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DEVELOP ACCELERATION AND BRAKE MONITOR SYSTEM

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16. Abstract

A literature search was conducted to summarize the results of previous work performed in establishing criteria for continuing the development of an instrument system which will aid pilots in making critical decisions during takeoff and landing rolls. The search revealed that many national and international studies had been made during the past 15 years, but interest diminished after 1963.

It appears that much talent and work were applied for creating a monitor but no acceptable units were produced. Additional research and evaluation is considered necessary.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

INTRODUCTION

Purpose.

The purpose of this report is to summarize the results of a literature search of work performed on acceleration and braking monitor systems. This information will be used to establish criteria for continuing the development of an instrument which will aid pilots in making critical decisions during takeoff and landing runs.

Background.

The airline pilot conducting a takeoff or landing roll of an airline transport aircraft needs to be assured that, if an unforeseeable problem occurs at any point along the runway, his aircraft has the ability either to stop safely or to continue.

During a takeoff, there exists a definite point on the runway beyond which the capability to stop in the remaining distance available is doubtful. Until the airplane has reached this point, it can be safely stopped. But once beyond this point, it is committed to takeoff. During the landing roll, the pilot also needs assurance that he can stop within the remaining distance or could abort his landing, apply power, and takeoff safely (Reference 1). The purpose of a monitor is: (1) to provide the pilot with an instrument that would eliminate the present method of "line checks" by assisting the pilot in keeping progress of a takeoff constantly in view, so as to make it easier to decide when a takeoff can safely be continued and when it should be abandoned, and (2) to supply information on the predicted safe stopping point of roll after landing.

Interest has intensified with the increased use of larger aircraft and the publication of reports showing that the aircraft ground run performance can be significantly reduced by water and snow on the runway (Reference 2). Since the potential nuisance value of a takeoff and landing prediction monitor would be high, it would soon fall into disrepute if its use leads to an increase in the number of takeoffs or landings that are abandoned in error. An abrupt wholesale loss in faith may occur when the effectiveness of a new instrument becomes doubtful.

Before the introduction of jet aircraft into airline transport aircraft operations, the opinion was generally expressed that the safety at takeoff of these aircraft would be dependent upon the use of two new instruments; namely, the takeoff monitor and the takeoff director.

Nevertheless, jet aircraft were brought into service prior to these instruments being developed and installed, and now there is a significant amount of experience in operation without their use.

Aspect of the first takeoff instrumentation receiving consideration was the need for a takeoff monitor to indicate to pilots when aircraft performance was unsatisfactory and when a takeoff might be safely abandoned.

The case made for takeoff monitors prior to the introduction into service of jet transports consisted essentially of stating that:

1. The performance of these airplanes would be highly variable and would be very sensitive to such factors as the presence of precipitation on the runway surface; and

2. Their ability to be lifted off early to compensate for prolonging the ground run due to loss of acceleration was negligible.

The above factors would be aggravated by:

a. Pilots' inability to assess when aircraft performance losses were occurring, and

b. The safety margins for large aircraft being smaller by comparison with those available to propeller-driven airplanes due to the relatively longer ground roll of the jet and the greater likelihood that its takeoff weight would be limited by runway length considerations.

Operation of airline jet transports has not shown great variability of basic performance during takeoff nor has it, with the exception of takeoff in slush, shown up any cases of loss of aircraft performance worse than that accepted in airline operation procedures. Moreover, deterioration of pilots' judgment has not occurred as anticipated. This experience and theoretical studies of the variability of takeoff distance indicate that variations in takeoff performance which affect the aircraft, and are detectable, during its ground roll, are small by comparison with those which occur in the later stages of the takeoff. The standard deviation of takeoff distance due to performance variations, which affect the takeoff roll, is approximately 3 percent of the takeoff distance on the same surface while the standard deviation due to later variations (chiefly due to rotation and climbout speed errors) is approximately 5 percent (Reference 3). Thus, the combined standard deviation in takeoff distance variation is 5.83 percent.

If the objective of developing new instrumentation is an aid to reduce the fluctuation of takeoff distances below that currently experienced, then the takeoff monitor does not offer great rewards. Since even if a perfect monitor is used to reject virtually all subaverage takeoffs, the total variability of takeoff distance would only be reduced from 5.85 percent to 5 percent.

Takeoff monitors can, however, make a contribution to controlling fluctuations by showing up variations which may occur from time-to-time and which are outside the range of variation which experience leads one to expect. Thus, for example, a monitor could be of use in slush operations. For this purpose, a comparatively crude and inaccurate instrument would serve the purpose.

