NASA
Technical
Paper
2383

January 1985

NASA-TP-2383 19850008559

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National Aeronautics
and Space Administration

Scientific and Technical
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SUMMARY

Fuel conservation is a significant concern in the commercial-aviation industry. Most airplane operators have adopted fuel-conservative flight procedures that also satisfy the constraints of the air-traffic-control (ATC) system. However, these fuel-efficient flight procedures may impose an additional mental work load on the pilot during the planning and conducting of the flight. A typical descent task, such as crossing a geographical waypoint at an altitude and an airspeed specified by ATC, requires the pilot to plan where to begin the descent to minimize the fuel used. If the descent is begun too early or too late, additional fuel will be used. Pilots use a variety of rules of thumb to plan their descents. Some methods are very simple, and others are more extensive. However, all the rule-of-thumb methods require some computations and therefore result in a higher mental work load for the pilot.

Various forms of guidance and displays have been developed which provide information to enable the pilot to operate his aircraft more efficiently and reduce this mental work load by eliminating the need for rules of thumb. One such form of guidance developed and evaluated in this study allows the pilot to descend on a reference energy-altitude profile from cruise altitude and airspeed to cross a geographical waypoint with a desired energy state (preselected altitude and airspeed). A reference energy-altitude profile was computed based on a fuel-conservative descent at idle-thrust power settings. Guidance was displayed on the attitude director indicator to show the pilot whether the aircraft was below or above the desired energy state on the reference energy-altitude profile. One of the desirable features of this guidance was that a pilot could trade altitude for airspeed (higher airspeed and lower altitude, or vice versa) and still maintain the proper energy profile required to cross the desired waypoint.

This descent guidance was evaluated in a piloted simulation. The test subjects were four airline pilots, who were asked to fly descents from cruise altitude to cross a designated waypoint at a preselected airspeed and altitude. For comparison purposes, the descents were made with and without the use of the guidance. The results of these tests showed that the average fuel consumed during the test cases was reduced for each of the test subjects between 15 lb (2.9 percent) and 41 lb (6.5 percent) with the use of the guidance. Use of the guidance decreased the airspeed error and had no effect on the altitude error when the designated waypoint was crossed. All the pilots reported that their mental work load was reduced by using the guidance, that the guidance was easy to use, and that they would like to have such guidance in an operational environment.

INTRODUCTION

Fuel conservation is a significant concern in the commercial-aviation industry. Most airplane operators have adopted fuel-conservative flight procedures that also satisfy the constraints of the air-traffic-control (ATC) system. However, these fuel-efficient flight procedures may impose an additional mental work load on the pilot during the planning and conducting of the flight. A typical descent task, such as crossing a geographical waypoint at an altitude and an airspeed specified by ATC, requires the pilot to plan where to begin the descent to minimize the fuel used. If the descent is begun too early or too late, additional fuel will be used. Pilots use

a variety of rules of thumb to plan their descents (ref. 1). Some methods are very simple, and others are more extensive. However, all the rule-of-thumb methods require some computations, and therefore result in a higher mental work load for the pilot.

Various forms of guidance and displays have been developed which provide information to enable the pilot to operate his aircraft more efficiently and reduce this mental work load by eliminating the need for rules of thumb. In reference 2, a concept and form of guidance are presented that allow the pilot to descend on an energy-altitude profile from cruise altitude and airspeed to cross a geographical waypoint with a desired energy state (preselected altitude and airspeed). Guidance was presented to the pilot on a profile indicator instrument which had a display format similar to a vertical-speed indicator. Pointers on the display face showed the ground speed of the airplane and the required vertical speed to descend on a constant slope (constant inertial flight-path angle) to the final waypoint. Allowances were also made in the guidance computations so that the aircraft could be slowed to the desired airspeed as the waypoint was crossed. One of the desirable features of this guidance was that a pilot could trade altitude for airspeed (higher airspeed and lower altitude, or vice versa) and still maintain the proper energy profile required to cross the desired waypoint.

This guidance concept was modified by NASA so that a reference energy-altitude profile could be computed that made allowances for wind and would result in a fuel-conservative, idle-thrust descent. Guidance was displayed on the attitude director indicator (ADI) to show the pilot whether the aircraft was above or below the desired energy state on the reference energy-altitude profile. A piloted simulation study was conducted to examine the use and benefits of this form of guidance. This report describes the computations of the reference energy-altitude profile and the guidance used in the simulation study. The results, including fuel usage, waypoint, descent performance, and pilot work load, are also discussed.

SYMBOLS

ADI	attitude director indicator
ATC	air traffic control
crsdev	course deviation, deg
$Dist_{decel}$	distance required to decelerate, ft
$Dist_{desc}$	distance required to descend, ft
$Dist_{hor}$	horizontal distance to reference waypoint, ft
DME	distance-measuring equipment
DME_{ind}	indicated DME, n.mi.
DME_{ref}	indicated DME of the reference waypoint, n.mi.
h	altitude, ft
$\dot{h}$	rate of change of altitude, ft/sec

h_c	cruise altitude, ft
h_{en}	energy altitude, ft
$h_{en,des}$	desired energy altitude, ft
$h_{en,error}$	energy-altitude error, ft
h_{gp}	geopotential altitude, ft
$h_{gp,c}$	geopotential cruise altitude, ft
$h_{gp,ref}$	geopotential reference altitude, ft
h_p	pressure altitude, ft
h_{ref}	altitude to cross reference waypoint, ft
$Time_{decel}$	time required for deceleration, sec
$Time_{desc}$	time required for descent, sec
T_o	standard sea-level temperature, 518.688°R
T'_o	nonstandard sea-level temperature, °R
TSRV	Transport Systems Research Vehicle
$T_{st,c}$	static temperature at cruise altitude, °R
V_{cas}	aircraft calibrated airspeed, knots
$\dot{V}_{cas}$	rate of change of aircraft calibrated airspeed, knots/sec
$V_{cas,ref}$	aircraft calibrated airspeed to cross reference waypoint, knots
V_{gs}	computed ground speed, knots
$V_{gs,c}$	computed ground speed at cruise altitude, knots
$V_{gs,ref}$	computed ground speed at reference altitude, knots
$V_{gs,ref,h}$	computed ground speed based on reference airspeed at current altitude, knots
VOR	very high frequency omnirange navigation radio
$V_{w,c}$	speed of head-wind component at cruise altitude, knots
$V_{w,ref}$	speed of head-wind component at reference altitude, knots
γ_{ref}	reference inertial flight-path angle, rad

DESCRIPTION OF GUIDANCE CONCEPT

The reference energy-altitude guidance concept was designed to provide information which would allow the pilot to descend in a fuel-efficient manner and cross a desired geographical waypoint (called the reference waypoint) at a predesignated altitude and airspeed (called the reference altitude and airspeed). The guidance shows energy-altitude deviations of the aircraft from a reference profile defined by energy altitude as a function of the distance from the reference waypoint. (See fig. 1.) The energy altitude of the aircraft is defined as the current altitude of the aircraft plus an incremented altitude based on the distance required to change from the current airspeed to the reference airspeed. The reference energy-altitude profile is computed with a constant descent angle based on the airspeed and altitude at which the reference waypoint is to be crossed. To obtain the desired fuel efficiency, the reference energy-altitude profile was computed based on speed and altitude changes with the airplane in a clean configuration (landing gear up, flaps at 0°, and speed brakes retracted) and engine thrust at flight idle. The guidance could also be generated using considerations other than fuel conservation for computing the reference energy-altitude profile.

