A LOW COST METHOD FOR GENERATING TAKEOFF GROUND ROLL CHARTS FROM FLIGHT TEST DATA

Maj Russell E. Erb
Department of Aeronautics
2354 Fairchild Dr, Suite 6H22
United States Air Force Academy, Colorado 80840-6222

Abstract

A new low cost method was developed to measure takeoff ground roll as part of a flight test program to determine the limiting density altitude for sailplane aerotow operations at the United States Air Force Academy. Data were collected for 262 takeoffs of the towplane-sailplane combination on a non-interference basis during summertime student training. Ground roll distances were triangulated using a transit, and atmospheric conditions were measured using common simple instruments.

Herrington suggests empirical relationships in the Flight Test Engineering Handbook for reducing takeoff ground roll data to standard conditions. The effectiveness of these relationships was investigated using published general aviation aircraft data and a wide range of flight test data for the towplane-sailplane combination. The flight test ground roll distances were reduced to standard conditions. The empirical relationships suggested by Herrington were found to work well for the towplane-sailplane aerotow combination. Traditional takeoff mean ground roll charts were generated along with additional charts showing expected dispersion. The methods for generating these charts are described.

Introduction

The United States Air Force Academy's "Soar for All" program introduces cadets to the world of flight by training the cadets to fly sailplanes. Most cadets progress up through solo during this program. While some cadets take the program during the academic semesters, the majority of the cadets learn to soar during 2-week periods in the summer between the spring and fall semesters.

Sailplanes are launched at the Academy by aerotow, being towed behind a Bellanca Scout on a 200-foot polypropylene rope. Because of the high elevation of the Academy airfield (6505 feet), density altitude was a major factor in aerotow performance, especially during the summer months. Assuming standard pressure (altimeter setting of 29.92), a temperature of 93° F, quite common during a Colorado summer, will result in a density altitude in excess of 10,000 feet.

In the past, the soaring operations at the Academy were suspended if the airfield density altitude exceeded 10,000 feet. The 94th Flying Training Squadron (FTS) requested the Department of Aeronautics to conduct a flight test program to investigate raising this restriction. As a part of this effort, the takeoff ground roll was evaluated to determine if available runway length was a limiting factor. Since very little funds other than flight time were available, a low cost method to measure takeoff ground roll was developed using equipment available at the Academy.

Test Item Description

A surveyor's transit (Figure 1) on a tripod was used to measure azimuth to determine ground roll distance. The transit used was of approximately World War II vintage and used protractor scales for measuring and bubble levels for leveling. The transit was equipped with a 100X scope. This method should be adaptable to more modern transits, although this was not investigated.

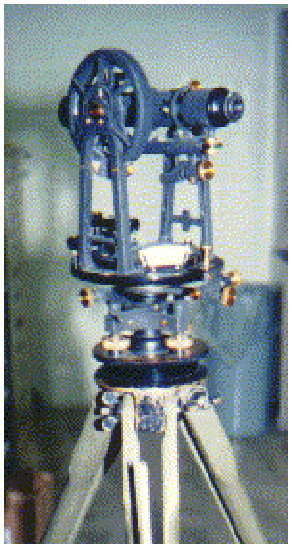

Figure 1 Surveyor's Transit

The towplanes were Bellanca Scouts (Figure 2), each equipped with a 180 horsepower Lycoming O-360-C2E and a fixed pitch MacCauley 8041 propeller. The Scout had a straight, strut-braced high wing with trailing edge flaps and ailerons. The flaps were set in the first notch (7 degrees) for aerotow operations. Landing gear was of the conventional (taildragger) type. For the glider towing mission, the aircraft was modified with pilot-releasable towhook immediately aft of the tailwheel.

Figure 2 Bellanca Scout Towplane

The sailplanes were Schweizer 2-33 (Figure 3), towed by a pilot releasable towhook under the nose ahead of the cockpit. The 2-33 had tandem seating with the student in the front cockpit and the instructor in the rear cockpit. The wing was a tapered, strut-braced high wing with trailing edge ailerons and upper and lower spoilers. Landing gear was a single centerline main wheel with tailwheel and wing tip wheels.

Figure 3 Schweizer 2-33 Sailplane

Takeoff Ground Roll Measurement

Because of the great uncertainty and large amount of scatter in takeoff data, it was impractical for the test team alone to fly a sufficient number of takeoff test points to collect enough data to be statistically meaningful. Therefore, it was decided to collect data by observing takeoffs of student training sorties. By this method, up to 17 takeoffs per hour could be recorded, significantly greater than would be possible by a single test crew. The 94th FTS was interested in the takeoff performance on a typical student sortie rather than with a trained test crew, which was better met by observing student takeoffs. While the pilot technique used by all of the tow pilots was essentially the same, student pilot technique was anything but well defined. These variations in pilot technique could be somewhat averaged out by observing many different tow pilots and student pilots. A total of 262 takeoffs were observed during this program.

Since data were being collected by observing student training, it was necessary to develop a technique that was also transparent to the aircrew. The aircrew could not be expected to participate in the data collection. Primary data collection was accomplished with a transit, set up as shown in Figure 4.

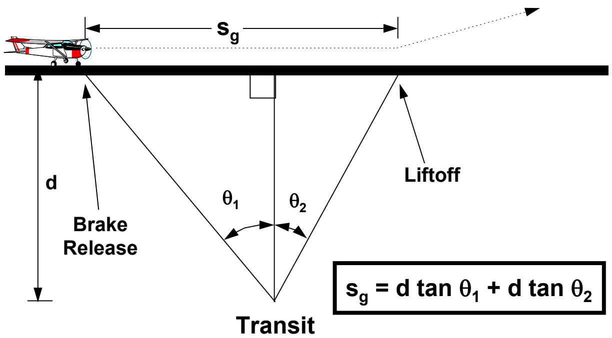

Figure 4 Measuring Ground Roll Distance

The general concept of this technique was to determine the ground roll by measuring the angles θ_1 and θ_2. The line separating θ_1 and θ_2 extended from the transit perpendicular to the runway centerline. Knowing these angles and the distance from the transit to the runway centerline, the ground roll distance (s_g) can be calculated by

$$s_g = d \tan \theta_1 + d \tan \theta_2 \qquad (1)$$

Note that this method assumed the aircraft lifted off on centerline.

After a location was chosen for the transit, the distance to the runway centerline (d) was measured with a 100-foot tape measure. This distance was measured perpendicular to the runway centerline. The perpendicular direction was determined using a magnetic compass.

It was possible to set up the transit such that the horizontal angle scale (measuring panning of the transit) was at zero when the transit was pointed perpendicular to the runway. However, doing so would have taken far more effort than necessary. The transit was set up, then using a magnetic compass, an object was located in the distance which was in the direction perpendicular to the runway centerline from the transit. The transit was pointed at this object and the reading of the horizontal angle scale was recorded. This reading was called the reference angle. The data reduction was simplified by setting up the transit such that the reference angle was greater than 90 degrees and less than 270 degrees. By doing this, all angles could be subtracted without having to add or subtract 360 degrees to get the expected angle.