Nevertheless, it is probably worthwhile to continue working on an accurate, sophisticated monitor in order to include the all-weather operation where the earlier misgivings concerning pilots' ability to assess performance may be realized. The same type of instrument may be important for stopping maneuvers at landing and in discontinued takeoffs where the achievement of satisfactory aircraft performance is greatly dependent upon the pilots' performance which may deteriorate seriously in a blind situation (Reference 3).

The takeoff performance of an aircraft is influenced by a number of factors varying in importance. When the brakes are released, the engine thrust, which is substantially constant on present jet aircraft, is opposed by rolling friction from the wheels, intake momentum drag from the engines, and aerodynamic drag proportional to the square of the indicated airspeed. In addition, any slope of the runway will help or hinder. The acceleration of the aircraft, therefore, decreases as the takeoff proceeds and in a typical case, for the Boeing 707, drops from about 7 ft/sec^2 by 35 percent at the takeoff speed. Windspeed also plays an important part, not only in modifying the groundspeed acceleration relationship, but also in determining the groundspeed, and hence, the distance at which the takeoff airspeed is reached (Reference 4). The above can be equated as:

Net Force = Thrust - Drag - Rolling Resistance

This relation can be developed as:

$$FN = Fo - \Delta F - C_D S \frac{\rho}{2} V^2 - (W - C_L S \frac{\rho}{2} V^2) \qquad (1)$$

where

FN = net or accelerating force

Fo = static thrust

ΔF - thrust variation due to forward speed

C_D = drag coefficient

S = wing area

ρ = air density

V = airspeed

μ = rolling resistance coefficient (usually between 0.010 and 0.015)

W = airplane weight

C_L = lift coefficient in ground attitude

For jet airplanes, in particular, the variation of thrust during takeoff will be relatively small generally so that little error will result from assuming:

$$\Delta F \approx K_F \frac{\rho}{2} V^2 \qquad (2)$$

The relation can be written:

$$FN = (Fo - \mu W) - (C_D S + K_F - C_L S) \frac{\rho}{2} V^2 \qquad (3)$$

Since modern airplanes are constrained by landing gear configuration to operate at essentially a constant angle of attack during most of the takeoff, the drag, and lift coefficients will be practically constant and the relation becomes:

$$FN = FNo - f_{D_e} \frac{\rho}{2} V^2 \qquad (4)$$

where

FNo = initial or static, net force

f_{D_e} = effective drag area of airplane

(References 5, 6, and 7) FNo and f_{D_e}, which are constants for a given takeoff environment, can be determined from engine and wind-tunnel test data or from takeoff acceleration measurements. There is a linear relationship between accelerating force and dynamic pressure, which could be used as the basis for determining the relations between the quantities describing the airplane's motion during takeoff; acceleration, time, velocity or the related quantity dynamic pressure, and distance.

DISCUSSION

Characteristics of Takeoff Monitors.

Takeoff monitors, in general, rely on the determination of the relationship between two or more of the motion quantities as the basis of operation; that is, from measurement of one of these quantities, the value that another should have if the airplane is performing normally, computed continuously and compared with measurement of this second quantity as the indication of whether or not the takeoff is progressing satisfactorily. It is apparent that by using different combinations of these quantities, say two at a time, a considerable variety of takeoff monitor arrangements is possible.

Several of the possible arrangements of takeoff monitor systems, which have been under development by various agencies are listed in the following table (Reference 5):

TABLE 1. CHARACTERISTICS OF SEVERAL TAKEOFF MONITOR SYSTEMS

TYPE	MEASURES	COMPUTES	AS FUNCTION OF	COMPARES
A	Acceleration Dynamic Pressure Distance	Takeoff Distance	Acceleration Dynamic Pressure Distance	Takeoff Distance
B	Acceleration Dynamic Pressure	Acceleration	Dynamic Pressure	Acceleration
C	Acceleration Distance	Acceleration	Distance	Acceleration
D	Airspeed Distance	Airspeed	Distance	Airspeed
E	Airspeed Time	Airspeed	Time	Airspeed
F	Groundspeed Distance	Groundspeed	Distance	Groundspeed
G	Dynamic Pressure Distance	Distance	Dynamic Pressure	Distance

The first monitor, Type A, could be classed as a predictor type, since it would provide a running prediction of the total takeoff distance based on the performance level of the airplane measured at any instant during the takeoff. This system requires three sensing elements; measuring horizontal acceleration, dynamic pressure, and distance traveled. From these continuously measured quantities and manual input information, the computer elements perform the computation of takeoff distance. This prediction of takeoff distance is then compared in the pilot's display with runway length available or a preflight estimate of takeoff distance required. This system requires manual input of information which takes into account airplane weight, drag, and lift coefficient as well as air density, windspeed, and runway slope. The predictor-type is probably about the closest approach possible to an ideal monitor since it can indicate the effects of performance deficiency immediately in terms of the increase in takeoff distance that may be expected, the quantity of most concern to the pilot. This type of monitor would require a moderately complex computer package. Another possibility is the use of radar as either airborne or ground equipment as a sensing means for use with the prediction system.