The aircraft may be flown on the vertical path defined by the reference energy-altitude profile if the reference airspeed is maintained during the descent. However, the guidance may also be nulled if the aircraft descends at a higher airspeed but flies at an altitude lower than that defined by the reference profile. In this example, the pilot is trading potential energy for kinetic energy. This feature allows flexibility for individual flying techniques, for increased thrust for pressurization and anti-icing constraints, and for unexpected ATC requests, and still maintains the energy-altitude profile. However, high-speed descents, early descents, or deviations from an idle-thrust power setting and a clean configuration result in additional fuel consumption.

Uncertainties in wind forecasts and the variabilities of the atmosphere may result in differences between the actual and the modeled winds. However, if the pilot keeps the deviations shown by the reference energy-altitude guidance nulled by slightly increasing the power (due to additional head wind) or drag (due to additional tail wind), the airplane will cross the waypoint at the desired airspeed and altitude. However, incorrect wind modeling results in more fuel being used than if the winds were modeled correctly.

During the piloted simulation evaluation, the deviation of the aircraft from the reference profile was presented with the fast/slow airspeed reference on the ADI as shown in figure 2. If the aircraft has the proper energy-altitude, the pointer is positioned at mid scale. Full-scale deviations represent energy-altitude errors of ±3000 ft. Figure 2 is an example of a higher-energy altitude than that defined by the reference profile. This indication meant that the aircraft had too much altitude and/or airspeed to continue at idle-thrust power in a clean configuration and cross the waypoint at the proper speed and altitude. The pilot would have to decrease total energy by increasing drag (i.e., using speed brakes, etc.) or decreasing thrust (if not already at flight idle power) to arrive at the desired waypoint at the desired airspeed and altitude.

REFERENCE ENERGY-ALTITUDE GUIDANCE COMPUTATIONS

The reference energy-altitude guidance computations were initialized with the computation of a reference energy-altitude profile. The energy-altitude profile may

be visualized as a straight line that passes through the reference altitude at the desired geographical waypoint from the cruise altitude. (See fig. 3.) The slope of this line is equal to the average descent angle at which the aircraft would glide if it were in a clean configuration at idle-thrust power and at a calibrated airspeed equal to the reference airspeed. The slope was determined by computing the inverse tangent of the difference between the cruise and the reference altitudes divided by the horizontal distance traveled during the descent. The horizontal distance traveled was computed by multiplying the average ground speed of the aircraft (accounting for wind and the effects of altitude on true airspeed) by the amount of time required to complete the descent. The time required to complete the descent was determined by dividing the difference between the cruise and the reference altitude by the average vertical speed of the aircraft. Figure 3 shows an example of the actual flight path and the reference energy-altitude profile with associated variables. In this example, the energy altitude of the aircraft and the desired energy altitude based on the reference profile are the same.

Approximate geopotential altitudes were determined for the slope computations to account for nonstandard temperatures. The pressure altitudes h_p used to define the cruise altitude and the reference altitude were changed to approximate geopotential altitudes by multiplying the pressure altitude by a temperature ratio of nonstandard and standard sea-level temperatures as follows:

$$h_{gp} = h_p(T'_o/T_o) \qquad [\text{ft}]$$

The standard sea-level temperature T_o is 518.688°R; the nonstandard sea-level temperature T'_o can be computed from the following temperature model for $h = 0$.

$$T'_o = T_{st,c} - (3.566 \times 10^{-3})(h - h_c) \qquad [°\text{R}]$$

where $T_{st,c}$ is the static air temperature measured at the cruise altitude. For the purposes of this simulation, a standard atmospheric temperature model was assumed, which resulted in a temperature ratio of one.

The next step in the reference energy-altitude profile computations was to compute the average vertical speed $\dot{h}$ that would be obtained during a constant-airspeed descent. The altitude rate was obtained by substituting the reference airspeed $V_{cas,ref}$ into the vertical-speed model derived in appendix A and shown here as follows:

$$\dot{h} = -0.00092V_{cas,ref}^2 + 0.349V_{cas,ref} - 53.32 \qquad [\text{ft/sec}]$$

The time required to descend $Time_{desc}$ from cruise altitude $h_{gp,c}$ to the reference waypoint altitude $h_{gp,ref}$ was then computed as follows:

$$Time_{desc} = \frac{h_{gp,ref} - h_{gp,c}}{\dot{h}} \qquad [sec]$$

In the next step, ground speeds were computed which would result if the airplane flew at a calibrated airspeed equal to the reference airspeed $V_{cas,ref}$ at the cruise altitude h_c and at the reference altitude h_{ref}. Ground speed was obtained by first computing approximate true airspeed as a function of the reference airspeed and altitude. The head-wind component, computed from the wind model, was then added to the true airspeed to obtain the ground speed as follows:

$$V_{gs,c} = \frac{V_{cas,ref}}{1 - \left(0.12 \times 10^{-4}\right)h_c} + V_{w,c} \qquad [knots]$$

$$V_{gs,ref} = \frac{V_{cas,ref}}{1 - \left(0.12 \times 10^{-4}\right)h_{ref}} + V_{w,ref} \qquad [knots]$$

The distance required to descend $Dist_{desc}$ was computed by multiplying the time required to descend by the average ground speed as follows:

$$Dist_{desc} = Time_{desc}\left(\frac{V_{gs,c} + V_{gs,ref}}{2}\right)1.69 \qquad [ft]$$

The reference inertial flight-path angle corresponding to an idle-thrust, constant-airspeed descent at $V_{cas,ref}$ was then generated using the following equation:

$$\gamma_{ref} = \tan^{-1} \frac{h_{gp,c} - h_{gp,ref}}{Dist_{desc}} \qquad [rad]$$

Computation of γ_{ref} completed the generation of the reference energy-altitude profile.

After the reference energy profile is calculated, the energy altitude of the aircraft is computed and compared with the reference energy-altitude profile. Deviations from this profile are displayed to the flight crew. The energy altitude of the aircraft is computed by determining the distance required to change from the present airspeed of the aircraft to the reference airspeed. This determination is accomplished by computing the time required to change airspeed by dividing the magnitude of the airspeed change by the average acceleration modeled for the

aircraft. The distance required is then found by multiplying the time required to change airspeed by the average ground speed of the aircraft. The corresponding energy-altitude increment is then found by multiplying the distance required to change the airspeed by the tangent of the reference flight-path angle. The actual altitude of the aircraft is then added to determine the energy altitude of the airplane. Figure 1 illustrates an example of the aircraft with a lower energy altitude than the reference energy-altitude profile. In this example the pilot would be shown a "low" indication on the reference energy-altitude profile deviation meter.

The desired energy altitude is found by multiplying the measured distance of the airplane from the waypoint by the tangent of the reference flight-path angle. The desired energy altitude is subtracted from the actual energy altitude. This difference is called the energy-altitude error and is displayed to the pilot on the reference profile deviation indicator (the fast/slow meter) on the ADI. The following paragraphs show the details of these computations.

