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A PRELIMINARY STUDY OF THE BENEFITS OF FLYING BY GROUND SPEED DURING FINAL APPROACH

Earl C. Hastings, Jr.

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NASA
National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia 23665

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SUMMARY

A study was conducted to evaluate the benefits of an approach technique which utilized constant ground speed on approach. It was determined that this technique reduced the capacity losses in headwinds experienced with the currently used constant airspeed technique. The benefits of this technique were found to increase as headwinds increased and as the wake avoidance separation intervals were reduced. An additional benefit noted for the constant ground speed technique was a reduction in stopping distance variance due to the approach wind environment.

INTRODUCTION

Reference 1 has shown that the delivery precision available with 4D navigation systems has the potential for increasing landing capacity by reducing arrival errors at the ILS gate. These navigation systems provide inputs to the autothrottle to change airspeed as required in order to maintain the required ground speed. The current automatic landing systems however, utilize the autothrottle to maintain a constant airspeed from the ILS gate to the threshold. These systems have been patterned after the typical manually flown approach which also relies upon the maintenance of a constant airspeed.

The need to maintain speed margin for manuevering (as well as wind changes) during final approach, and years of experience tend to support the need for an approach with constant airspeed. However, the advent of new radio precision approach equipment (Microwave Landing System) and the desire to improve capacity in the future Air Traffic Control environment, suggest the need for an examination of new approach techniques which take advantage of the new precision approach equipment.

This report presents the results of a preliminary study of the effects on landing capacity of the constant ground speed approach technique. The operational factors which limit both the constant airspeed and constant ground speed approach techniques are defined. The results of landing capacity analyses for both techniques are presented and compared for several steady state wind environments. The effect of wind shear on stopping distance is also discussed in the report

SYMBOLS AND ABBREVIATIONS

SYMBOLS

h	height above ground level, m
H	designates aircraft classified as Heavy
i	designates the leading aircraft in a pair
j	designates the following aircraft in a pair
L	designates aircraft classified as Large
s	stopping distance, m

t_{ij}	interarrival time between aircraft, i and j at the runway, sec
V_A	airspeed, kts
$V_{A_{max}}$	maximum approach airspeed, kts
V_g	groundspeed, kts
V_W	steady wind speed,kts (positive values denote headwinds
ΔV_W	airspeed correction factor in steady winds, kts.
γ	length of approach path between the ILS gate and the projected touchdown point, km
δf	flap angle, deg
δ_{ij}	wake turbulence separation interval between aircraft i and j, km
Θ_{FUS}	fuselage pitch attitude, deg, (nose down is negative)
λ	landing capacity, operations/hr
Subscript	
o	zero wind conditions

ABBREVIATIONS

FAA	Federal Aviation Administration
ILS	Instrument Landing System
LRC	Langley Research Center

DATA ANALYSIS

For purposes of this preliminary study, steady state conditions were assumed in the landing capacity analysis. As a result the wind field was uniform (i.e. wind direction and magnitude were the same at all altitudes and there were no gusts or random turbulence). An additional result of this assumption was that in the capacity analysis the airspeed and ground speed did not change between the ILS gate and the projected touchdown point.

The method of landing capacity analysis was the same as described in reference 2, but with the appropriate equations modified to account for steady winds. The modified equations for the interarrival time, t_{ij}, between aircraft i and j in steady winds were

$$t_{ij} = \frac{\delta_{ij}}{V_{g_j}} \qquad \text{where} \quad V_{g_i} \leq V_{g_j} \tag{1}$$

$$t_{ij} = \frac{\delta_{ij}}{V_{g_j}} + \gamma\left(\frac{1}{V_{g_j}} - \frac{1}{V_{g_i}}\right) \qquad \text{when} \quad V_{g_i} > V_{g_j} \tag{2}$$

Values of V_g were determined from (3)

$$V_g = V_{A_o} - V_W + \Delta V_W$$

The procedure for calculating the landing capacity, λ, using t_{ij} values from equations (1) and (2) is also presented in reference 2.

The landing mix used in this study included two types of commercial jet aircraft:

(1) Large(L) aircraft with takeoff weights between 5670 kg (12,500 lbm) and 136,078 kg (300,000 lbm)

(2) Heavy(H) aircraft with takeoff weights greater than 136,078 kg

RESULTS AND DISCUSSION

CONSTANT AIRSPEED APPROACH TECHNIQUE

As previously noted, current automatic landing systems on commercial jets use basically the constant airspeed approach technique. With this technique the approach airspeed (V_A) is selected by adding an airspeed correction factor (ΔV_w) to the "zero wind" approach airspeed (V_{A_o}) to account for steady winds and gusts. This selected V_A is then maintained at a constant value by the autothrottle or the pilot.

In order to avoid changes in ground speed due to winds, it would be necessary to select V_A so that $V_g = V_{g_o}$ for any value of V_w. Because of operational limitations, however, this is not possible with this approach technique. The dashed line in figure 1 shows V_A required for $V_g = V_{g_o}$ and the solid line shows the variation of V_A with V_w when operational limitations are imposed. These operational limitations are for the 737-100 aircraft with full landing flaps ($\delta_F = 40^o$) at a landing weight of 37,648 kg (83,000 lbm).

The solid line in figure 1 shows that in tailwinds V_A must be greater than required for $V_g = V_{g_o}$ since V_A can not be less than V_{A_o} without reducing the manuever margin. In addition, operations in tailwinds in excess of 10 kts are unusual; the FAA certification requirements on autoland systems are limited to 10 kts tailwind at most (ref. 3).

