual.
Figure 29. Wind correction to landing distance to 50 feet at all weights, altitudes, temperatures, and runway slopes. Reference RCR applies. Data computed from the flight-test expansion model appear as symbols. Conservative curves have been faired through the data at each wind to form curves for the flight manual.

Figure 30. RCR correction to landing distance to 50 feet at all weights and altitudes. Reference temperature, slope, and wind conditions apply. Data computed from the flight-test expansion model appear as symbols. Conservative curves have been faired through the data at each RCR to form curves for the flight manual.
Figure 31. RCR correction to landing distance to 50 feet at all weights, altitudes, temperatures, runway slopes, and winds. Data computed from the flight-test expansion model appear as symbols. Conservative curves have been faired through the data at each RCR to form curves for the flight manual.
Figure 32. Flight manual chart for balanced field length (BFL), sheet 1 of 2.
Figure 33. Flight manual chart for balanced field length (BFL), sheet 2 of 2.
Figure 34. Flight manual chart for unbalanced field length (UBFL), sheet 1 of 3.
Figure 35. Flight manual chart for unbalanced field length (UBFL), sheet 2 of 3.
Figure 36. Flight manual chart for unbalanced field length (UBFL), sheet 3 of 3.
Figure 37. Flight manual chart for landing distance to 50 feet, sheet 1 of 3.
Figure 38. Flight manual chart for landing distance to 50 feet, sheet 2 of 3.
Figure 39. Flight manual chart for landing distance to 50 feet, sheet 3 of 3.
Figure 40. Comparison of CFL results from the expansion and flight-manual models. The 1:1 slope line corresponds to perfect correlation. Points below the line are conditions where the flight manual is non-conservative; points above the line are points where the flight manual is conservative. Sample is the full source matrix used to create the flight manual charts with all perturbations of input parameters. N=193,815. Points with CFL greater than 20,000 feet removed.

Figure 41. Cumulative probability distribution for error in the flight-manual model for CFL. Sample is the full source matrix used to create the flight manual charts with all perturbations of input parameters. N=193,815. Points with CFL greater than 20,000 feet removed.
Figure 42. Comparison of landing distance to 50 feet results from the flight-test expansion and the flight-manual models. The 1:1 slope line corresponds to perfect correlation. Points below the line are conditions where the flight manual is non-conservative; points below the line are points where the flight manual is conservative. Sample is the full source matrix used to create the flight manual charts with all perturbations of input parameters. N=199,200.

Figure 43. Cumulative probability distribution for error in the flight-manual model for landing distance to 50 feet. Sample is the full source matrix used to create the flight manual charts with all perturbations of input parameters. N=199,200.
Figure 44. Hypothetical frequency and cumulative probability distributions for operational takeoff weights: 
(i) corresponds to operational set #1; (ii) corresponds to operational set #2.

Figure 45. Hypothetical frequency and cumulative probability distributions for operational landing weights: 
(i) corresponds to operational set #1; (ii) corresponds to operational set #2.

Figure 46. Hypothetical frequency and cumulative probability distributions for operational airfield pressure 
altitudes: (i) corresponds to operational set #1; (ii) corresponds to operational set #2.

Figure 47. Hypothetical frequency and cumulative probability distributions for temperature deviations from 
standard day (ISA): (i) corresponds to operational set #1; (ii) corresponds to operational set #2.
Figure 48. Hypothetical frequency and cumulative probability distributions for operational runway slopes encountered: (i) corresponds to operational set #1; (ii) corresponds to operational set #2.

Figure 49. Hypothetical frequency and cumulative probability distributions for operational winds encountered: (i) corresponds to operational set #1; (ii) corresponds to operational set #2.

Figure 50. Hypothetical frequency and cumulative probability distributions for operational RCR values encountered: (i) corresponds to operational set #1; (ii) corresponds to operational set #2. Note, operational set #2 assumes RCR takes values of 5 (icy), 12 (wet), and 23 (dry) only.
Figure 51. Comparison of CFL results from the expansion and flight-manual models. The 1:1 slope line corresponds to perfect correlation. Points below the line are conditions where the flight manual is non-conservative; points above the line are points where the flight manual is conservative. Sample is Monte Carlo data for operational set #1. N=50,000. Points with CFL greater than 20,000 feet removed.

Figure 52. Cumulative probability distribution for error in the flight-manual model for CFL. Sample is Monte Carlo data for operational set #1. N=50,000.
Figure 53. Comparison of landing distance to 50 feet results from the flight-test expansion and flight-manual models. The 1:1 slope line corresponds to perfect correlation. Points below the line are conditions where the flight manual is non-conservative; points below the line are points where the flight manual is conservative. Sample is Monte Carlo data for operational set #1. N=50,000.

Figure 54. Cumulative probability distribution for error in the flight-manual model for landing distance to 50 feet. Sample is Monte Carlo data for operational set #1. N=50,000.
Figure 55. Comparison of CFL results from the expansion and flight-manual models. The 1:1 slope line corresponds to perfect correlation. Points below the line are conditions where the flight manual is non-conservative; points above the line are points where the flight manual is conservative. Sample is Monte Carlo data for operational set #2. N=50,000. Points with CFL greater than 20,000 feet removed.

Figure 56. Cumulative probability distribution for error in the flight-manual model for CFL. Sample is Monte Carlo data for operational set #2. N=50,000.
Figure 57. Comparison of landing distance to 50 feet results from the flight-test expansion and flight-manual models. The 1:1 slope line corresponds to perfect correlation. Points below the line are conditions where the flight manual is non-conservative; points below the line are points where the flight manual is conservative. Sample is Monte Carlo data for operational set #2. N=50,000.

Figure 58. Cumulative probability distribution for error in the flight-manual model for landing distance to 50 feet. Sample is Monte Carlo data for operational set #2. N=50,000.
References