The distance required to change from the present airspeed to the reference airspeed was determined by computing the time required to accomplish the speed change with the following equations:

$$\mathrm{Time}_{decel} = \frac{V_{cas,ref} - V_{cas}}{\dot{V}_{cas}} \qquad [\mathrm{sec}]$$

Acceleration $\dot{V}_{cas}$ was computed with the following empirically derived model described in appendix A and shown here as follows:

$$\dot{V}_{cas} = \begin{cases} 9.3 \times 10^{-6} h - 1.267 V_{cas} > 300 \\ 8.0 \times 10^{-6} h - 0.91 V_{cas} \leqslant 300 \end{cases} \qquad [\mathrm{knot/sec}]$$

Although $\dot{V}_{cas}$ was modeled only for airspeed reductions, the same model was used for speed increases, and did not appear to present any operational problems. The distance required to change speed was computed by multiplying the average ground speed on this segment by the time Time_{decel} as follows:

$$\mathrm{Dist}_{decel} = \frac{V_{gs,ref,h} + V_{gs}}{2}\left(\mathrm{Time}_{decel}\right)1.69 \qquad [\mathrm{ft}]$$

The horizontal distance required to descend from the present geopotential altitude to the geopotential reference altitude along the reference energy-altitude profile was calculated by dividing the altitude difference by the tangent of the reference flight-path angle γ_{ref} as follows:

$$\mathrm{Dist}_{desc} = \frac{h_{gp} - h_{gp,ref}}{\tan \gamma_{ref}} \qquad [\mathrm{ft}]$$

The current aircraft energy altitude was then computed by combining the geopotential reference altitude with the sum of the distance to decelerate and the distance to descend multiplied by the tangent of the reference flight-path angle as follows:

$$h_{en} = h_{gp,ref} + (Dist_{decel} + Dist_{desc}) \tan \gamma_{ref} \qquad [ft]$$

After the actual energy altitude was calculated, the desired energy altitude was computed by adding the geopotential reference altitude to the product of the horizontal distance to the reference waypoint $Dist_{hor}$ and the tangent of the reference flight-path angle as follows:

$$h_{en,des} = h_{gp,ref} + (Dist_{hor}) \tan \gamma_{ref} \qquad [ft]$$

The horizontal distance to the reference waypoint was computed from distance-measuring equipment (DME) indications that were corrected for the difference in altitude between the aircraft and indicated DME of the reference waypoint and corrected for lateral deviation from the desired course as follows:

$$Dist_{hor} = \left[\left| DME_{ind} - DME_{ref} \right|^2 - (h_{gp} - h_{gp,ref})^2 \right]^{1/2} \cos (crsdev) \qquad [ft]$$

The deviation from the reference profile was then computed by taking the difference between the actual energy altitude and the desired energy altitude as follows:

$$h_{en,error} = h_{en} - h_{en,des} \qquad [ft]$$

This quantity was continuously computed and displayed to the pilot on the reference energy-altitude deviation meter on the ADI.

SIMULATOR DESCRIPTION

The reference energy-altitude guidance was evaluated in the Langley Visual/Motion Simulator (VMS). The VMS is a six-degree-of-freedom, motion-base simulator capable of presenting realistic acceleration and attitude cues to the pilot. A general purpose, scientific mainframe computer with a nonlinear, high-fidelity digital representation of the NASA TSRV B-737 airplane provided inputs to drive the VMS motion-base system. Audio cues for engine thrust and aerodynamic buffet were also provided. The simulator had a generic cockpit with conventional flight controls and instrumentation. Flight controls included a column and control wheel, rudder pedals, throttle, speed brake, and flap controls located on a center console. Flight instrumentation included conventional flight and navigation instruments and engine instrumentation. The VMS facility is described in more detail in reference 3.

An attitude control-wheel-steering mode (rate command, attitude hold) was used during the simulation evaluation. With this control mode the pilot made pitch changes by pushing and pulling the column from the detent (neutral) position, thus commanding a pitch rate proportional to the column displacement, until the desired pitch attitude was achieved. When the column was returned to the detent position, the current pitch attitude was held by the flight control system. Roll attitude changes were made in the same manner with the wheel.

TEST DESIGN

The simulation test was designed for evaluating the use of the reference energy-altitude guidance to conserve fuel and to reduce the mental work load of the pilot in planning the descent. No attempt was made to design and evaluate an interface for the flight crew to make inputs to the descent guidance algorithm, such as the reference altitude and airspeed and the reference waypoint location.

Test Conditions

Four test cases were defined for use in evaluating the benefits of using the reference energy-altitude guidance. The test conditions for each case, including the reference airspeed, the reference altitude, and the atmospheric conditions, are summarized in table I. The initial conditions for cases 1, 2, and 3 were the same; the aircraft was located 90 n.mi. from the reference waypoint and was configured for cruise flight at an altitude of 28 000 ft, a heading of 90°, and an airspeed of 300 knots. The pilot was instructed to cross the reference waypoint at an altitude of 15 000 ft and at an airspeed of 250 knots. Wind conditions were varied for each case. Test case 1 had no wind. Test case 2 had a wind model with a constant direction from 270°. The magnitude of the wind speed decreased linearly as a function of altitude. (See fig. 4.) This wind model resulted in a tail-wind component on the aircraft. In test case 2, the pilot was given wind information in the form of a standard winds-aloft weather forecast (i.e., altitude, direction, speed) that conformed to the wind model.

In test case 3, the pilot was given the same winds-aloft forecast as in case 2. However, the actual wind used was biased 20 knots less. (See fig. 4.) This test case was included to assess the use of the guidance in the realistic situation, where the actual winds and the forecast winds were not the same.

In test case 4, the pilot had a route approximately 114 n.mi. long which simulated a typical descent to an airport. Various ATC instructions were issued, and navigation tasks such as tuning the VOR stations and selecting the proper radials were included to simulate a normal work load. The purpose of this case was to determine the benefits of using the reference energy-altitude guidance to cross an intermediate waypoint on which an altitude constraint had been placed by ATC. The initial conditions for this case included the aircraft in level flight at 24 000 ft, at a heading of 90°, and with an airspeed of 310 knots. Test case 4 used a linear wind model as depicted in figure 4. The wind direction was constant from 250°, which resulted in a right quartering tail-wind component on the aircraft. The winds-aloft weather forecast conformed to the wind model.

Standard atmospheric temperature and pressure conditions were used in all test cases. Light turbulence was present in each case to provide a more realistic mental and physical work-load environment.

Test Subjects

Four commercial airline pilots were used as test subjects in the evaluation of the reference energy-altitude guidance. Three of the four pilots were management-level pilots that were current in transport aircraft. None of the three management-level pilots were current in the B-737 airplane, although all had flown the B-737 in the past. The fourth test subject was a line pilot who was actively flying the B-737 airplane at the time the simulation tests were performed.

Test Procedures

The pilots were told that their task in each test case was to cross a specified waypoint at a designated altitude and airspeed while complying with all pertinent ATC regulations. Each pilot was briefed that the reference energy-altitude profile was computed based on speed changes made in level flight and descents at constant airspeed. They were also told that, although the guidance was based on aircraft performance for idle thrust and a clean configuration, they should use thrust or drag devices (e.g., speed brakes) as necessary to cross the reference waypoint at the proper airspeed and altitude.

The pilots flew four or five practice descents, with and without the guidance, to become familiar with the simulator and the guidance characteristics. After this familiarization, the pilots flew four test cases without the reference energy-altitude guidance to obtain baseline data for unaided descents. The test cases were then repeated with the guidance provided. As shown in table II the order in which each pilot flew the sequence of test cases differed. The practice descents and differing sequences of test cases were done to ensure that no learning effects in the data would impact the overall analysis.