Figure 1 also shows that for the 737-100 approaching in headwinds V_A is always less than required for $V_g - V_{g_o}$ since reference 4 specifies that in headwinds ΔV_w should be 0.5 V_w up to a value no greater than ΔV_w = 20 kts. Restrictions of this type are generally applied to other commercial jets as well and are necessary to restrict the maximum approach airspeed, $V_{A_{max}}$. Otherwise, an encounter with an adverse headwind shear during approach might result in an excessively large stopping distance requirement after touchdown. (This effect is discussed in more detail in a later portion of this paper.)

Figure 2 shows the variation of ground speed with this technique. In tailwinds $V_g > V_{g_o}$ and in all headwinds $V_g < V_{g_o}$. The reduction in V_g between V_w = 0 and V_w = 40 kts is because ΔV_w is only half of V_w. Beyond V_w = 40 kts the more rapid reduction in V_g is because $V_{A_{max}}$ has been reached.

Constant Ground Speed Approach Technique

This technique utilized throttle changes as required to maintain constant V_g during approach. In principle, V_g would be held constant at V_{g_o} in all wind conditions and V_A would have the value required to keep $\Delta V_w = V_w$. As with the preceeding technique, however, operational factors impose limits on the application of this concepts.

In tailwinds, for example, V_A can not be reduced because of manuevering speed margin requirements. In headwinds the value of $V_{A_{max}}$ is imposed by the minimum acceptable pitch attitude of the aircraft. This is illustrated in figure 3. This figure shows the 737-100 fuselage pitch angle, Θ_{FUS} as a function of V_A. The data are for a height of h = 46.8m (no ground effects), a center of gravity location of 20% of the mean aerodynamic chord, and flap deflections of $\delta_F = 30^o$ and $\delta_F = 40^o$. The figure also shows a lower limit of $\Theta_{FUS} = -2.5^o$ determined from LRC flight experience with an experimental aircraft of the 737-100 type. With the automatic flare laws currently used with this aircraft, $\Theta_{FUS} \lesssim -2.5^o$ on approach prior to flare initiation will result in unacceptable nose down attitudes at landing.

The data in figure 3 show that for the 737-100 with full approach flaps ($\delta_F = 40^o$) this lower pitch trim limit fixes $V_{A_{max}}$ at 140 kts. However, if δ_F is reduced to 30^o a significant increase in $V_{A_{max}}$ to 158 kts is achieved. The corresponding maximum values of ΔV_W are 20 kts and 38 kts.

It should be noted that with this approach technique, the more restrictive limitations on ΔV_W of the constant airspeed technique (see Table I) are not required since ground speed and consequently the stopping distance requirements are controlled during the approach by the autoland system or by the pilot.

Figures 4 and 5 show, respectively, V_A and V_g as functions of V_W for this technique. The data in these figures show that, with this technique, it is possible to approach at the V_A required for $V_g = V_{g_o}$ between $V_W = 0$ and $V_W =$ 20 kts with full flaps and between $V_W = 0$ and $V_W = 38$ kts with partial flaps (fig. 4). As a result, there are no ground speed losses (fig. 5) in these headwind ranges when this technique is used.

A comparison of the data in figures 4 and 5 with the constant airspeed data in figures 1 and 2 indicates that the constant ground speed technique offers constant ground speed capability until $V_{A_{max}}$ is reached, and also that the highest value of $V_{A_{max}}$ is provided by the constant ground speed technique with partial flaps.

From equations (1) and (2) it is evident that, in headwinds, the higher ground speeds available with the constant ground speed technique will result in smaller values of t_{ij} and consequently higher landing capacity than the constant airspeed technique. The following section of the report discusses the impact of these ground speed differences on the landing capacity when applied to an assumed mix of commercial jet aircraft flying straight in approached from the ILS gate.

Landing Capacity

Landing capacity studies were done for both approach techniques with the following common conditions:

- V_{A_o} for type L aircraft - 135 kts
- V_{A_o} for type H aircraft - 142 kts
- mix contained 60% type L aircraft and 40% type H aircraft
- 3^o glideslope

In order to provide a reasonable basis for evaluating the results, three wind environment categories were determined from U.S. Weather Bureau data for New York City (refs 5 and 6) which are shown in figure 6. From these data, values of V_W between 0 and 5 kts were categorized for this study as light, values between 5 kts and 35 kts as normal, and values over 35 kts as strong.

Figure 7 shows the results of a baseline capacity analysis using current vortex avoidance separation intervals (Table II) and a flight path length of γ = 14.83 Km (8 n. mi.). Both of the approach techniques show an increase in λ in tailwinds. This change is regarded as academic since landing operations rarely occur in significant tailwinds. The more important changes are in the three headwind categories.

In light headwinds, the data in figure 7 show that the capacity benefit offered by the constant ground speed technique was small. In normal headwinds however, this benefit became significant particularly with the partial flap configuration. At V_W = 30 kts for example, this technique with partial flaps provided $\lambda = \lambda o$, while the constant airspeed technique resulted in a 12 percent reduction in λ due to the headwind. The benefit offered by the constant ground speed technique increased as V_W increased. In strong headwinds, this technique with partial flaps showed a benefit of approximately 15 percent relative to the constant airspeed technique. This technique with full flaps offered smaller benefits in normal headwinds.

Figure 7 also shows the importance of making the constant ground speed approaches, in normal and strong headwinds, at the highest possible approach airspeed (i.e. using partial flaps rather than full flaps).