Figure 5 shows the transit setup on the airfield at the USAF Academy. After the tow rope was attached to the sail plane and the towplane taxied forward to remove the slack, the transit was pointed at the right main wheel by looking through the telescope. The reading on the horizontal angle scale was recorded as the initial angle. Because of the magnification of the telescope, the right main wheel and strut filled the field of view. Therefore, it was not possible to track the towplane during the takeoff run by looking through the telescope without losing the towplane from the field of view. Instead, the towplane was tracked

Figure 5 Data Collection Setup

during the takeoff roll by looking over the top of the telescope, aligning two screws on top of the telescope with the right main wheel. This was very similar to using a traditional gunsight on a rifle not equipped with a scope. As the towplane lifted off the ground, the transit was released and not touched again until after reading on the horizontal angle scale. This reading was recorded as the final angle. Judging the liftoff point required practice, as the initial climb angle was very shallow, resulting in a slow separation between wheel and pavement. Judging the liftoff point was also made difficult by the distance from the observer to the towplane.

In addition to the takeoff ground roll distance, other data were required, including barometric pressure, temperature, aircraft gross weight, and wind direction and velocity. Since no electrical power was available at the data collection site, plug-in laboratory instruments could not be used. Therefore, barometric pressure was measured as pressure altitude on a spare aircraft altimeter. Air temperature was measured by a glass thermometer taped to the tripod leg. The thermometer was shaded from the sun by another high-tech innovation, namely an empty quart juice carton obtained from the cadet dining hall with one side cut out (Figure 6). A portable anemometer and wind vane could be set up to determine winds. However, at the USAF Academy, wind speed and direction were read as part of the takeoff clearance. Thus, wind speed and direction were determined by monitoring the tower frequency.

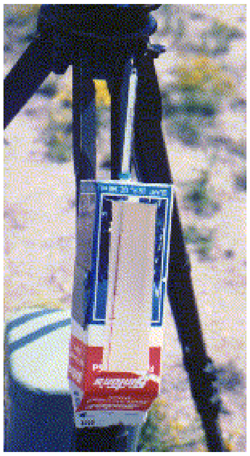

Figure 6 Thermometer and Sunshade

Aircraft gross weight was not measured directly. Prior to each takeoff, the tail number for the towplane and sailplane were recorded. The time of engine start for the towplane and the pilot's name were recorded after each refueling. The empty weights for each towplane and each sailplane were kept on file. The weights for tow pilots, sailplane instructor pilots and sailplane student pilots were also kept on file. The fuel weight was calculated by subtracting the engine start time from the takeoff time, and multiplying by an assumed fuel flow rate of 7 gallons per hour. This fuel flow rate was obtained from the towplane operators based on years of experience in these operations. USAF Academy soaring procedures required recording the names of the sailplane aircrew and the takeoff time for each sortie. Using these logs, the names of the aircrew were determined by matching the tail numbers and takeoff times recorded by the test team with the tail numbers and takeoff times in the aircrew logs. With the aircrew names, the aircrew weight was determined from a roster of names and weights. All weights were then added to compute the gross weight of the towplane and sailplane.

To standardize the takeoff data, the liftoff airspeed was required. Since this data collection technique was to be non-interference with the student training flights, it was not possible to call the student or tow pilot on the radio and ask for the liftoff airspeed. Fortunately, the tow pilots were consistent in their technique, such that a liftoff airspeed could be assumed. During nine sorties flown by the test team, the sailplane indicated airspeed was recorded when the towplane main gear lifted off of the runway. These airspeeds varied from 50 mph to 55 mph, with an average airspeed of 53 mph. Therefore, the liftoff indicated airspeed for all takeoffs was assumed to be 53 mph.

As also shown in Figure 5, it is recommended that the test team be supplied with beverages and high-fructose snacks to maintain morale while collecting data. Use of a good high-SPF sunscreen is also highly recommended. The test team commented on results of not following this recommendation, although those comments were not suitable for publication.

Takeoff Ground Roll Measurement Error

The location of the transit relative to the takeoff run affected the error present in the takeoff ground roll measurement. In many cases, the location of the transit will be determined by topographical features, such as airport boundaries or hills obstructing view of the runway.

If the airport topography allowed, three possible positions for the transit were suggested. The derivative of Equation 1 shows that the error in distance measurement resulting from an error in angular measurement is

$$\frac{ds}{d\theta} = d * \sec^2 \theta \qquad (2)$$

This error was minimized if θ was 0, which would imply placing the transit abeam the brake release point or abeam the expected liftoff point. However, two angles were measured, and by minimizing the error at one end, the error at the other end is increased because θ is so much larger. Therefore, another possibility was placing the transit abeam the halfway point of the expected takeoff run.

The first case of placing the transit abeam the brake release point was the least practical. While a very accurate reading of the starting position would be possible, the liftoff point would have a large error because of the large measurement angle. A better choice would be to put the transit abeam the expected liftoff point. Since the aircraft was stationary prior to brake release, it would be possible to get an accurate angle measurement. At liftoff, the motion of the aircraft will contribute to the angular measurement error, so it would be better to measure the liftoff angle in a range where the resulting distance error is less. A still better choice would be to place the transit abeam the midpoint of the expected takeoff ground roll. (Note that this analysis assumes equal probability of error at both ends of the takeoff run; the probability of error is actually higher at the liftoff end since the aircraft is moving.)

Figure 7 shows the variation of the measurement error as a function of the distance between the transit and the runway centerline. A takeoff distance of 1000 feet and a 1-degree measurement error at each end of the takeoff run were assumed for this figure. The angular errors were assumed to be in opposite directions, such that the effect was cumulative. The upper curve assumed the transit was located abeam the liftoff point, as shown in Case 1 of Figure 8. The lower curve shows the error for the transit located abeam the midpoint of the takeoff run, as shown in Case 2 of Figure 8. The resulting minimum measurement error for Case 2 was 36 feet, or 3.6 percent of the takeoff distance.