In test cases 1 and 2, flown without the guidance, the pilots were instructed to use whatever descent procedures they typically used during routine airline flights. Two of the four pilots flew constant-airspeed descents at 280 knots, and two flew constant airspeed descents at 250 knots. The guidance was calculated with the assumption that a constant-airspeed descent of 250 knots would be used, because 250 knots was the desired airspeed at the reference waypoint. When the guidance was provided, the pilots were instructed to use the same airspeeds they used on the descents without the guidance. The two pilots whose descent speeds differed from the reference airspeed of 250 knots also repeated test cases 1 and 2 with guidance using a descent speed of 250 knots. When all runs in test cases 1 and 2 were completed, each pilot had flown descents using the same descent airspeed, with and without guidance, and all pilots had flown descents with guidance using a 250-knot descent speed.

In test case 3, the pilots were instructed to use a descent airspeed of 250 knots both with and without guidance. In test case 4, they were instructed to use a descent airspeed of 300 knots.

After each test run, the pilot completed the questionnaire shown in appendix B. The purpose of the questionnaire was to obtain the pilots' subjective comments and ratings of levels of work load. All comments made by the pilots during the test runs were also recorded.

RESULTS AND DISCUSSION

Profile Comparison

The guidance was designed to aid the pilot by providing information about the state of the aircraft relative to the fuel-conservative reference profile. In operational practice a fuel-efficient descent typically involves descending at idle thrust in a clean configuration and crossing the desired waypoint just as the desired altitude and/or airspeed is obtained. Planning the descent requires the pilot to calculate the point at which to begin to descend. Descending early would require the use of extra thrust to maintain the desired altitude and airspeed until the waypoint was crossed. Descending late results in the throttle remaining at cruise power longer, requires the use of higher descent rates to achieve the desired altitude, and requires the use of drag devices to slow to the desired airspeed. Descending early or late both have fuel penalties associated with them. The guidance was intended to show the pilot when to descend for a fuel-efficient descent and to give him continuous feedback on how closely he was following the reference energy-altitude profile. Thus, the pilot would be relieved of the mental work load of planning the descent.

To illustrate the typical differences resulting in the descents flown with and without guidance, a comparison of the altitude, calibrated airspeed, and reference energy-altitude error profiles flown by one pilot during test case 2 is shown in figure 5. The altitude profiles show that the pilot began the descent too late (closer to the reference waypoint) when guidance was not used. When the test subject realized his altitude was too high, he increased the descent rate by reducing the pitch angle. This adjustment resulted in an increased airspeed being maintained during the descent. The test subject used speed brakes near the end of the descent to reduce the airspeed to the desired reference airspeed. The higher airspeed (increased drag) and the use of speed brakes resulted in the use of more fuel during the descent without the guidance. The difference in fuel usage between the two profiles shown was 32 lb, or a 5.6-percent improvement, when guidance was provided. The energy-altitude error is shown for the descents flown with and without the guidance. Since the test subject was not aware of the error when no guidance was provided, he did not correct it until he realized that his altitude was high. In contrast, when guidance was provided, the error was nulled much earlier and remained nulled for the rest of the descent. The comparison shown in figure 5 is representative of the differences in the profiles flown with and without guidance.

Fuel Usage

Fuel usage was examined for each of the test cases to determine the effect of the guidance on fuel efficiency. The effect on fuel usage, with and without the use of the reference energy-altitude guidance, is plotted in figure 6. Circles were used in the plot where similar airspeeds were used in the descents. Triangles denote the data obtained when a 250-knot airspeed was flown with guidance and when a 280-knot airspeed was flown without guidance. (Additional fuel savings result from a reduction in airspeed, regardless of the use of the guidance.) It can readily be seen that fuel efficiency improved when the guidance was used.

The average fuel savings from the use of the guidance was computed for each test case (including all the pilots) and for each pilot (including all test cases). Only test runs with the same descent speed, with and without guidance, were used in these computations. The average savings obtained on each case ranged from a 2-lb improvement in test case 2 to a 47.5-lb improvement in test case 3. Each pilot averaged

less fuel used with the guidance between a range of 14 lb (2.9 percent) and 41 lb (6.5 percent) for the four test cases.

A t-test for a hypothesis with one mean, as described in reference 4, was performed on the difference in fuel usage between test runs, made with and without guidance, that used the same descent speed. The t-test was done on the difference because each test case was run with different conditions, such as winds and length of descent, and therefore had different fuel usages. As shown in table III, there was an average of 25 lb less fuel used when guidance was provided to the pilot. A t-value of 3.18 indicates a statistically significant improvement in fuel usage at the 99.5-percent confidence level.

Arrival Accuracy

The airspeed and altitude errors (deviation from reference values) resulting when the aircraft crossed the reference waypoint were examined to determine the effect of the guidance on arrival accuracy. These errors are presented graphically in figure 7. One-tailed t-tests on the hypothesis with two means as described in reference 4 were applied to determine if any statistically significant differences resulted in the altitude and airspeed errors when the guidance was used compared with when it was not used.

The difference in altitude error for test cases 1, 2, 3, and 4 when the reference energy-altitude guidance was used was not significant at the 95-percent confidence level, as determined by the t-test. (See table IV.) Most of the altitude errors in test cases 1, 2, and 3 were less than 100 ft. The maximum altitude error obtained in these cases was 184 ft high (case 3 with guidance). The magnitudes of the altitude errors were slightly larger in test case 4 than those obtained in test cases 1, 2, and 3 (fig. 7). The maximum altitude error in test case 4 was 406 ft. The subject pilots indicated that these errors were acceptable since it was an intermediate waypoint and they could reduce the error subsequently in the descent to the final waypoint.

In figure 7 it can be seen that the airspeed error at the reference waypoint was typically lower when guidance was used. The maximum error was 16 knots with the guidance and 44 knots without the guidance.

The one-tailed t-test was applied to the airspeed errors obtained in all test runs to determine if there was a reduction in airspeed error when guidance was provided. As shown in table V, the test resulted in a t-value of 2.30. This result indicates, with a confidence level of 97.5 percent, that the airspeed error decreased when guidance was provided.

Considering all test cases, use of the guidance did improve the accuracy of arrival on airspeed, but did not improve the accuracy of arrival on altitude. Pilot comments indicated that without guidance they had no difficulty arriving at a point at a particular airspeed and altitude by simply descending early. They considered the errors made without guidance to be acceptable, although use of the guidance did improve the arrival accuracy.

Physical Work Load

Control activity was recorded to provide an indication of the physical work load. The controls used for the task of nulling the reference energy-altitude errors were a column, throttles, and speed brake. The speed brake was rarely used, and throttles were typically changed once or twice during each descent. The column was used to control the descent rate and/or airspeed. The amount of time the pilot was moving or holding the column out of its detent position was measured for comparison purposes. Table VI shows the result of the t-test performed on the percentage of time the column was out of detent. The t-test shows that column activity increased significantly, with a 97.5-percent level of confidence, when guidance was used. Even though the column activity increased, pilots commented that the physical work load was very low and was quite acceptable when guidance was provided.

Mental Work Load

The guidance was designed to reduce the pilot's mental work load by relieving him of the task of planning a fuel-efficient descent. A questionnaire was used to subjectively quantify the effects that the guidance had on mental work load. (See appendix B.) After each run, the pilot completed the questionnaire.

Based on pilot comments and the results of the questionnaire, the mental work load was reduced significantly. The more complicated the descent was to plan, the more the mental work load was reduced. The guidance relieved the pilot of the mental effort necessary to plan a fuel-efficient descent.