The results of this baseline analysis showed that the largest capacity benefits in headwinds, were achieved with an approach technique which allowed full headwind compensation ($\Delta V_w = V_w$) and a high approach airspeed. In this particular analysis these conditions were best met by the constant ground speed approach technique using partial flaps. The results would be the same however, for any approach technique which resulted in the same combination of these two factors.

The preceeding baseline analysis utilized the current separation intervals from Table II. Since reduced intervals have been shown to increase capacity for the constant airspeed technique and may be used in the future (refs. 1 and 2) an additional analysis was performed to evaluate the effect of this interval with the constant ground speed technique. Data in figure 8 show λ for the two approach techniques using δ_{ij} = 3.70 km (2nmi) as a common separation interval.

A comparison of the data in figure 8 for reduced intervals with the data in figure 7 for current intervals shows that the capacity benefits (in ops./hr.) offered by the constant ground speed technique were increased when the separation interval was reduced. This is because changes in V_g are more significant when δ_{ij} is reduced (equations (1) and (2)). This result shows that the technique has application in future terminal area operations which may utilize reduced intervals as well as those using the current intervals.

An analysis was also performed to define the effects of the length of the approach path, γ . In all of the preceeding analyses γ has a value of 14.83

Km (8 n. mi.). It was found that, with current δ_{ij} values, reducing γ to 11.12 Km (6 n. mi.) increased λ less than 1% and increasing γ to 18.53 Km (10 n. mi.) reduced less than 1%. This result is consistent with that noted in reference 2 for earlier capacity studies.

The relative insensitivity of λ to changes in γ in these analyses is because the values of V_A for the i and j aircraft are not widely different and the increase in t_{ij} between the fast-slow pairs (equation 2) due to changes in γ are not significant. Another contributing factor is that for the landing mix used in this study, fast-slow aircraft pairs occurred only 24% of the time.

Effects of Winds on Stopping Distance

Stopping distance after touchdown is a function of V_g and, with the constant airspeed technique, V_g is a function of the wind environment. Consequently, the wind environment can significantly influence the stopping distance. With the constant ground speed technique, however, the stopping distance variation is less sensitive to the wind environment since V_g is the controlled speed parameter.

Some preliminary, unpublished, analyses of the response of a twin engine jet aircraft to gusts and wind shears during approach have been performed by Mr. W. W. Kelley of NASA Langley Research Center. These analyses are for the experimental NASA aircraft described in reference 7 making automatic constant airspeed approaches and automatic constant ground speed approaches. These results show that, in severe wind shears, the variation in V_g from the expected value may be about 6 kts with the constant ground speed technique, and in excess of 20 kts with the constant airspeed technique.

The impact of these variations on stopping distance, is illustrated in figure 9. The ordinate, s, is the stopping distance of the 737-100 aircraft with the autobraking system set for medium deceleration (ref. 8) and the abscissa, ΔV_g, is the difference between the expected ground speed at touchdown (120 kts in this illustration) and the actual ground speed at touchdown. A variation of 6 kts, for the constant ground speed technique, changes s by about 70 meters (230 ft). A variation of 20 kts, for the constant airspeed technique, changes s by about 280 meters (919 ft.) Although additional study is needed in this area, it appears that the constant ground speed technique may offer a decided advantage in reducing the variance in stopping distance created by the approach wind environment.

CONCLUDING REMARKS

Results have been presented from a preliminary study of the benefits of constant ground speed approaches. The results included the effects of several wind environments, wake avoidance separation intervals, and flight path lengths on landing capacity. The effect of winds on stopping distance was also discussed.

The results showed that constant ground speed approaches can reduce the losses in landing capacity associated with constant airspeed approaches in headwinds. This capability resulted in landing capacity benefits which increased as headwinds increased. A constant ground speed technique using partial flaps (which allowed the highest approach speed) resulted in capacity benefits of about 12% for a 30 kts headwind. In stronger headwinds, the benefit was about 15%. A constant ground speed technique, using full flaps, offered smaller gains in normal headwinds.

It was also found that the capacity benefits of the constant ground speed technique increased when the separation intervals were reduced. This indicated that this technique is applicable to future as well as current terminal area operations.

The variation in stopping distance of an aircraft after touchdown was shown to be less sensitive to the wind environment with the constant ground speed technique. A brief analysis indicated that this technique may significantly reduce the variance in stopping distance created by this environment.

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TABLE I: AIRSPEED CORRECTION FACTORS USED IN THE CAPACITY ANALYSIS

Type of Approach	ΔV_w, kts				
	V_w=-10	V_w=0	V_w=20	V_w=40	V_w=50
Constant Airspeed	0	0	10	20	20
Constant Ground Speed					
Full Flaps	0	0	20	20	20
Partial Flaps	0	0	20	38	38

TABLE II: CURRENT SEPARATION INTERVALS USED IN THE CAPACITY ANALYSIS

Aircraft Pair		Separation Interval, δ_{ij}	
i	j	Km	n. mi.
L	L	5.56	3
L	H	5.56	3
H	L	9.25	5
H	H	7.40	4