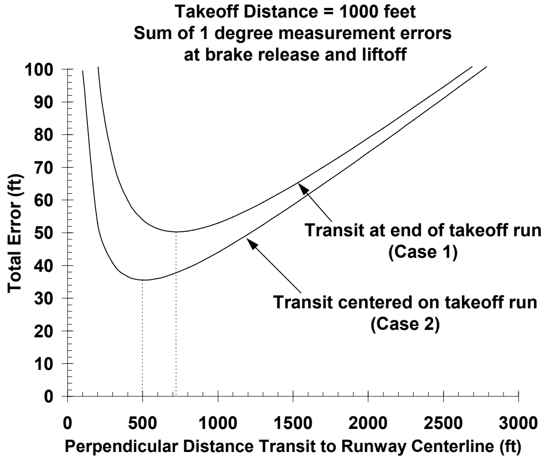

Figure 7 Takeoff Ground Roll Measurement Error

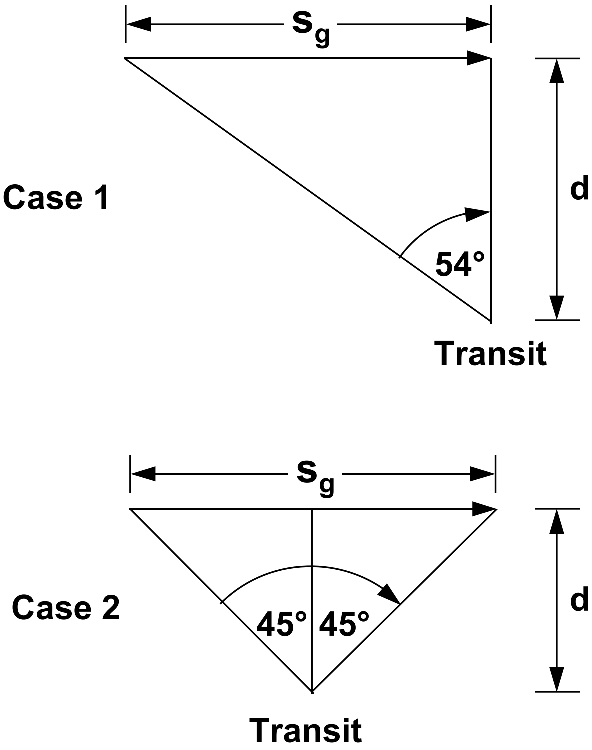

Figure 8 Takeoff Ground Roll Measurement Cases

Ground Roll Distance Data Standardization

The objective of standardizing takeoff data was to determine the takeoff ground roll distance at standard conditions. For this analysis, standard conditions were sea level, standard day, standard weight, no wind, on a dry, level runway. Since the standard condition was fully defined, all takeoff distances should reduce to a single distance.

Unfortunately, takeoff testing is filled with uncertainty. According to Herrington,

> **The take-off performance of any aircraft is highly dependent on pilot technique. Even with experienced well-qualified pilots it is difficult to make the aircraft take off at the same value of lift**

> **coefficient each time. As this is the rule rather than the exception, a rigorous mathematical treatment of reducing observed take-off data to standard conditions is not warranted; therefore, no mathematically exact solutions will be given for reducing data. (Reference 1)**

The best way to handle pilot technique was to standardize it (i.e., do it the same way every time). A possible technique could look something like

1. Apply full throttle while holding the brakes.
2. Release brakes.
3. Accelerate to 55 knots.
4. Rotate until the cowling is on the horizon.
5. Wait until the aircraft lifts off.
6. Climb out at 70 knots.

Once the takeoff distance at standard conditions was determined, it could be expanded to any non-standard conditions by reversing the standardization process.

Herrington's Method - The following equations are a summary of the takeoff data standardization section in Reference 1. This method corrects for runway slope, winds, weight, and density, and the equations must be applied in the order presented. Note that this order is exactly opposite the order used in a takeoff ground roll chart to predict the takeoff ground roll, since this chart is essentially expanding the standardized data.

Runway Slope Correction

$$s_{level} = \frac{s_{slope}}{1 + \frac{2 g s_{slope} \sin\theta}{V_{to_{slope}}^2}} \qquad (3)$$

where:

s_{level}	takeoff distance corrected to level runway
s_{slope}	measured takeoff distance on sloped runway
g	acceleration of gravity
θ	runway slope angle (not percent slope), measured from horizontal (+ for uphill, - for downhill)
$V_{to_{slope}}$	liftoff ground speed

Wind Correction

$$s_w = s_{level}\left(\frac{V_{to} + V_w}{V_{to}}\right)^{1.85} \qquad (4)$$

where:

s_w	takeoff distance corrected for wind
s_{level}	takeoff distance corrected for runway slope
V_{to}	liftoff ground speed
V_w	component of wind velocity down runway (+ for headwind, - for tailwind)

Note that the fraction inside the parentheses of Equation 4 can alternatively be expressed as liftoff true airspeed divided by liftoff ground speed.

Weight Correction

$$s_{wt} = s_w \left(\frac{W_s}{W_t} \right)^{2.4} \tag{5}$$

where:

s_{wt}	takeoff distance corrected for weight
s_w	takeoff distance corrected for wind
W_s	standard weight
W_t	actual test weight

Density Correction

$$s_{std} = s_{wt} \left(\frac{\sigma_s}{\sigma_t} \right)^{-2.4} \tag{6}$$

where:

s_{std}	takeoff distance corrected for density, final standardized distance
s_{wt}	takeoff distance corrected for weight
σ_s	density ratio at standard altitude
σ_t	actual test density ratio

This correction completes Herrington's method for standardizing takeoff ground roll distance for aircraft using fixed pitch propellers. For aircraft using constant speed propellers, additional corrections are made for engine RPM and brake horsepower. These corrections were not applicable to this test program.

Verification Using Published General Aviation Data - Herrington's method for standardizing takeoff ground roll data contains empirical constants; and therefore, begs for justification of these empirical constants. According to Reference 1, the complete study and analysis can be found in Reference 2. However, this work was not available to the test team. Therefore, possible verification was sought by studying Flight Manual takeoff data for three different general aviation aircraft from three different manufacturers. This analysis was accomplished by assuming the manufacturers used the relationships in Equations 4 - 6, and then adjusting the empirical exponent in each equation to achieve the best fit with the manufacturer's data. The results of this analysis are shown in Table 1.

These results lead to a few observations. First, the three manufacturers' results do not agree with each other. This observation further supports the premise that takeoff data standardization is not straightforward. Second, the Cessna exponents match very well with Herrington's exponents. Third, these results imply reasonable values for the empirical exponents. Any exponents used that differ greatly from these results would be suspect.

Table 1

ANALYSIS OF PUBLISHED TAKEOFF DATA

Headwind Exponent	Tailwind Exponent	Weight Exponent	Density Exponent	Source
0.987	1.44	1.37	-2.34	Beechcraft Sierra, Sundowner
1.07	2.46	2.12	-3.73	Piper Tomahawk, Archer II
1.88	---	2.39	-2.4	Cessna T-41C/D
1.85	1.85	2.4	-2.4	Herrington
2.00	2.00	2.00	-2.00	Analytical

The last row of Table 1 shows the exponents as given by analytical techniques. These exponents come from the equation

$$s = \frac{1.44W^2}{g\rho SC_{L_{max}}\left\{T - \left[D + \mu_r(W - L)\right]_{avg}\right\}} \qquad (7)$$

as given in Reference 3. The numerator of this equation shows that the ground roll distance is proportional to the square of the weight. While density appears explicitly only once in the denominator, thrust is approximated as directly proportional to density. Therefore, ground roll distance is inversely proportional to the square of the density.

Wind effects can be seen from another form of the equation, showing the relationship of ground roll distance, ground speed, and acceleration:

$$s = \frac{V_{to}^2}{2a} \qquad (8)$$

To produce lift equal to weight at the specified lift coefficient, the aircraft must lift off at a specific true airspeed. Any headwind is subtracted from this true airspeed, reducing the ground speed (V_{to}) necessary for takeoff. From Equation 8, the ground roll distance is proportional to the square of the ground speed. From these equations, it follows that the ground roll distance would vary with the square of the headwind speed, since the headwind is the difference between the true airspeed needed for liftoff and the ground speed to which the aircraft must accelerate.