Questionnaire Results

Figure 8 is a summary of the responses to questions 1, 2, 3, and 5 through 8 in the questionnaire completed by the pilots, with related questions grouped together. The pilots were asked in question 1 to rate the difficulty of the task of arriving at the reference waypoint at the reference altitude and airspeed. The task was rated to be easier in the runs made with guidance. Several pilots commented that the task of arriving at the waypoint at the reference altitude and airspeed was simple, but that doing it in a fuel-efficient manner required more effort. The pilots were asked in question 5 what effect the guidance had on their ability to arrive at the reference waypoint on altitude and airspeed relative to no guidance. Most pilots responded that their performance improved, although on several runs they indicated that the guidance had no effect at all.

In question 2, the pilots were asked to rate the level of physical work load to fly the descent. As shown in figure 8, the pilots rated the level of physical work load somewhat lower in the test cases where guidance was provided. When asked, in question 6, what effect the guidance had on physical work load, most responses also indicated that the guidance reduced physical work load.

In question 3, the pilots were asked to rate their level of mental work load. The responses to this question showed that the mental work load was lower when the guidance was provided. In question 7, they were asked to rate the effect of the guidance on mental work load. All pilots responded that the mental work load was reduced; work load was reduced moderately to a great deal. The pilots stated that the reduction in work load was significant, since the guidance relieved them of the mental effort required to plan a fuel-efficient descent.

In question 4, the pilots were asked what methods they used to plan a fuel-efficient descent when they had no guidance. All pilots reported that they mentally calculated the distance from the reference waypoint at which to begin an idle-thrust descent, such that when they reached the target altitude they would be crossing the waypoint. They computed this distance by using a ratio of the number of miles over the ground covered for each 1000 ft of descent. The ratio used by two of the pilots was 3 miles per 1000 ft of altitude to lose; the other two pilots used 4 miles per 1000 ft of altitude to lose. The pilots used the practice runs to estimate the specific ratios and added to that calculation the effects of the predicted winds. They also estimated the distance required to slow to the reference airspeed. Three of the pilots continuously recomputed the descent distance throughout the descent to determine if their altitude was too high or too low. The fourth pilot computed the distance once and modified it in subsequent descents based on previous descents; he called it the "that looks about right" method.

In question 8, the pilots were asked to rate the ease of use of the information as presented. All pilots rated the guidance very easy or trivial to use. Their comments indicated that they found the guidance to be very useful and that they would like to have such guidance in the operational environment.

CONCLUSIONS

Analysis of the results from the simulator evaluation of the reference energy-altitude guidance concept led to the following conclusions:

1. Fuel usage was reduced when the reference energy-altitude guidance was used.

2. Mental work load was reduced by use of the guidance. When the guidance was provided, the pilot was relieved of the mental effort required to plan a fuel-efficient descent.

3. Pilots found the reference energy altitude guidance very easy to use with the display format presented on the ADI, and would like to see it used in an operational environment.

4. Use of the guidance decreased the airspeed error when the reference waypoint was crossed but did not affect the altitude error.

5. An increase in column activity was found when guidance was provided. However, the level of work load was considered to be low by the pilots and was well within acceptable limits.

Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
October 1, 1984

APPENDIX A

AIRPLANE PERFORMANCE MODELING

Empirical models of vertical speed and acceleration rate were developed for the NASA TSRV B-737 twin-engine commercial transport airplane. The models were developed from data obtained from a piloted simulation under the same conditions used in the simulator evaluation of the guidance. The airplane had an initial gross weight of 85 000 lb, was flown in a clean configuration, and was operated in condition of a standard atmospheric temperature and pressure.

The vertical-speed model was derived from data recorded during a piloted simulation of the airplane performing idle-thrust, constant-airspeed descents. Descents were made at constant airspeeds between 210 knots and 350 knots. The average vertical speed of the airplane for each descent was computed by dividing the total altitude lost during the descent by the time required to complete the run. The initial altitudes for each run ranged 35 000 ft (for 210 knots) to 23 000 ft (for 350 knots). The final altitude for all runs was sea level. The average descent speed was plotted as a function of the calibrated airspeed V_{cas} maintained during the descent. A quadratic-regression analysis of the data resulted in the equation shown below. (See fig. 9.)

$$\dot{h} = -0.00092V_{cas}^2 + 0.349V_{cas} - 53.32 \qquad \text{[ft/sec]}$$

The acceleration model was derived from data recorded during a piloted simulation of the airplane performing idle-thrust, constant-altitude airspeed reductions. Data were recorded for the level-flight speed reductions at altitude multiples of 5000 ft between sea-level and 35 000 ft. The initial speed of the airplane was the maximum allowed (limited by either Mach number or airspeed); the final airspeed for each run was 210 knots. The average rate of airspeed change was computed by dividing the total change in airspeed by the time to complete the run. The resulting average deceleration is plotted as a function of altitude in figure 10. The average deceleration rates derived from the simulation data could be described with two linear curves as shown in figure 10. For V_{cas} greater than 300 knots, the deceleration rate could be approximated with the following equation

$$\dot{V}_{cas} = 9.3 \times 10^{-6}h - 1.267 \qquad \text{[knots/sec]}$$

When V_{cas} is less than or equal to 300 knots, the following equation approximated the simulation data:

$$\dot{V}_{cas} = 8.0 \times 10^{-6}h - 0.91 \qquad \text{[knots/sec]}$$

APPENDIX B

REFERENCE ENERGY-ALTITUDE DESCENT ALGORITHM EVALUATION QUESTIONNAIRE

1. Rate the difficulty of the task of arriving at the waypoint on altitude and airspeed.

Trivial	Very easy	Easy	Some effort required	Difficult	Very difficult	Impossible

Comments or qualifications

_____

_____

_____

2. Rate the level of physical work load required.

None	Very slight	Slight	Moderate	High	Very high	Impossibly high

Comments or qualifications

_____

_____

_____

3. Rate the level of mental work load.

None	Very slight	Slight	Moderate	High	Very high	Impossibly high

Comments or qualifications

_____

_____

_____

APPENDIX B

With no guidance only:

4. What method of planning the descent did you use?

_____

_____

_____

Guidance only:

5. Relative to no guidance, what effect did the guidance have on your ability to arrive at the waypoint on altitude and airspeed?

Greatly improved performance	Improved performance	Slightly improved performance	None	Slightly degraded performance	Degraded performance	Greatly degraded performance

Comments or qualifications

_____

_____

_____

6. What effect did use of the guidance have on physical work load?

Reduced a great deal	Reduced moderately	Reduced slightly	None	Increased slightly	Increased moderately	Increased a great deal

Comments or qualifications

_____

_____

_____

7. What effect did use of the guidance have on mental work load?

Reduced a great deal	Reduced moderately	Reduced slightly	None	Increased slightly	Increased moderately	Increased a great deal

Comments or qualifications

8. Rate the ease of use of the information as presented.

Trivial	Very easy	Easy	Some effort required	Difficult	Very difficult	Unusable

Comments or qualifications

9. Any general comments?

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1. Curry, Renwick E.: Human Factors of Descent Management. Proceedings of the 18th IEEE Conference on Decision and Control Including the Symposium on Adaptive Processes, Volume 1, 79CH1486-OCS, IEEE Control Systems Soc., Dec. 1979, pp. 422-425.

2. Vietor, C. W.: Time, Space, and Energy Management in the Airways Traffic Control Medium. Navigation, vol. 20, no. 2, Summer 1973, pp. 159-170.

3. Parrish, Russell V.; and Bowles, Roland L.: Motion/Visual Cueing Requirements for Vortex Encounters During Simulated Transport Visual Approach and Landing. NASA TP-2136, 1983.