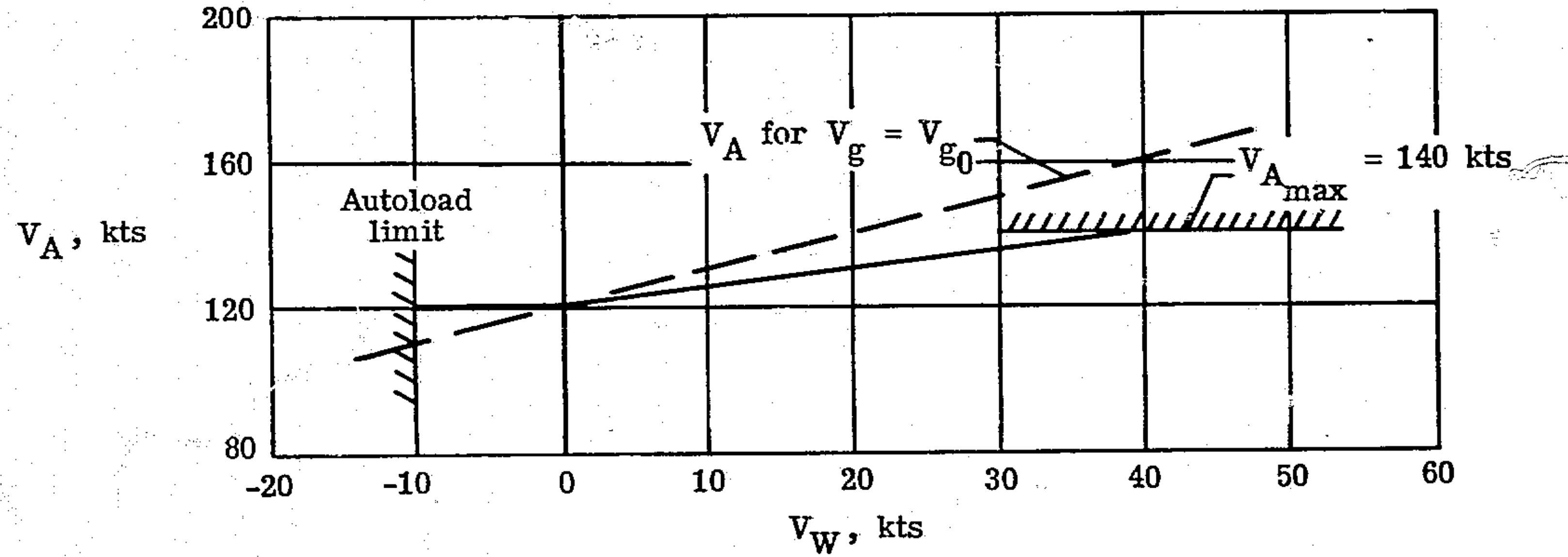

Figure 1.- Variation of airspeed for the constant airspeed technique.

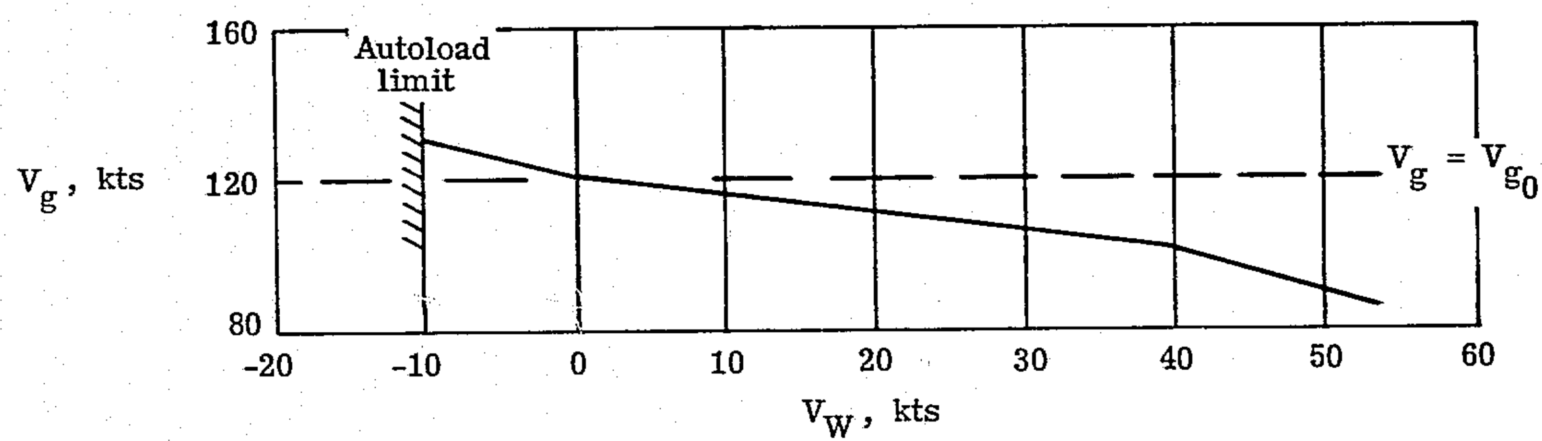

Figure 2.- Variation of ground speed for the constant airspeed technique.