The remaining monitor types listed might be classed as comparator types as distinguished from the monitor type. They provide less information but require fewer sensing elements and simpler computer units. The simpler "go-no-go" systems would lack the quantitative aspect and provide less opportunity for exercise of pilot's judgment in making a decision to abort or continue (Reference 5).

SUMMARY OF RESULTS

Operational Evaluations.

Takeoff monitors, also known as takeoff progress indicators or takeoff instrumentation, were under test by the Aeronautical Systems Division at Wright-Patterson Air Force Base, Dayton, Ohio, from about 1959 to 1962. The units tested were supplied by Kollsman Instrument Corporation, Sperry Gyroscope Company, John Oster Manufacturing Company, and Minneapolis-Honeywell Regulator Company. (References 8, 9, and 10). The evaluations indicated that both the acceleration - q *and the speed time monitors measured their respective values with accuracy, but the operational tests indicated that the speed time monitor had no practical value. The acceleration - q monitor consistently met with such a high degree of pilot approval in all tests that there remained little doubt that this type of takeoff monitor, designed by NASA (Reference 5), would be an extremely valuable adjunct to the pilots instrument panel. The percent of pilots favoring each takeoff monitor is shown in the following table:

TABLE 2. PILOTS APPROVAL SURVEY (Reference 10)

Statement	Sperry KC-135	Kollsman KC-135	Oster KC-135	Sperry T-33	Sperry B-47
Type	A	E	E	A	A
The system is easier to use than the line-speed check.	100%	0%	72%	100%	Results
The display is adequate.	95%	50%	87%	63%	Were
The system is preferred to the line-speed check under various wind conditions.	82%	0%	83%	100%	Not Tabulated
An acceleration monitor is preferred over a speed-time monitor.	----	100%	----	----	----

*This system primarily depicts airplane acceleration biased by dynamic pressure "q." It was taken from a theory pioneered by the National Aeronautics and Space Administration and known as "acceleration - q" which fundamentally sums airplane horizontal acceleration with dynamic pressure q.

The type of instrument that was submitted for evaluation by Sperry Gyroscope Company and the John Oster Manufacturing Company used the factors of the characteristic takeoff curve for jet aircraft shown in Figure 1 as their design principal. The aircraft performance is represented by the acceleration of the aircraft from brake release to takeoff speed, relative to a computed acceleration based upon design characteristics and practical external considerations. Since this acceleration decreases as airspeed increases, a bias proportional to calibrated airspeed must be incorporated into any instrument measuring aircraft acceleration, in order that the instrument will present a constant indication throughout the takeoff roll; this is illustrated in Figure 1 (Reference 10). These type of instruments, known as the acceleration - γ monitor, proved to be the most acceptable means yet devised for determining performance during takeoff.

Figure 2 illustrates the characteristic aircraft acceleration and deceleration curves. This illustrates that if an aircraft progresses along the slightly subnormal acceleration line to the computed refusal (Point C) where one engine is lost, the pilot will make an erroneous decision to abort. If he uses a refusal distance (Point D), he will make the correct decision to continue the takeoff (Reference 10).

The development of a takeoff monitor has proceeded very slowly, primarily due to the different tangents taken by some designers in developing a suitable system. There were many attempts to oversimplify the problem, to make the system mechanically foolproof, to give the pilot a precise measurement where none could be obtained, and to build complexity into the use of the system; however, there is no practical substitute for good pilot judgment. A takeoff monitor must aid pilot judgment, not replace it. Throughout this literature search, information after 1963 became scarce and interest on the subject appeared to deteriorate.

Design of Monitors (Reference 12).

The basic equation involved in monitoring a takeoff is that giving the acceleration of the aircraft.