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TABLE I.- TEST CONDITIONS

Case	Initial conditions			Reference altitude, ft	Reference airspeed, knots	Atmospheric conditions	
	Altitude, ft	Airspeed, knots	DME_{ind}, n.mi.			Wind	Turbulence
1	28 000	300	90	15 000	250	None	Light
2	28 000	300	90	15 000	250	Case 2 wind profile (see fig. 4), Wind direction = 270°	Light
3	28 000	300	90	15 000	250	Case 3 wind profile (see fig. 4), Wind direction = 270°	Light
4	24 000	310	50	14 000	300	Case 4 wind profile (see fig. 4), Wind direction = 250°	Light

TABLE II.- SEQUENCE IN WHICH PILOTS FLEW TEST CASES

Test run	Pilot											
	A			B			C			D		
	Case	Guidance	Descent speed, knots	Case	Guidance	Descent speed, knots	Case	Guidance	Descent speed, knots	Case	Guidance knots	Descent speed,
1	2	No	250	4	No	300	3	No	250	1	No	280
2	4	No	300	3	No	250	1	No	250	2	No	280
3	3	No	250	1	No	280	4	No	300	3	No	250
4	1	No	250	2	No	280	2	No	250	4	No	300
5	2	Yes	250	2	Yes	250	1	Yes	250	4	Yes	300
6	4	Yes	300	1	Yes	250	3	Yes	250	1	Yes	280
7	1	Yes	250	4	Yes	300	2	Yes	250	2	Yes	250
8	3	Yes	250	3	Yes	250	4	Yes	300	3	Yes	250
9				2	Yes	280				1	Yes	250
10				1	Yes	280				2	Yes	280

TABLE III.- DIFFERENCE IN FUEL USAGE AND t-VALUE

Difference in fuel usage		t-value[a]
Mean, lb	Standard deviation, lb	
25.6	32.1	[b]3.18

[a]Assumes unequal population variances (ref. 4).
[b]Indicates 99.5-percent confidence level.

TABLE IV.- ALTITUDE ERRORS AT WAYPOINT AND t-VALUE

Without guidance		With guidance		t-value[a]
Mean, ft	Standard deviation, ft	Mean, ft	Standard deviation, ft	
57	98	26	138	0.79

[a]Assumes unequal population variances (ref. 4).

TABLE V.- AIRSPEED ERRORS AT WAYPOINT AND t-VALUE

Without guidance		With guidance		t-value[a]
Mean, knots	Standard deviation, knots	Mean, knots	Standard deviation, knots	
9.1	19.3	-1.1	6.0	[b]2.30

[a]Assumes unequal population variances (ref. 4).
[b]Indicates 97.5-percent confidence level.

TABLE VI.- PERCENTAGE OF TIME COLUMN OUT OF DETENT AND t-VALUES

Without guidance		With guidance		t-value[a]
Mean, percent	Standard deviation, percent	Mean, percent	Standard deviation, percent	
44.563	15.898	54.3	10.6	[b]2.20

[a]Assumes unequal population variances (ref. 4).
[b]Indicates 97.5-percent confidence level.

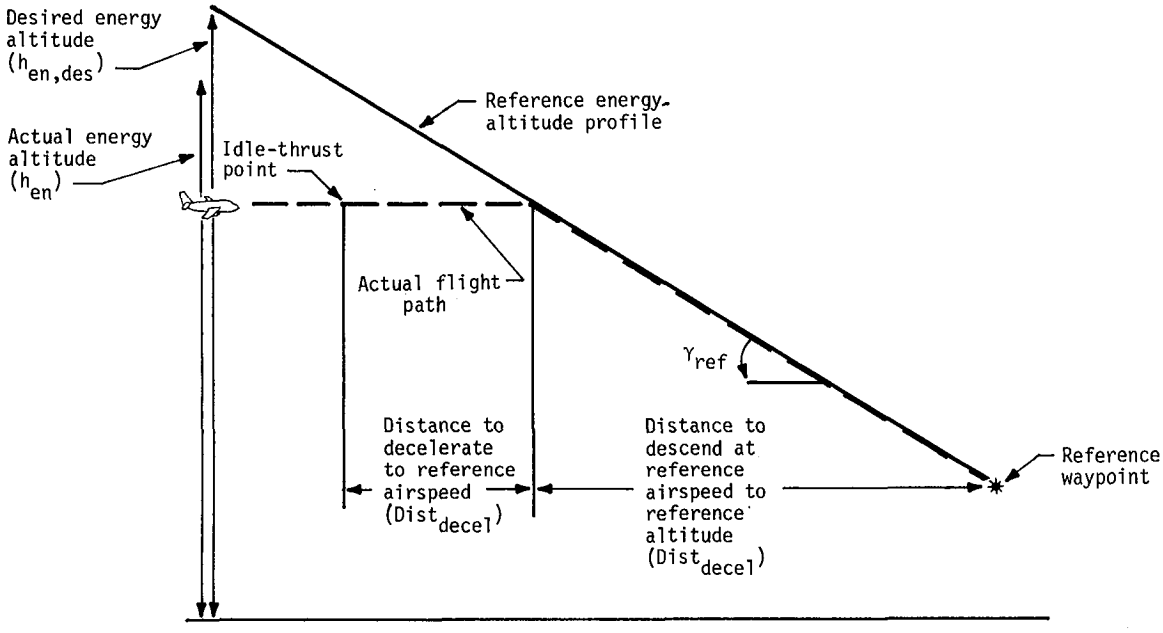

Figure 1.- Reference energy-altitude profile and actual flight path with aircraft below desired energy altitude.

Reference energy-altitude profile deviation meter

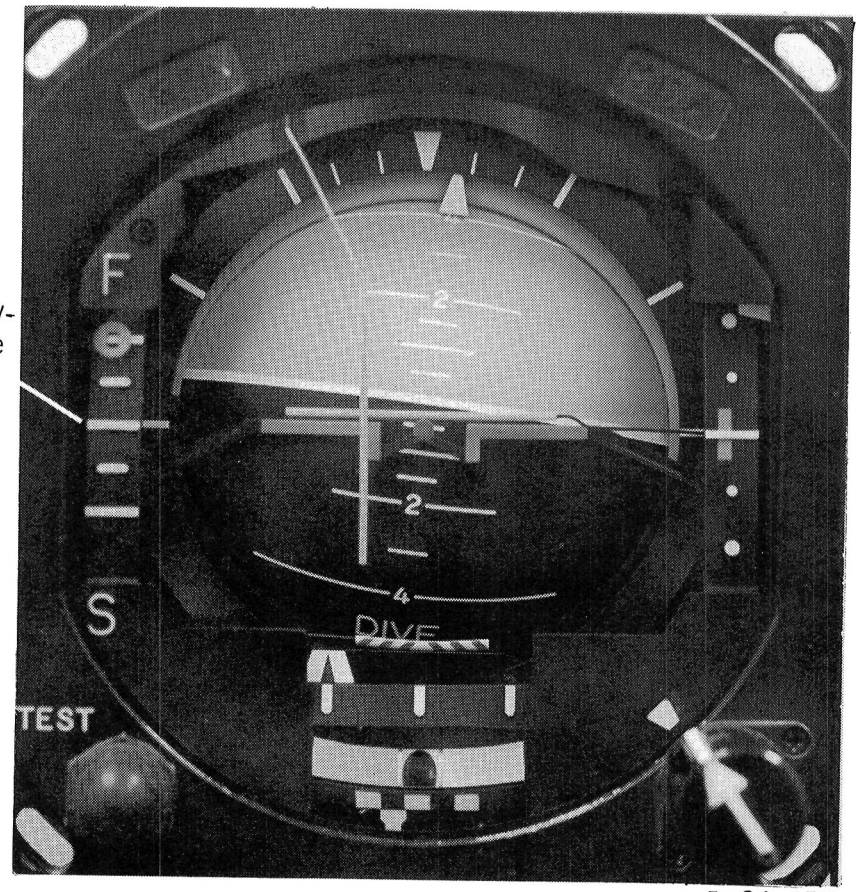

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Figure 2.- Reference energy-altitude profile deviation meter on attitude director indicator.