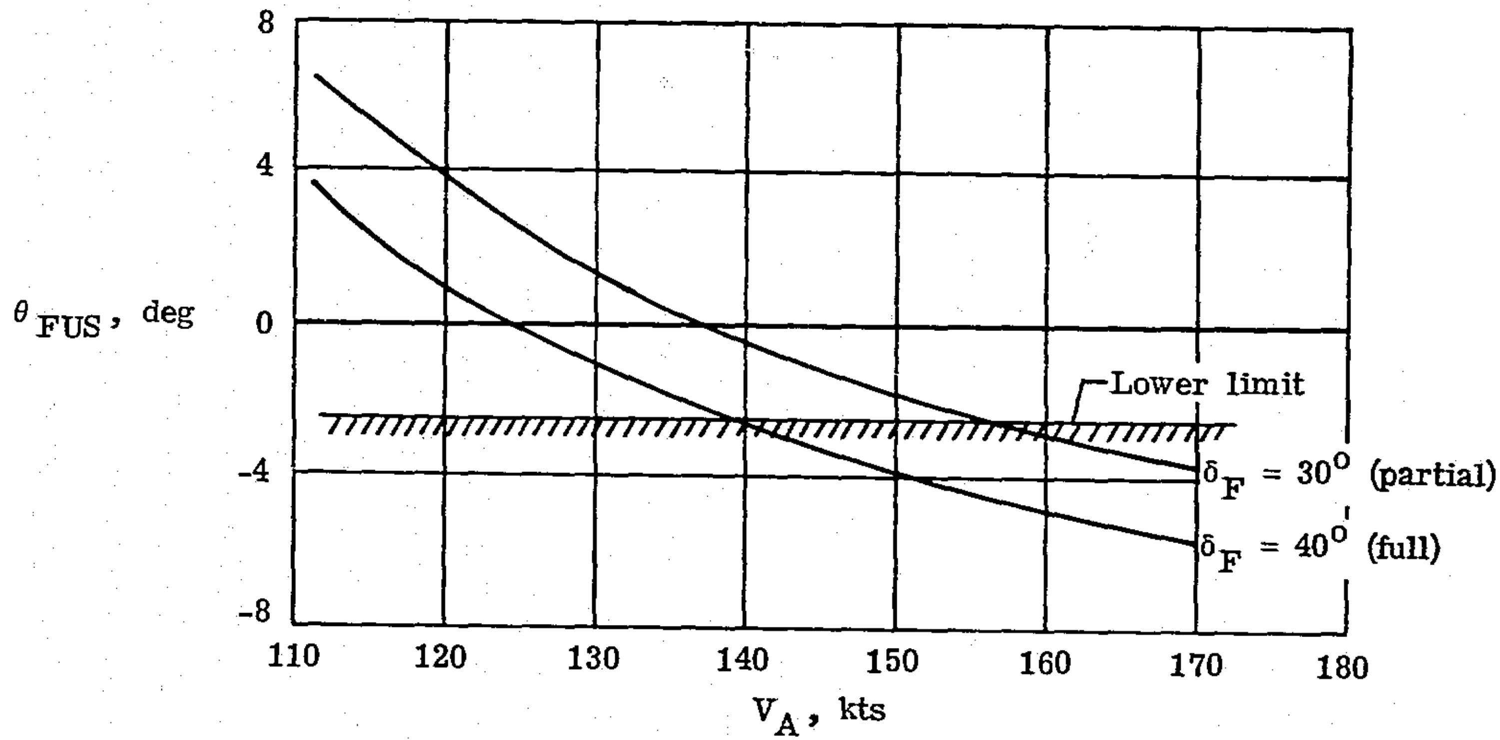

Figure 3.- Body pitch attitude at initiation of automatic flare manuever.

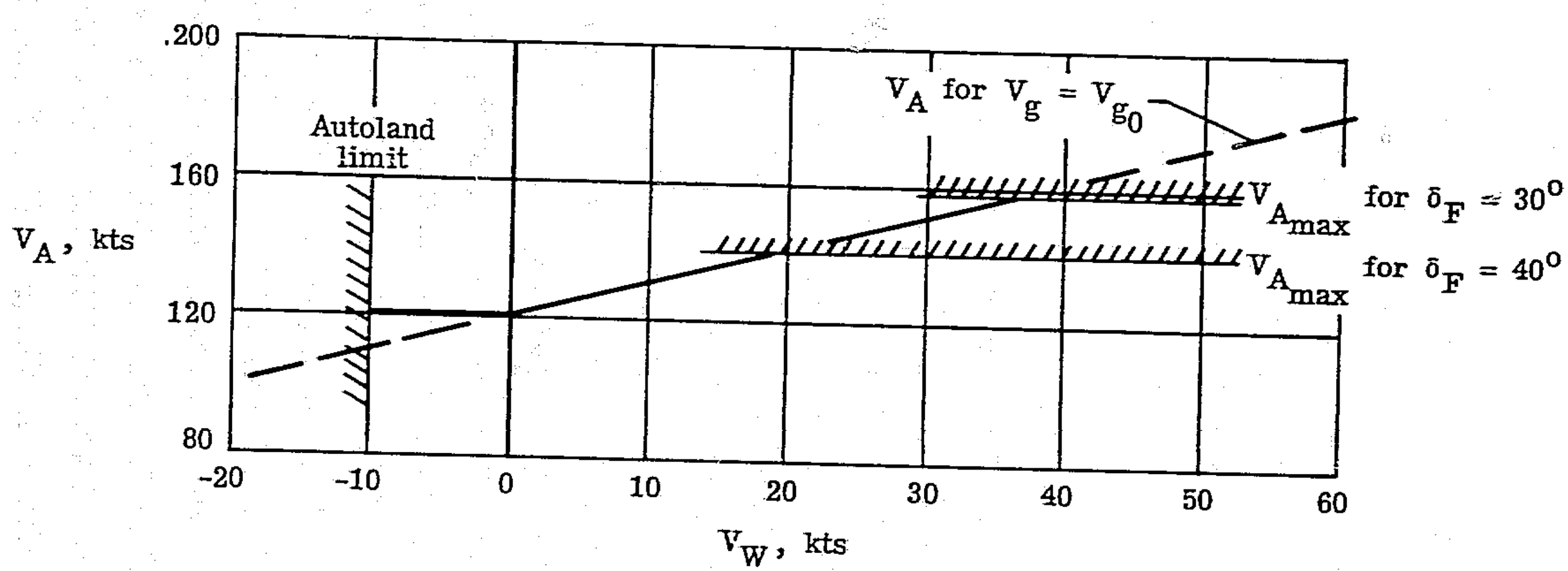

Figure 4.- Variation of airspeed for the constant ground speed technique.