In terms of the groundspeed V, this is the form,

$$a = \frac{dV}{dt} = A - BV - CV^2 \tag{5}$$

where

$$A = \frac{gT}{W} - \mu g - \gamma g - V_W \cdot \frac{M}{W} - \frac{1}{2} \rho \, g \, \frac{S}{W} (C_D - \mu C_L) \, V_W{}^2$$

$$B = 2 \, V_W \cdot \frac{1}{2} \rho \, g \, \frac{S}{W} (C_D - \mu \, C_L) + \frac{M}{W}$$

$$C = \frac{1}{2} \rho g \, \frac{S}{W} (C_D - \mu \, C_L)$$

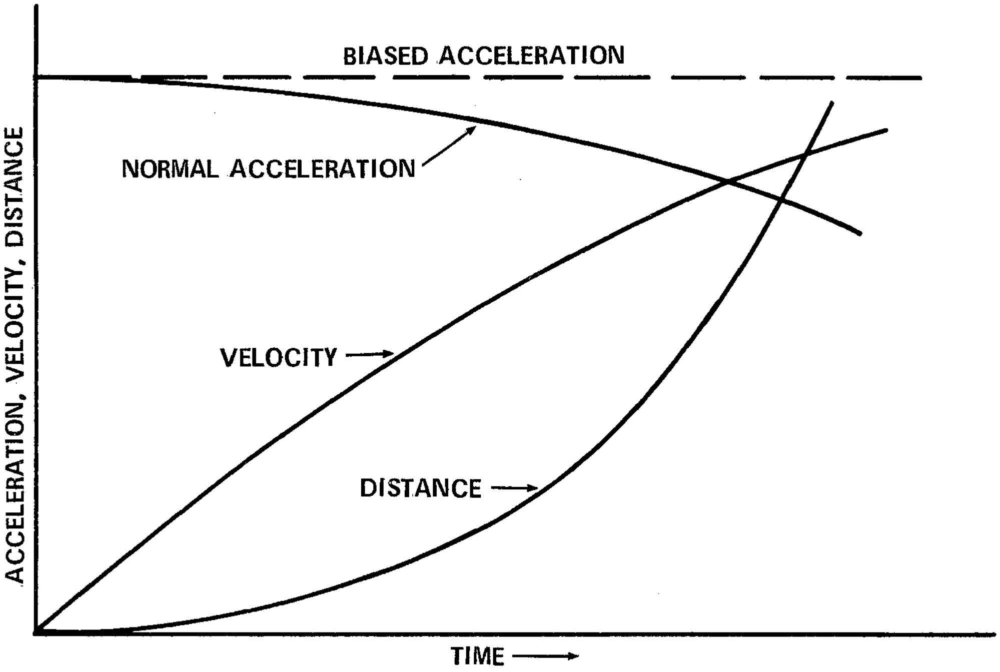


FIGURE 1 CHARACTERISTIC TAKEOFF CURVE FOR JET AIRCRAFT

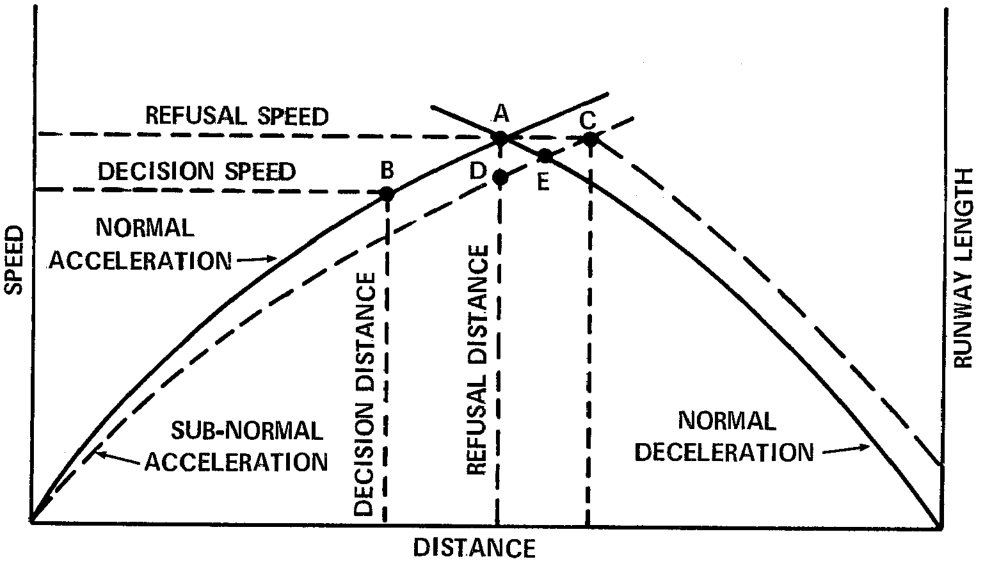


FIGURE 2 CHARACTERISTIC AIRCRAFT ACCELERATION AND DECELERATION CURVES

where C_D = drag coefficient

CL = left coeffieient in ground altitude

M = the total engine mass flow

V_W = windspeed

γ = runway gradient

μ = coefficient of friction

S = wing area

T = total gross engine thrust

V = aircraft groundspeed

W = aircraft weight

ρ = air density

This applies directly to jet aircraft and neglects any variation of gross thrust with forward speed, which appears to be negligible on present jet engines. When it is desired to give the pilot a prediction of the future speed or position of the aircraft, it is necessary either to integrate the acceleration equation or to compute an approximation to the integral. This actual result, obtained from real time computation, can then be compared with those which would have been reached at the same point in time according to the initial assumptions made. The differences can then be used in predicting approximately the conditions at a later point in the takeoff.