The analytically derived exponents do not match the empirically derived exponents exactly. This mismatch can be attributed to the assumptions made in the analytical analysis, primarily using an average value of excess thrust for accelerating. The average excess thrust is the excess thrust at 0.7 V_{to}. Propeller thrust varies with airspeed, decreasing as velocity increases. Drag and lift increase with the square of the velocity. Weight effects on rolling friction are also averaged out. Engine power and propeller thrust are assumed to be inversely proportional to density, which is a close but not an exact approximation. Changes in drag during rotation are not considered.

Even with these assumptions, the analytical exponents are close to the empirical exponents, which lends further confidence to the empirical exponents.

Verification Using Flight Test Data - The final question with regards to this flight test program was even if Herrington's method worked for reciprocating engine powered, fixed pitch propeller aircraft, would it work for one towing a sailplane? Could the aerotow combination be considered as one aircraft with a weight equal to the total weight, a wing area equal to the total wing area, and its own drag polar? The answer was yes.

During this test program, 262 aerotow takeoffs were observed. All of these takeoffs were with the Bellanca Scout towplane. Of these takeoffs, 251 were with the Schweizer 2-33, 10 with the ASK-21, and 1 with the Schweizer 1-26. Of the six towplanes flown, one was found to have noticeably better performance than the others, and one was found to have noticeably poorer performance than the others. Using only the 2-33 takeoffs with the four remaining towplanes left 156 takeoffs for analysis.

Slope Correction - No verification of the slope correction was required. This relation was a simple mathematical derivation with no empirical exponents.

Wind Correction - If the wind correction was good, then a set of takeoff ground roll distances at the same density altitude and weight corrected for runway slope would converge to the same takeoff ground roll distance when the wind correction was applied. If these corrected takeoff ground roll distances were plotted against headwind speed, they would form a horizontal line. If the data formed a line with a negative slope, the data would be under-corrected. If the data formed a line with a positive slope, the data would be over-corrected.

Unfortunately, the data interpretation was not that simple. It was complicated by two factors. First, it was difficult to get a large sample of data at the same weight and density altitude. Variations in weight and density caused additional data scatter. Second, the many sources of uncertainty, such as variations in pilot technique and measurement errors, caused additional data scatter.

Figure 9 shows 10 sets of takeoff ground roll data corrected for runway slope but not corrected for wind effects. Each set of data were at approximately the same density altitude and weight. As shown in Table 2, the maximum density altitude range was 286 feet, and the weight range of each group was approximately 20 lbs, or less than 1 percent of the total weight. A least squares linear curve fit is shown for each set of data. These curve fits are not meant to imply the functional relationships, but only to show the general trend of the highly scattered data. These lines should not be given a lot of weight, given the poor correlation shown in Table 2. The R^2 value states what percentage of the variation in the y value can be attributed to the variation in the x value. While some R^2 values appear to be good (i.e., close to 1), these values only appear on data sets with very few data points. In fact, none of the data sets really have enough data points to be statistically significant. Therefore, only general trends will be considered.

Table 2

WIND CORRECTION DATA STATISTICS

Weight (lbs)	Number of Data Points	Correlation (R^2)
Density Ratio: 0.7748-0.7810 Density Altitude: 8207-8465 feet		
2809-2829	4	0.9590
2850-2869	7	0.1505
2870-2889	5	0.8801
2900-2919	8	0.5048
2934-2954	4	0.9966
Density Ratio: 0.7598-0.7666 Density Altitude: 8802-9088 feet		
2820-2839	7	0.3671
2845-2864	9	0.8798
2865-2884	9	0.1538
2890-2913	7	0.4800
2927-2946	6	0.5698

Figure 10 shows the data from Figure 9 after applying the wind correction of Equation 4. While the lines shown are not all horizontal, they did move in the appropriate direction, namely increasing the no-wind takeoff distance for data points with large headwinds without changing the takeoff distance for data points with no headwind. Because of the problems introduced by data scatter, it was difficult using just these data to prove that 1.85 was the right exponent. With the null hypothesis that 1.85 was the right exponent, and with the support for 1.85 expressed in Table 1, the corrected data did not give sufficient weight to reject the null hypothesis. Therefore, 1.85 was accepted as an appropriate exponent. Additionally, any problems with the wind correction would show up in the final standardized data, to be investigated later.

Weight Correction - If the weight correction was good, then a set of takeoff ground roll distances at the same density altitude corrected for runway slope and wind would converge to the same takeoff ground roll distance when the weight correction was applied. If these corrected takeoff ground roll distances were plotted against weight, they would form a horizontal line. If the data formed a line with a negative slope, the data would be under-corrected. If the data formed a line with a positive slope, the data would be over-corrected.

Figure 11 shows two sets of takeoff ground roll data corrected for runway slope and wind but not corrected for weight effects. Each data set was at approximately the same density altitude. As shown on Figure 11, the maximum density altitude range was 286 feet. A least squares linear curve fit is shown for each set of data. These curve fits are not meant to imply the functional relationships, but only to show the general trend of the highly scattered data. Again, these lines should not be given a lot of weight, given the poor correlation (R^2 = 0.1112 and 0.0334) for each group. The first data series has 31 points and the second data series has 51 points. However, because of the large amount of scatter, only general trends will be considered.

The lines in Figure 11 seem to imply that the takeoff ground roll data were not a function of weight, which is an absurd conclusion. This conclusion further points to the danger of quick conclusions from data with lots of scatter.

Figure 12 shows the data from Figure 10 after applying the weight correction of Equation 5. While the lines shown are not horizontal, they did move in the appropriate direction, namely increasing the standard weight takeoff distance for data points below standard weight without changing the takeoff distance for data points at standard weight. Because of the problems introduced by data scatter, it was difficult using just these data to prove that 2.4 was the right exponent. With the null hypothesis that 2.4 was the right exponent, and with the support for 2.4 expressed in Table 1, the corrected data did not give sufficient weight to reject the null hypothesis. Therefore, 2.4 was accepted as an appropriate exponent. Additionally, any problems with the weight correction would show up in the final standardized data, to be investigated later.

Density Correction - If the density correction was good, then the takeoff ground roll distances corrected for runway slope, wind, and weight would converge to the same takeoff ground roll distance when the density correction is applied. If these corrected takeoff ground roll distances are plotted against density, they would form a horizontal line. If the data formed a line with a positive slope, the data would be under-corrected. If the data formed a line with a negative slope, the data would be over-corrected.

Figure 13 shows all of the takeoff ground roll data corrected for runway slope, wind, and weight but not corrected for density effects. A least squares linear curve fit is shown for the data. This curve fit is not meant to imply the functional relationship, but only to show the general trend of the highly scattered data. For the 156 data points, this line has a correlation (R^2) of 0.0043. Because of the large amount of scatter, only the general trend will be considered.