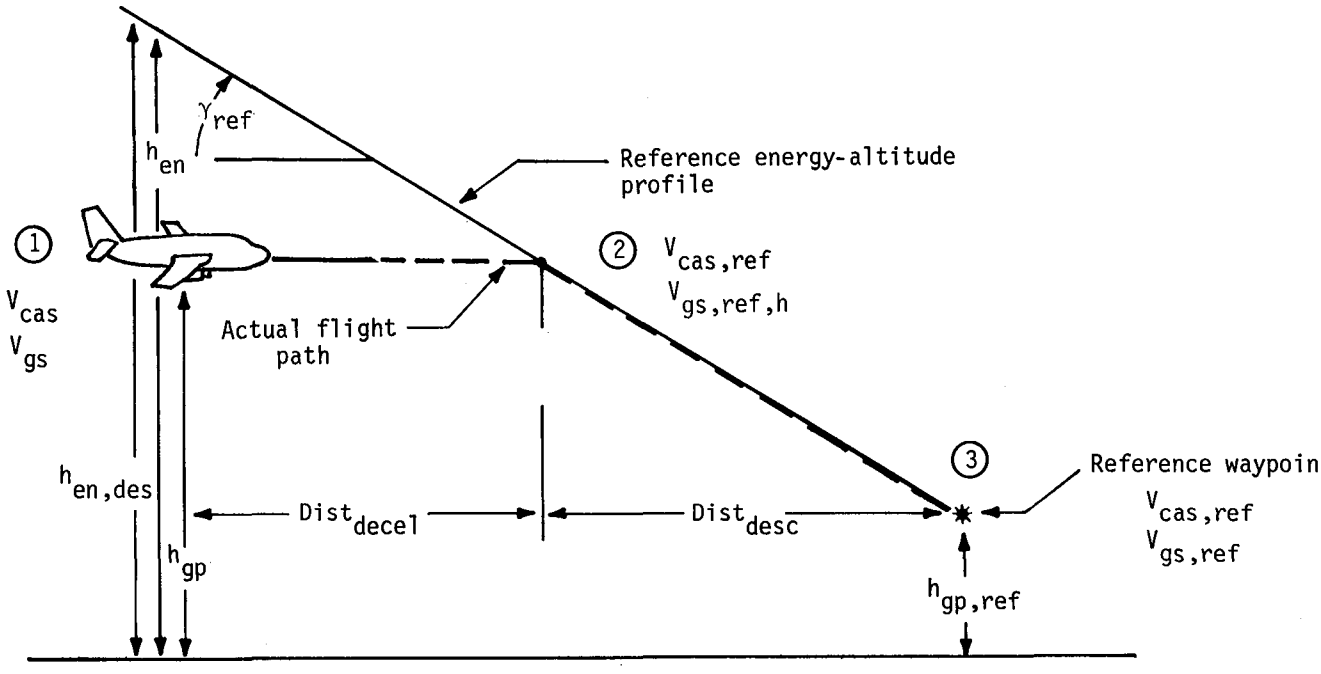
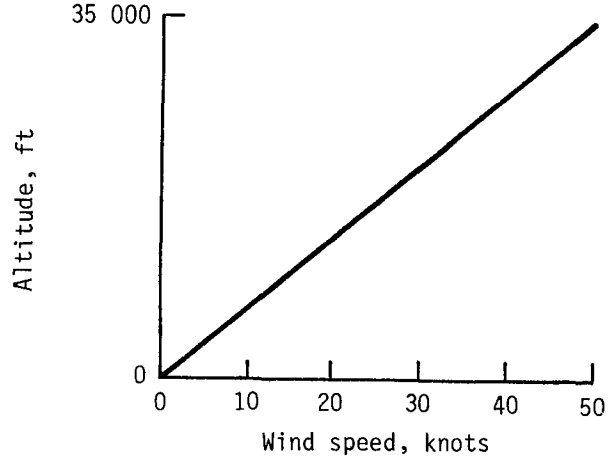
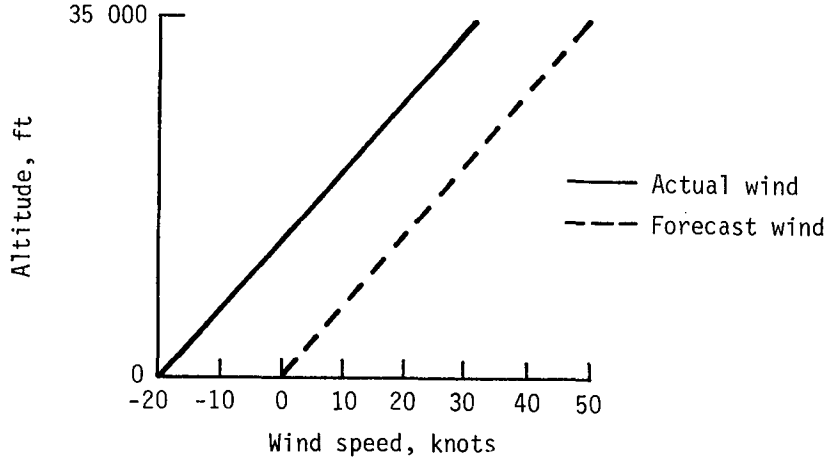


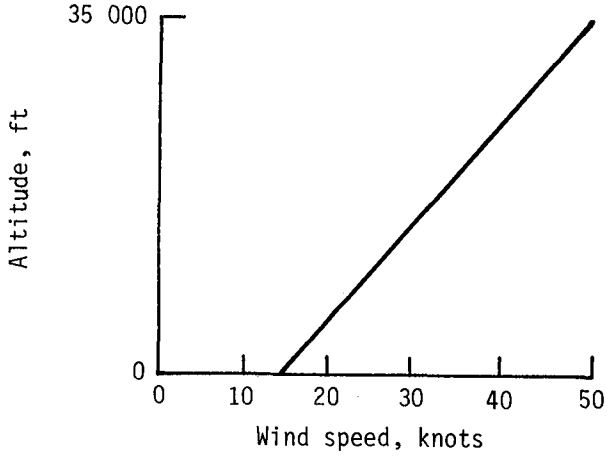
Figure 3.- Reference energy-altitude profile and actual flight path with aircraft at desired energy altitude.



(a) Wind profile used in test case 2.



(b) Wind profile used in test case 3.



(c) Wind profile used in test case 4.

Figure 4.- Wind profiles for simulation test.