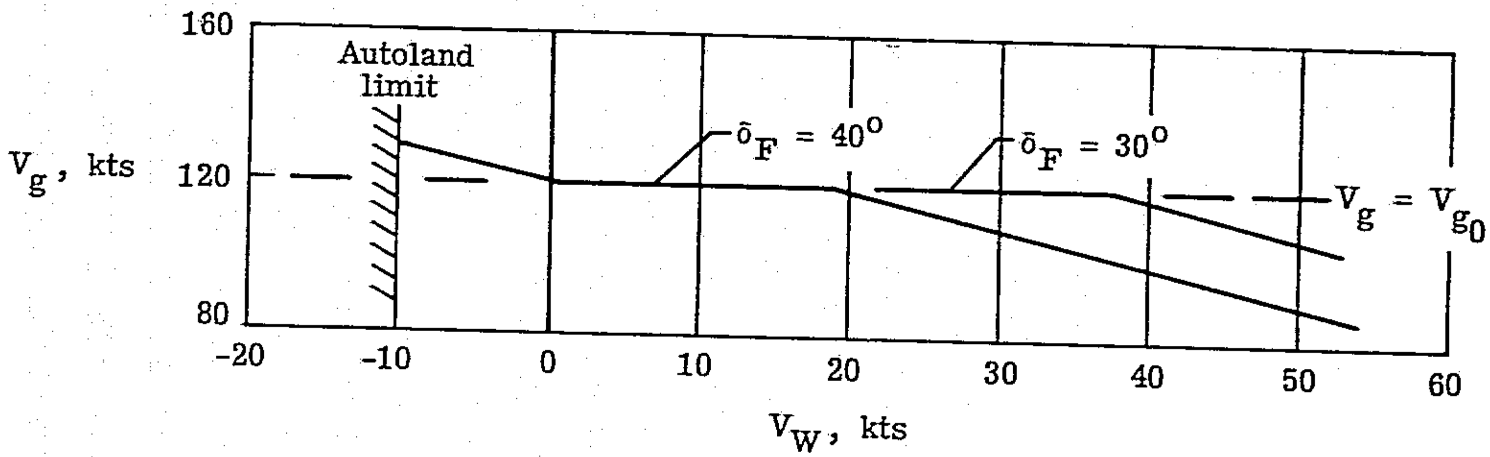

Figure 5.- Variation of ground speed for the constant ground speed technique.

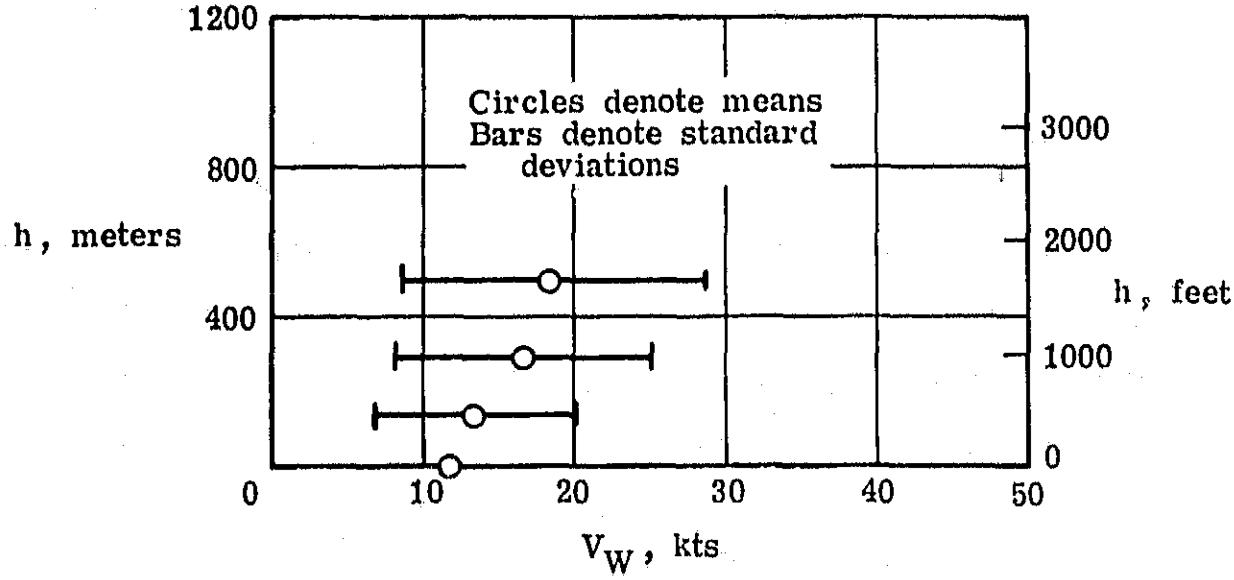

Figure 6.- Wind observations for New York City.