The line in Figure 13 does show an increasing takeoff ground roll distance with increasing density altitude, as would be expected. Figure 14 shows the data from Figure 13 after applying the density correction of Equation 6. The line in Figure 14 is very close to horizontal as was originally expected. This line adds confidence that -2.4 was the right exponent for the density correction, and supports the validity of the entire method given in Reference 1. Therefore, the data standardization method was considered usable for fixed pitch propeller driven aircraft, including the towplane-sailplane combination.

The extent of the data scatter can be seen in the standardized data. The mean standardized takeoff ground roll was 864 feet, and the standard deviation was 150 feet. Multiplying by 1.96 to find the two-tailed 95 percent confidence interval gives a data scatter range of ±294 feet, or ±34 percent. While for most testing ±34 percent would be considered horrendous data scatter, for takeoff testing this scatter was actually reasonable.

Ground Roll Chart Construction

The mean takeoff ground roll shown in Figure 15 is shown in a format similar to that used by several general aviation manufacturers. This chart was created basically by reversing the data standardization process.

After standardizing all of the takeoff data, ideally every takeoff would standardize to the same distance as all of the other takeoffs, which would be the takeoff distance at sea level, at standard weight, with no wind on a level runway. Of course, the result was a distribution with a mean and a standard deviation. Starting with the mean takeoff distance, the density correction was created by varying pressure altitude and temperature to change the density ratio in the equation

$$s_{wt} = \frac{s_{std}}{\left(\frac{\sigma_s}{\sigma_t}\right)^{-2.4}} \tag{9}$$

The weight correction guide lines were created by selecting a distance at standard weight (s_{wt}). This distance was the value of the curve at the weight reference line. The remainder of the curve was formed by varying W_t in the equation

$$s_w = \frac{s_{wt}}{\left(\frac{W_s}{W_t}\right)^{2.4}} \tag{10}$$

The wind correction guidelines were created by selecting a distance at zero wind (s_w). This distance was the value of the curve at the wind reference line. The remainder of the curve was formed by varying V_w in the equation

$$s_{level} = \frac{s_w}{\left(\frac{V_{to} + V_w}{V_{to}}\right)^{1.85}} \tag{11}$$

where V_{to} was the takeoff ground speed and $V_{to} + V_w$ was the takeoff true airspeed.

The dispersion charts shown in Figure 16 and Figure 17 were created using the standard deviation of the standardized takeoff distances. Assuming the takeoff data were normally distributed, a one-tailed test was used, since takeoffs shorter than the mean distance were not an operational concern. For a 95-percent confidence interval, the normal distribution gives a z = 1.65. For a 99-percent confidence interval, the normal distribution gives a z = 2.33. Multiplying the standard deviation by the appropriate z value gave the dispersion at sea level, at standard weight, with no wind on a level runway. To adjust the dispersion for density, the density ratio was varied in the following equation, where s_{std} was the dispersion at standard conditions.

$$s_{wt} = \frac{s_{std}}{\left(\frac{\sigma_s}{\sigma_t}\right)^{-2.4}} \qquad (12)$$

To adjust for weight, W_t in the following equation was varied.

$$s_w = \frac{s_{wt}}{\left(\frac{W_s}{W_t}\right)^{2.4}} \qquad (13)$$

No correction was made for headwind since any headwind would shorten the takeoff run.

$$s_{level} = s_w \qquad (14)$$

Conclusions

A low cost method was developed for measuring takeoff ground roll distance using a transit and simple instruments. The measurement error was minimized by placing the transit abeam the midpoint of the expected takeoff roll at a distance from the runway equal to half the expected takeoff roll. The empirical relationships for standardizing the takeoff ground roll given by Herrington were supported by analysis of published general aviation takeoff data and the flight test data from the towplane-sailplane aerotow combination. From the standardized data, charts for the mean takeoff ground roll distance and takeoff ground roll distance dispersion were developed. (Results of the Academy flight test program will be published separately.)

References

1. Herrington, Russel M., Major, USAF, et al, *Flight Test Engineering Handbook*, AF Technical Report 6273, AFFTC, Edwards AFB, California, 1966.

2. Lush, K. J., *Standardization of Take-Off Performance Measurements for Airplanes*, Technical Note R-12, AFFTC, Edwards AFB, California.