For a takeoff monitor to be of maximum use, it must predict the distance which the aircraft will cover from its unstick point until it reaches a height of 35 feet. The monitor can only predict accurately the distance which will be covered by the aircraft if a standard piloting technique is used. It would be the task of a takeoff director to assist the pilot to use this technique through the airborne phase.

In order for the monitor to present to the pilot continuous information about stopping distances, during the ground run, it would be necessary for the computer to compute the integral,

$$\int_{V}^{0} \frac{U\,dU}{-A^{1} - B^{1}\,U - C^{1}\,U^{2}} \tag{6}$$

where

$$U^2 = 1/2\ [V^2 + (VTo - Vw)^2]$$

A^1 , B^1 , and C^1 are expressions generally similar to A, B, and C but obtained by using values of T and M, either zero or for engines idling, and by using a value of μ approximate to braking friction. A digital computer is preferred over an analog computer in order to obtain evaluations more rapidly and more accurately (Reference 12).

Display.

It is considered that any form of display to the pilot must give a continuous presentation. With an on/off display, the pilot has no warning of an approaching problem and no opportunity to exercise his judgment in critical cases where it might be hazardous either to continue or discontinue the takeoff.

The simplest form of continuous display is that of an acceleration monitor. This consists of one dial with a needle showing the difference between the predicted and actual acceleration, the dial being divided into "safe" and "unsafe" sectors. If the needle moves into the unsafe sector, the pilot abandons the takeoff, unless he has already passed the critical speed.