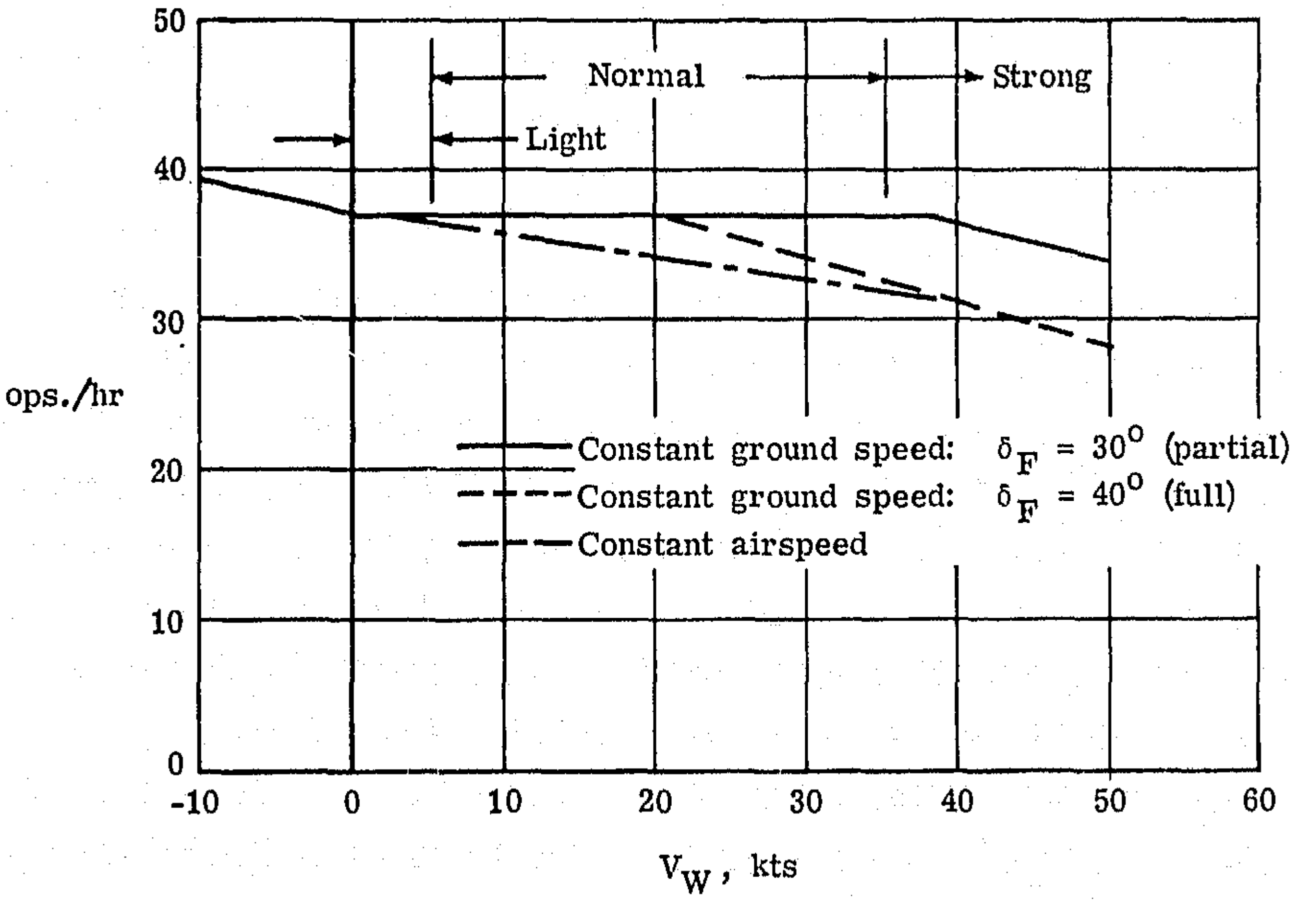

Figure 7.- Landing capacity using current separation intervals and an approach path length of 14.83 km.