3. Anderson, John D., Jr., *Introduction to Flight*, 3rd ed., McGraw-Hill Book Company, New York, 1989.

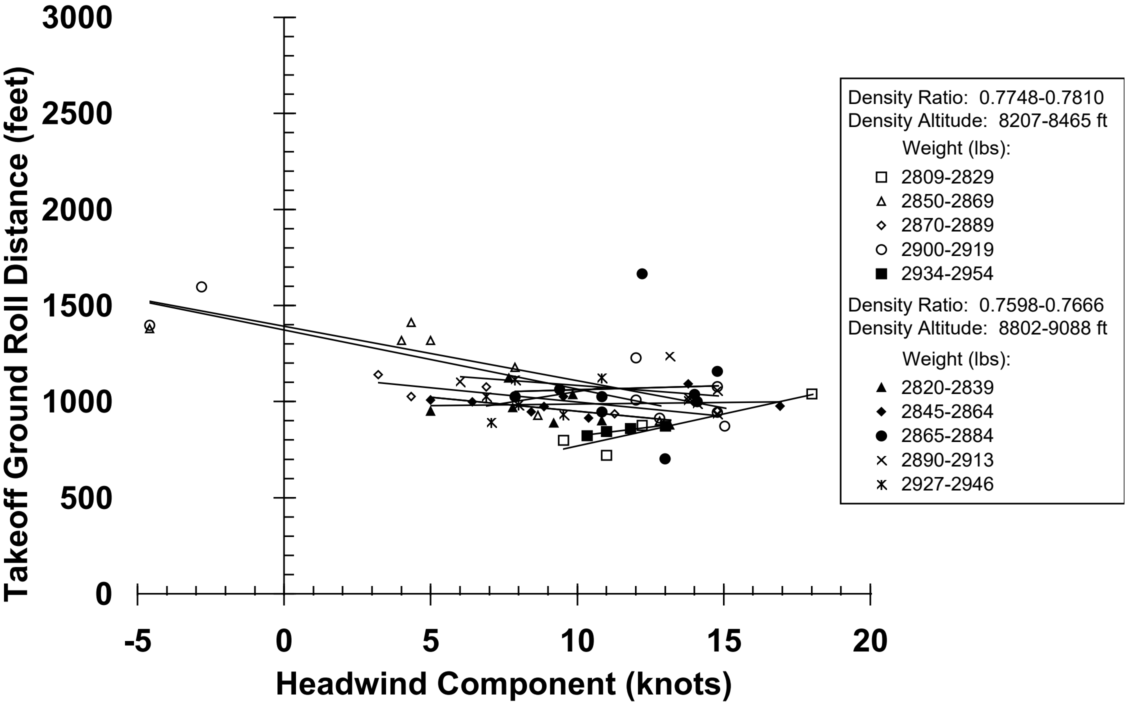

Figure 9 Slope Corrected Takeoff Ground Roll Data Prior to Wind Correction

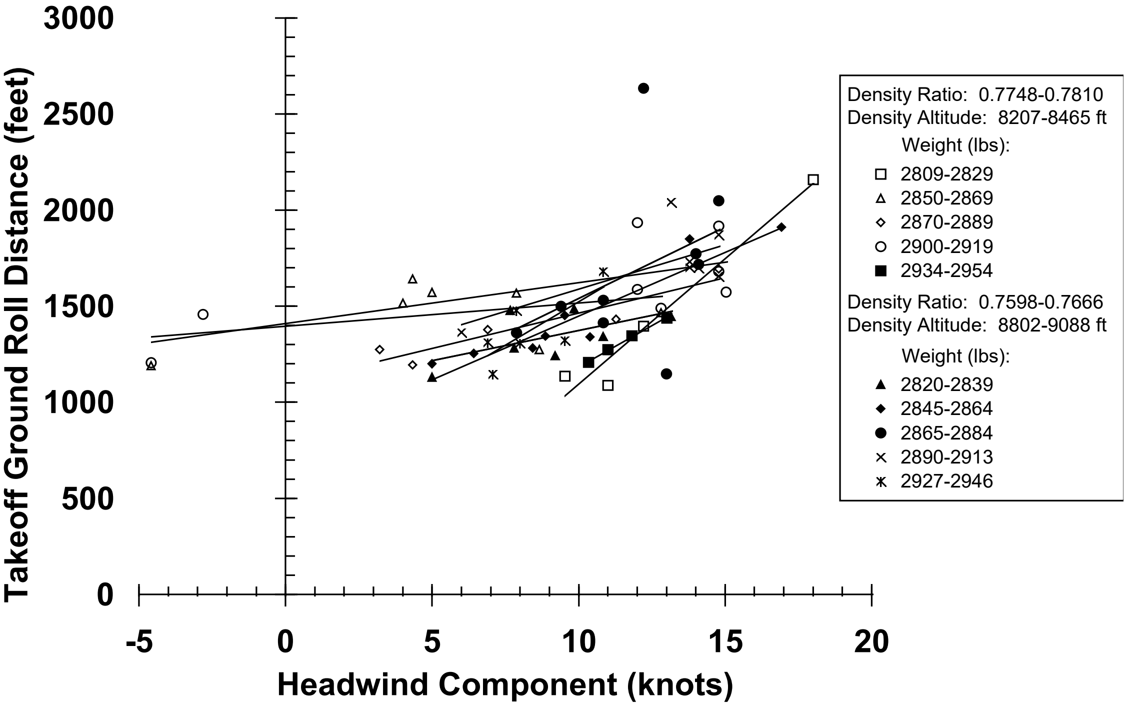

Figure 10 Wind Corrected Takeoff Ground Roll Distance

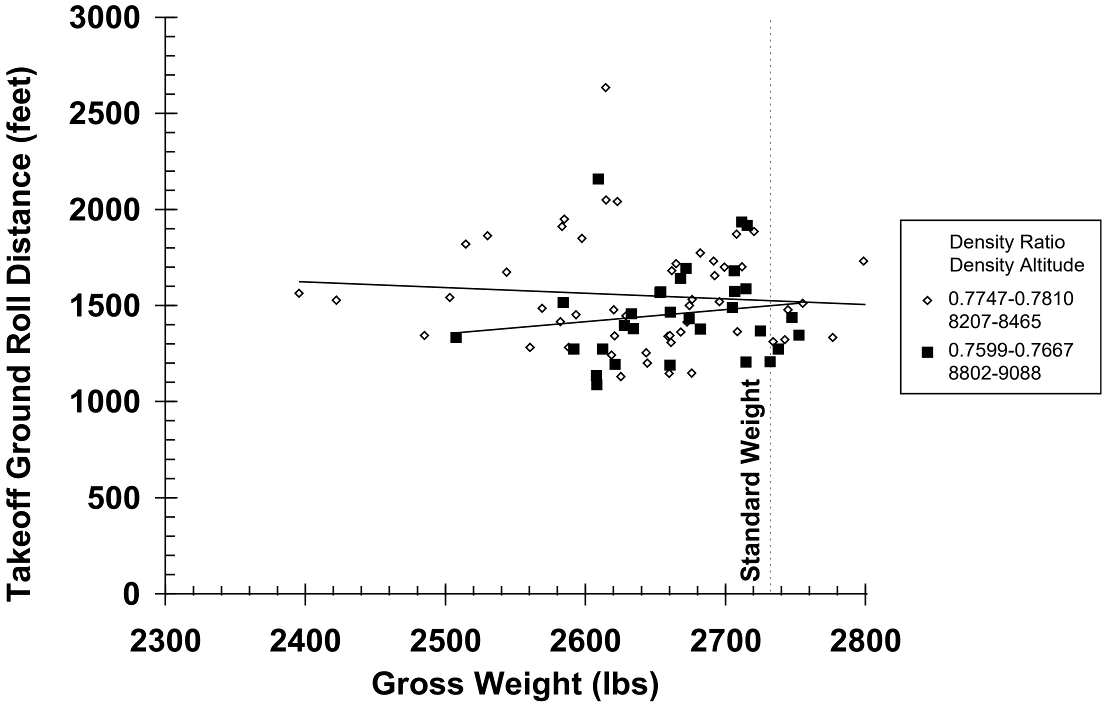

Figure 11 Wind Corrected Takeoff Ground Roll Data Prior to Weight Correction

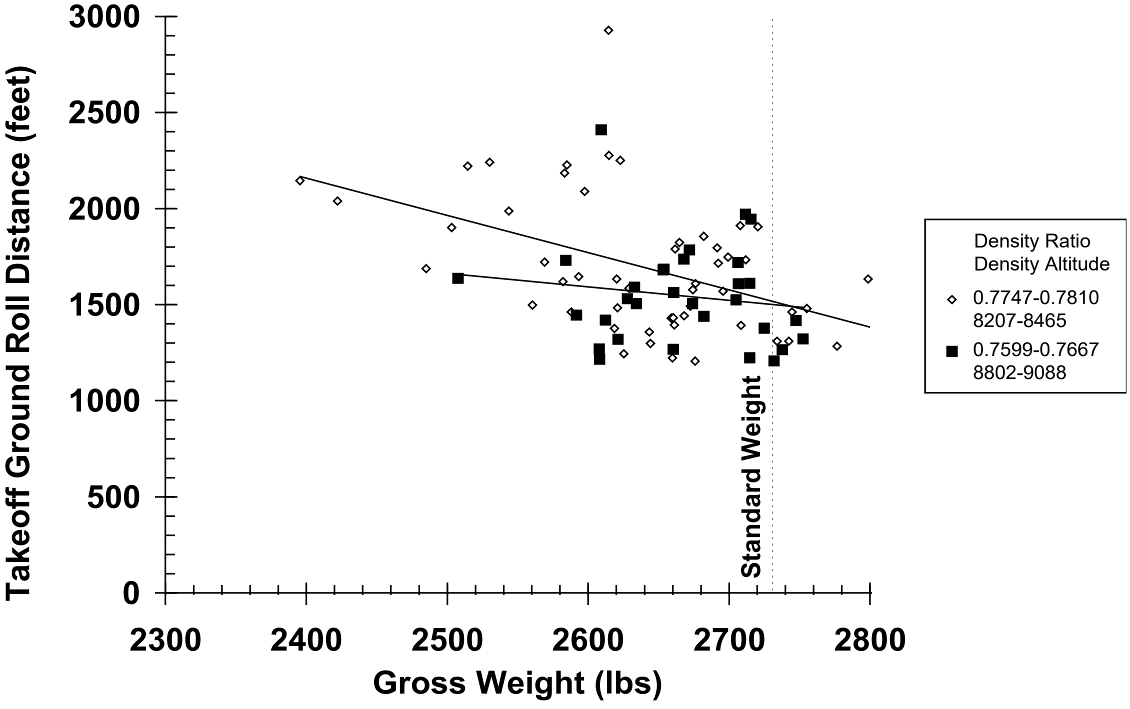

Figure 12 Wind Corrected Takeoff Ground Roll Distance

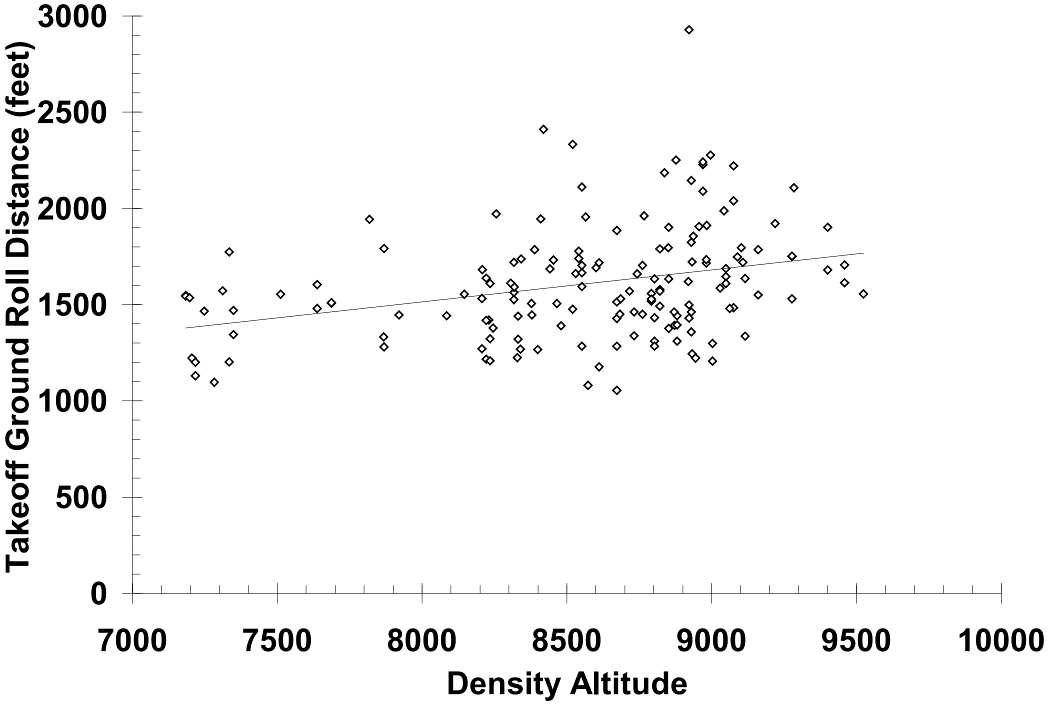

Figure 13 Weight Corrected Takeoff Ground Roll Data Prior to Density Correction