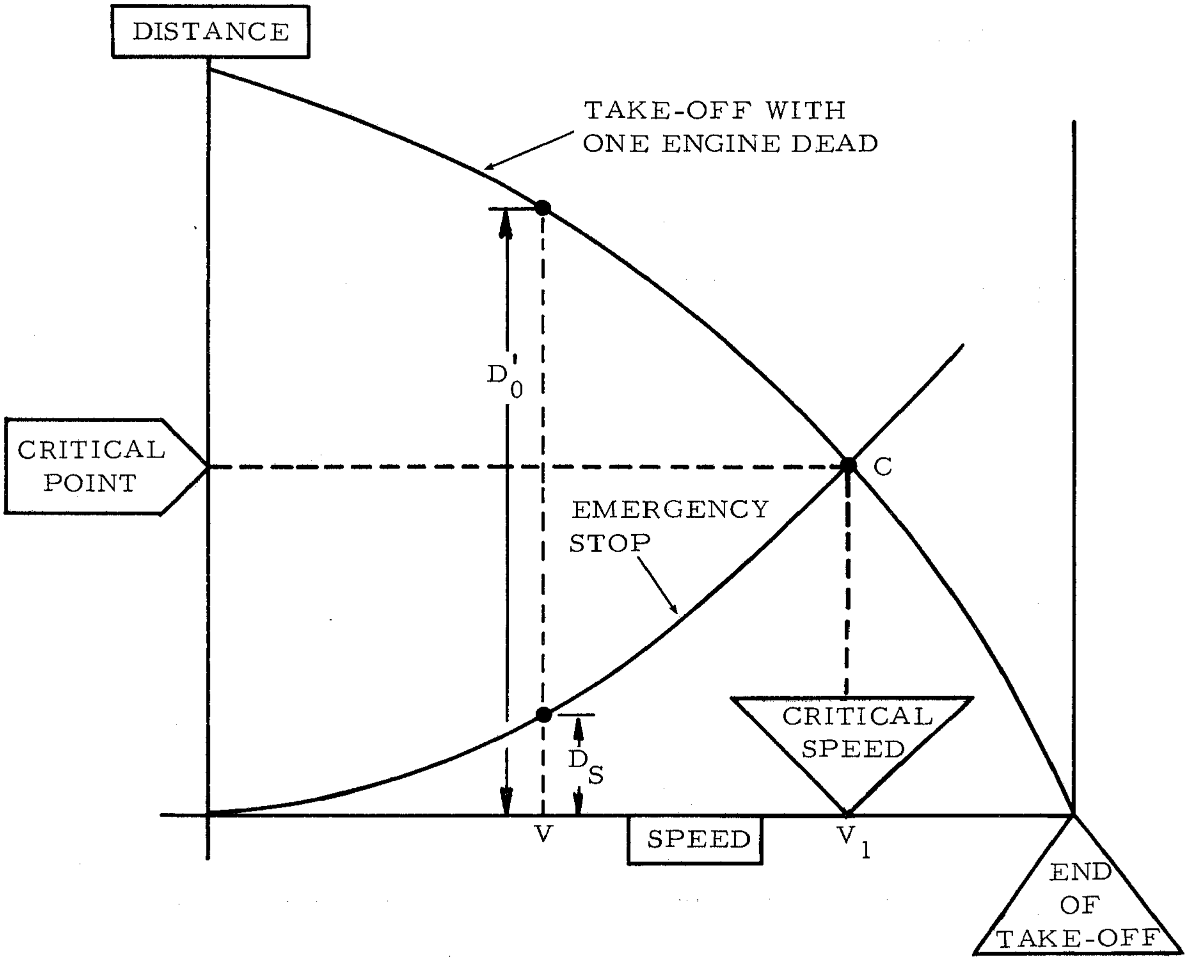
The advantages of this display are its simplicity and its immediate reaction to such abnormalities as an engine failure. Its disadvantage is that it cannot relate a deficiency in an acceleration to the runway length, the distance already covered, and the previous history of the takeoff so as to discriminate properly between safe and unsafe situations. It would cause the abandoning of many takeoffs which could have been safely completed, and might, unless it were sometimes very pessimistic, allow the continuation of some unsafe takeoffs. The quantity in a display must be computed on the basis of measured acceleration in order to permit predicted speed or distance margins to react immediately to sudden changes in performance and will show their true importance. Data for displays can be illustrated by the following curves: Figure 3 defines the critical speed; Figure 4 is a continuation of Figure 3 and illustrates the distance required either to complete a takeoff to a height of 35 feet following an engine failure at V, or to bring the aircraft to rest from a speed V; Figure 5 involves the prediction of the speed which the aircraft should reach at the chosen point, and this is compared with the speed expected, or the most pessimistic speed that would be allowed; and Figure 6 illustrates a display representing three continuous critical conditions during ground run. These are the predicted distance required to reach a height of 35 feet, based on present conditions; the predicted distance to 35 feet on the assumption that an engine fails at the present moment; and the predicted point at which the aircraft will come to rest if the takeoff is abandoned immediately.