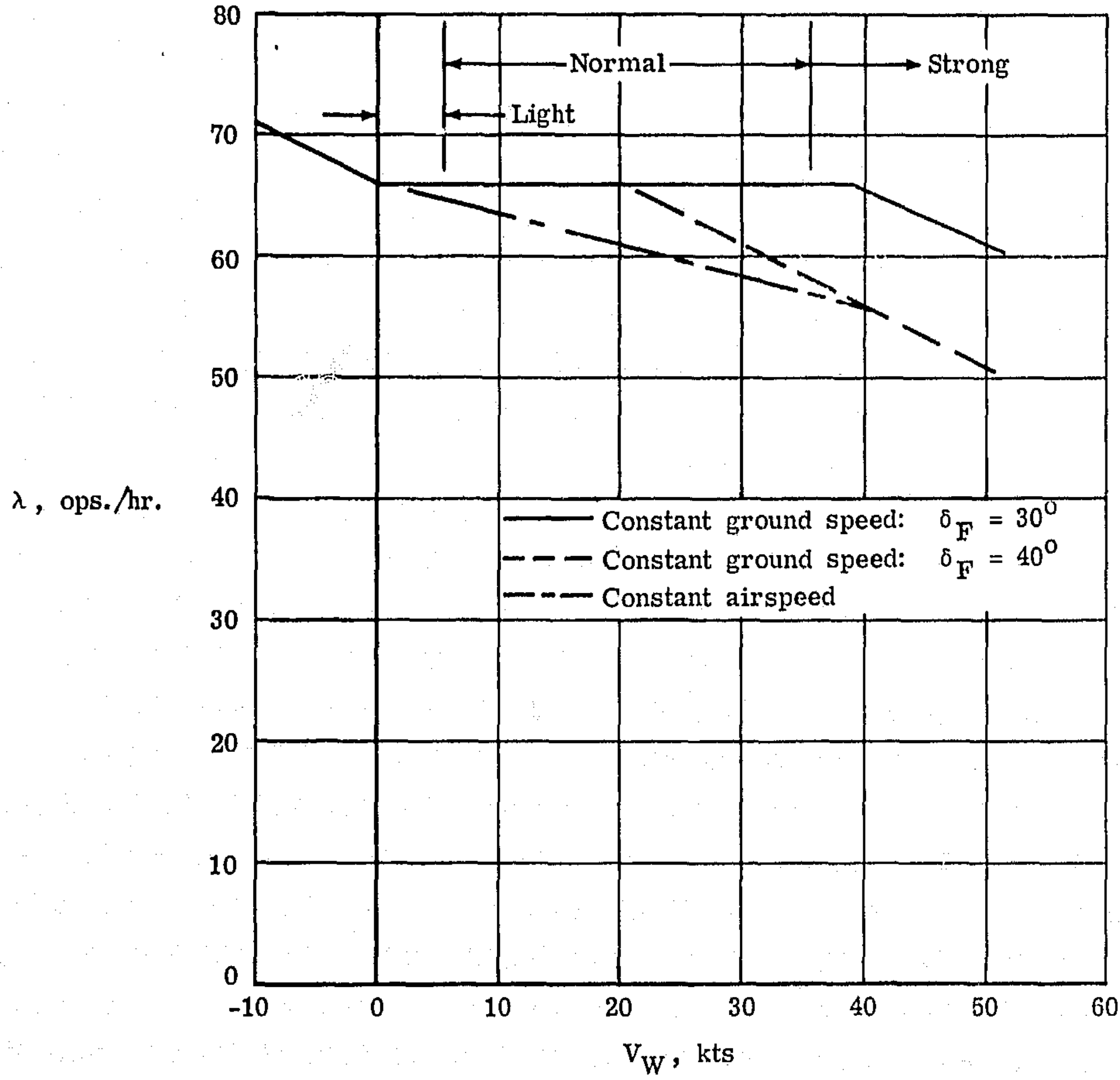

Figure 8.- Landing capacity using reduced separation intervals and an approach path length of 14.83 km.

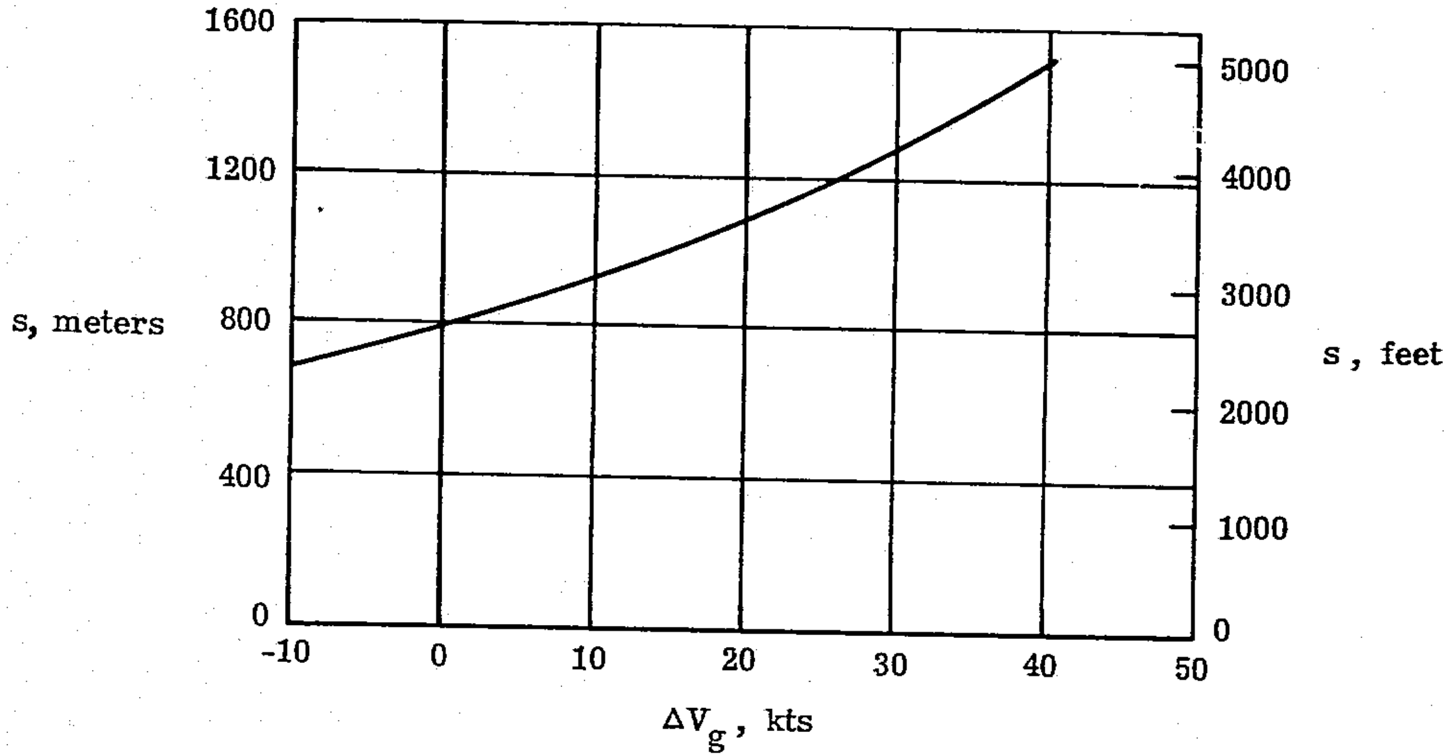

Figure 9.- Effect of touchdown speed on stopping distance.