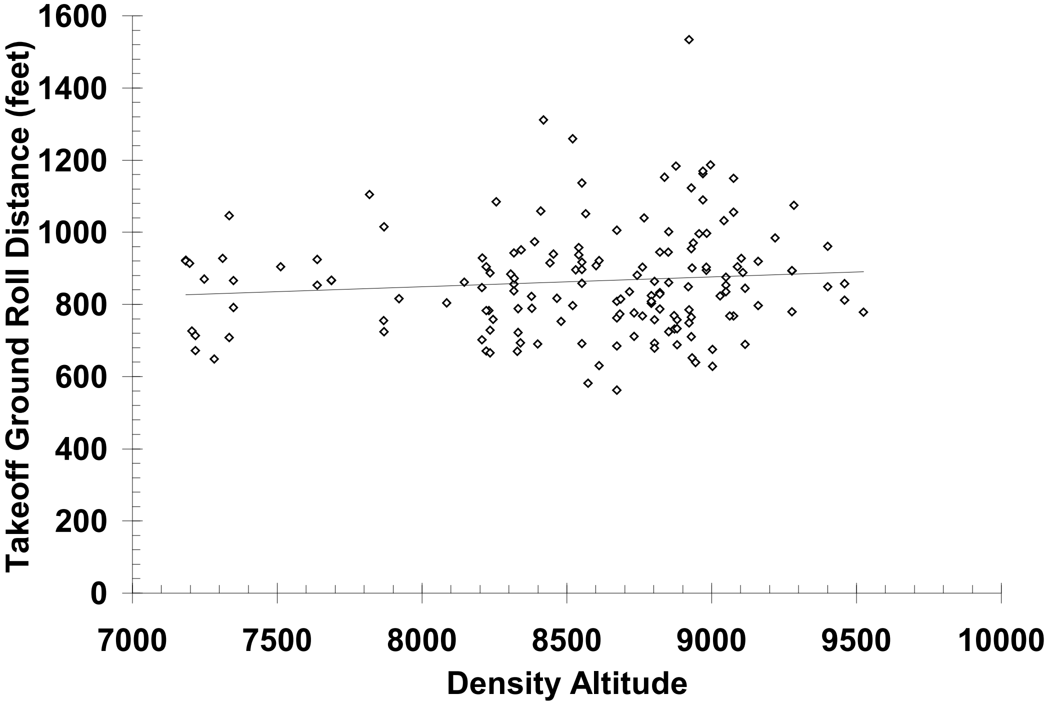

Figure 14 Density Corrected Takeoff Ground Roll Distance

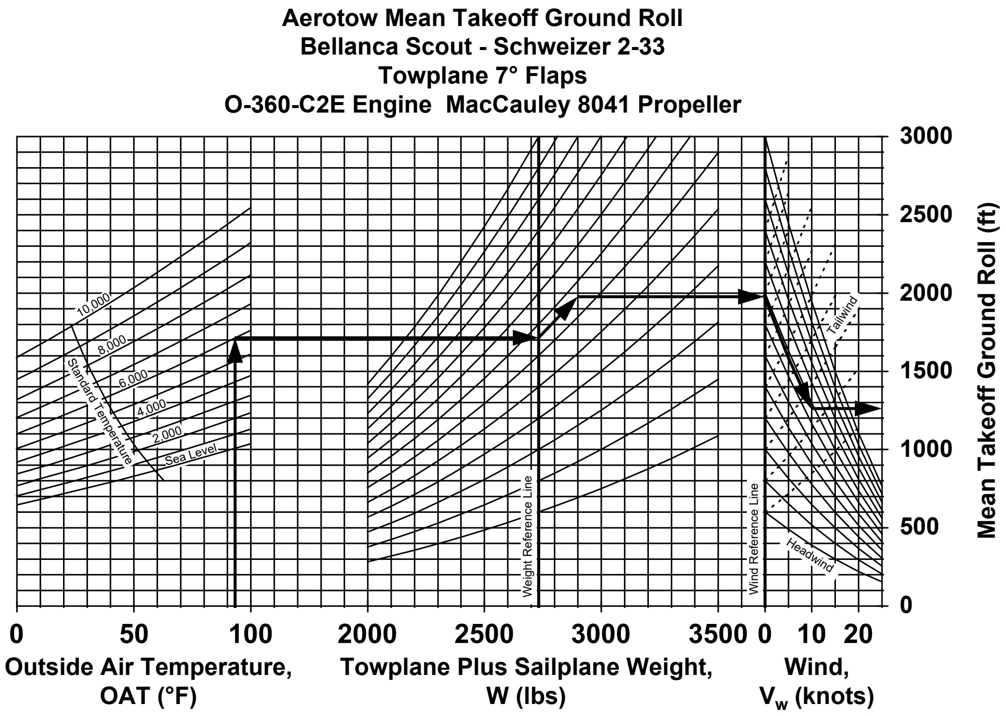

Figure 15 Mean Takeoff Ground Roll Chart

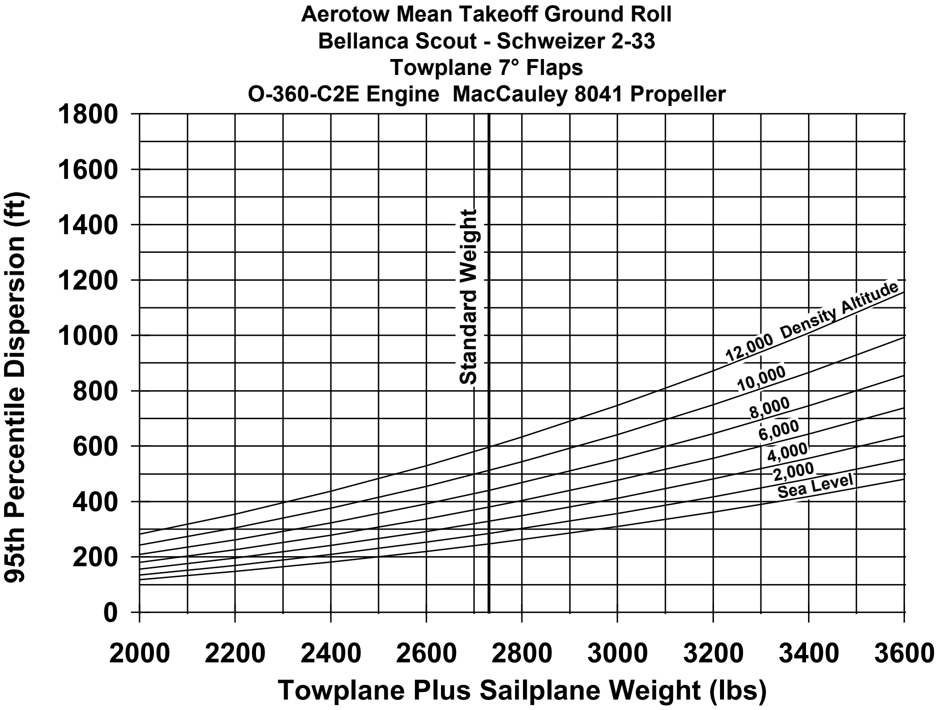

Figure 16 95th Percentile Dispersion Chart

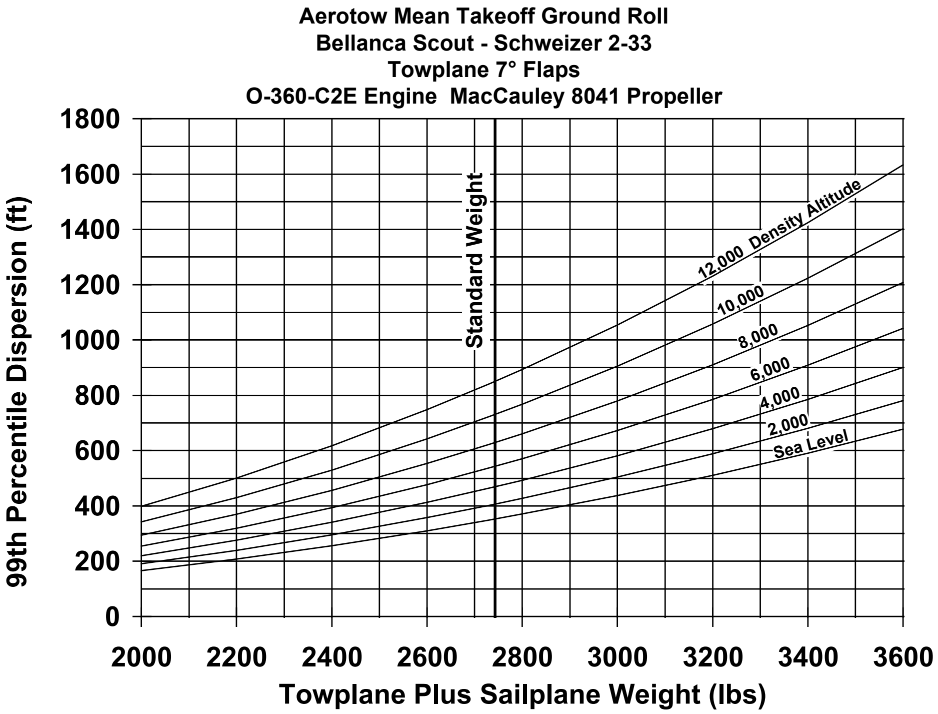

Figure 17 99th Percentile Dispersion Chart

Biography

Maj. Russell E. Erb graduated as a flight test engineer from the USAF Test Pilot School in class 89B. "A Low Cost Method for Generating Takeoff Ground Roll Charts from Flight Test Data" is based on a flight test program that he conducted at his previous assignment as an Assistant Professor in the Department of Aeronautics at the United States Air Force Academy. Russ has also worked as the Chief Engineer on the MC-130H Combat Talon II at Edwards AFB and in aircraft/stores compatibility at Eglin AFB. He graduated in 1983 from the USAF Academy with a B.S. in Aeronautical Engineering and in 1985 from Texas A&M University with a M.S. in Aerospace Engineering. While at Texas A&M, he joined SFTE as a one of the first student members. He is a past secretary-treasurer of the Antelope Valley Chapter, and has recently been assigned back at Edwards AFB in the 413th Flight Test Squadron.