These predictions, which are related to the runway, display to the pilot sufficient information to tell him at all times whether or not it is safe to continue or abandon the takeoff.

If this amount of information is too much for a pilot to handle, a simpler display must be accepted in spite of any shortcomings it might have. Only experiment can show what is the best combination of displayed quantities and what is the best technique of presentation.

Accuracy (Reference 12).

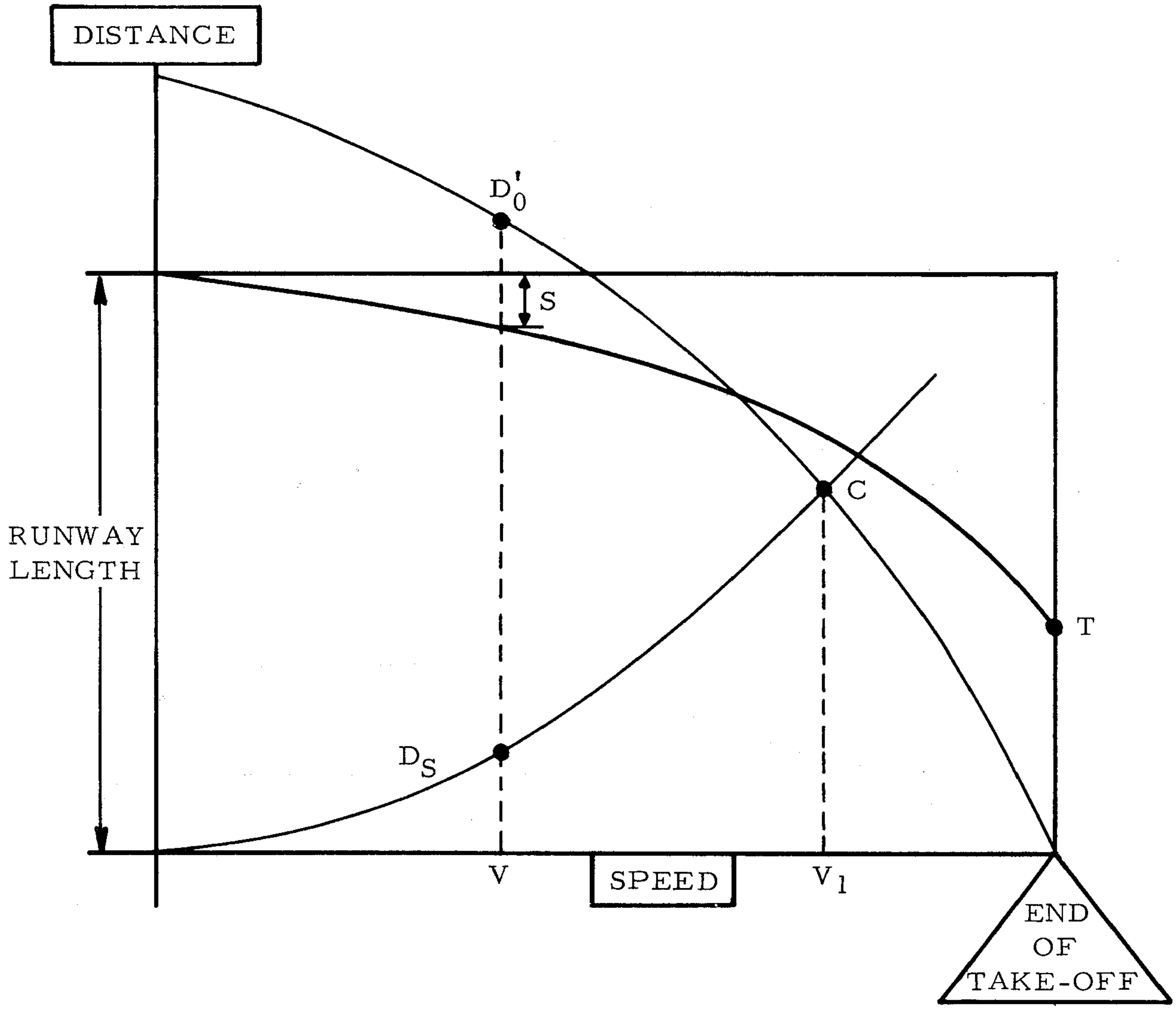
A study was made by the Royal Aircraft Establishment in England of the effects on the calculated takeoff performance of the Boeing 707 of incorrect inputs and errors in the measurement of variables. It was found that the primary sources of inaccuracy during the ground run are errors in the measurement of acceleration, speed, assumed coefficient of friction, and variations in windspeed. Windspeed has to be measured continuously in the aircraft, as the difference between ground and airspeeds, in order to avoid dangerous situations arising from unexpected wind changes. It was found that it is possible to predict takeoff distance within a 2-percent standard deviation which the Air Registration Board of England suggested as being desirable. To make this possible, a digital type of computer must be used and variations in pilot technique must be minimized by the use of a takeoff director. It is not considered possible to predict stopping distance with an accuracy equal to that of takeoff distance.



D_S = PREDICTED DISTANCE REQUIRED TO STOP FROM SPEED V.

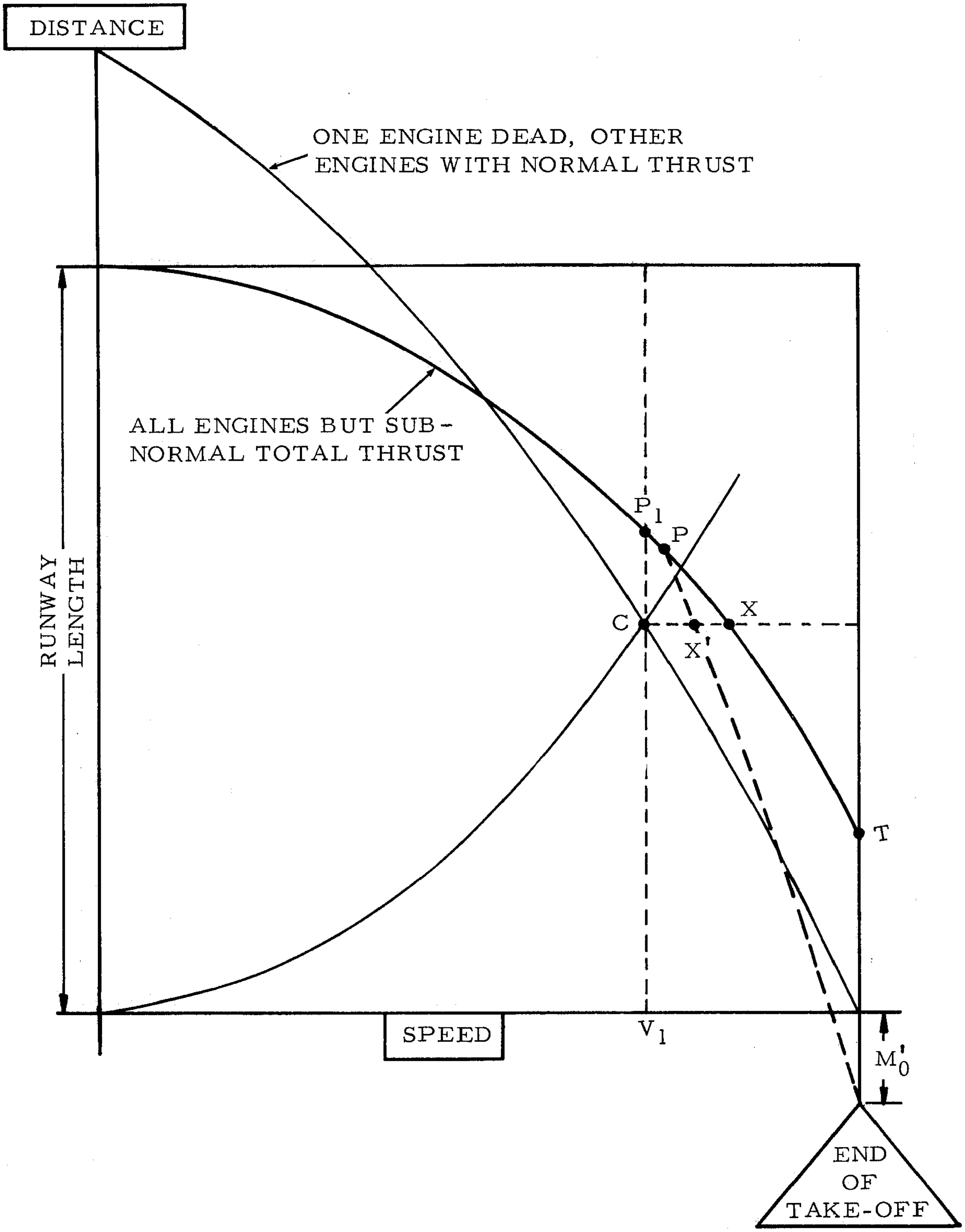
D_0' = PREDICTED DISTANCE REQUIRED TO COMPLETE TAKE-OFF WITH ONE ENGINE DEAD

FIGURE 3 DEFINITION OF CRITICAL SPEED



S = DISTANCE GONE (NORMAL PERFORMANCE)

FIGURE 4 NORMAL TAKEOFF REFERRED TO CRITICAL POINT AND RUNWAY LENGTH



XC AND X'C ARE SPEED MARGINS AT THE CRITICAL POINT.
P_1C = DISTANCE MARGIN AT THE CRITICAL SPEED.

FIGURE 5 DEFINITION OF MARGINS RELATED TO CRITICAL POINT AND CRITICAL SPEED

CONCLUSIONS

Based upon the literature search of accelerating and braking system monitors during takeoff and landing procedures, it is concluded that:

1. Pilots current ability to assess performance takeoff for jet aircraft is much better than originally anticipated since inception of jet aircraft.

2. The predictor type of monitor, requiring a moderately complex digital computer package, is probably the closest approach to the ideal monitor.

3. From the monitors evaluated to date, the acceleration - δ type met with the highest degree of pilot approval.

4. Because there is no practical substitute for good pilot judgment, the monitor must aid pilot judgment rather than replace it.

5. The form of display to the pilot must give a continuous presentation in order to provide the pilot opportunity to exercise his judgment in critical cases. Flight test would be necessary to approach the optimum design.

6. Coefficients of friction, variations of wind velocity imposed on the aircraft, and runway gradients are the most difficult and critical inputs obtainable for a computer to successfully provide a reliable degree of accurate predictions.

7. It is considered impossible to predict stopping distance with an accuracy equal to that of takeoff distance due to probable large variances of coefficient of friction on a rubber-coated wet runway.

8. A comprehensive flight test program would be required to evaluate a new system.

9. The requirements for and design of a takeoff and landing monitor are very controversial subjects. It is a field that the experts have been investigating for the past 15 years, but no item for practical acceptance has been produced. It is agreed generally that it would be a good item to have if it were accurate and reliable, lightweight, inexpensive, simple, did not clutter up the instrument panel nor require additional concentration or thought on the part of the pilot. Because the ratio of aborted takeoffs and overruns to the number of takeoffs made is small, the requirements placed on a monitor are greatly intensified in order to significantly reduce this already minute ratio. There is evidently no quick and inexpensive solution to this problem but rather an involved study is required in the human engineering field for a warning or display system as well as design engineering techniques for actuating such a system. It is possible that with continual advancement of aviation, a system for monitoring takeoff and landing will eventually be produced for all-weather flying.

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