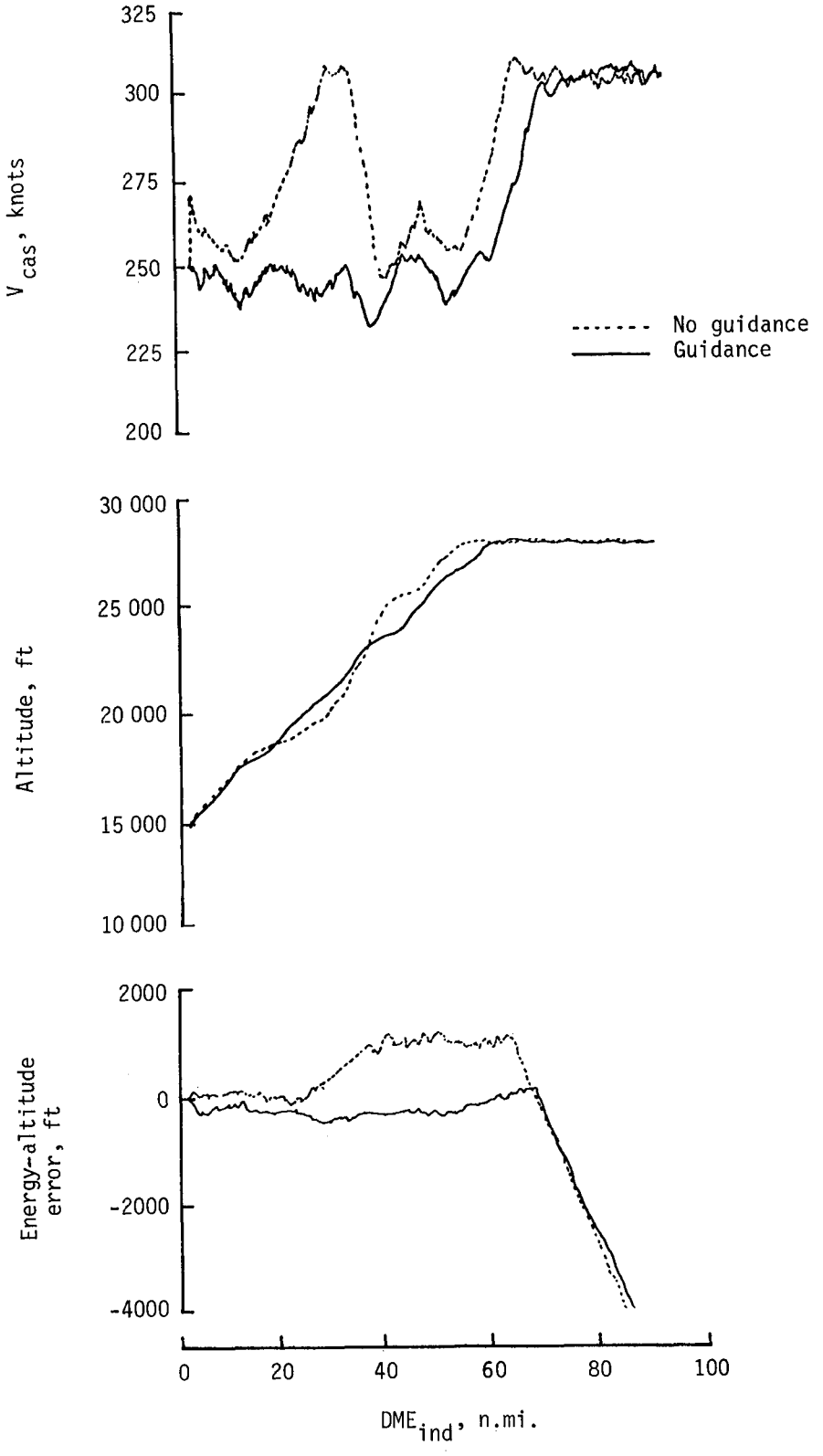
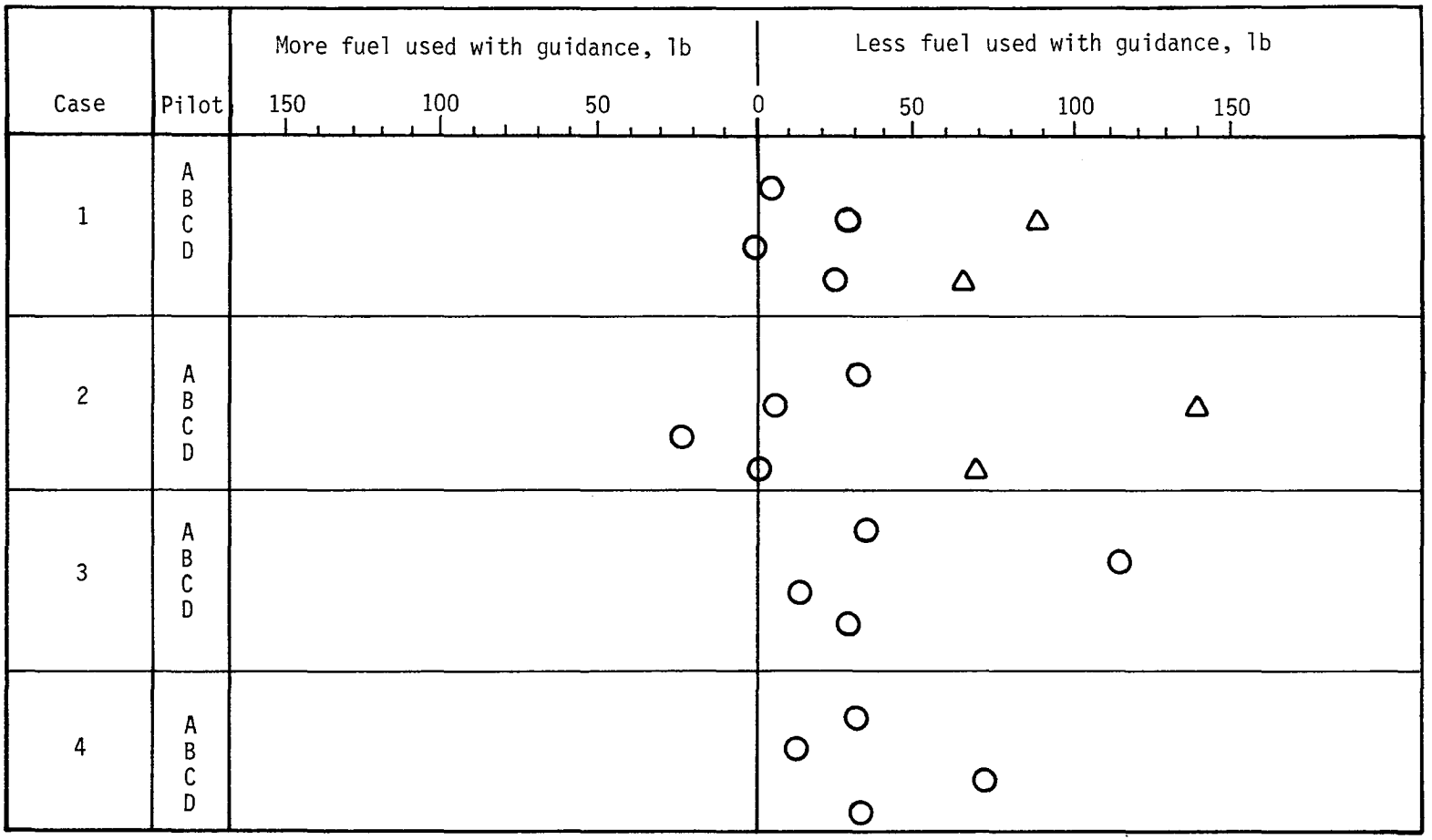


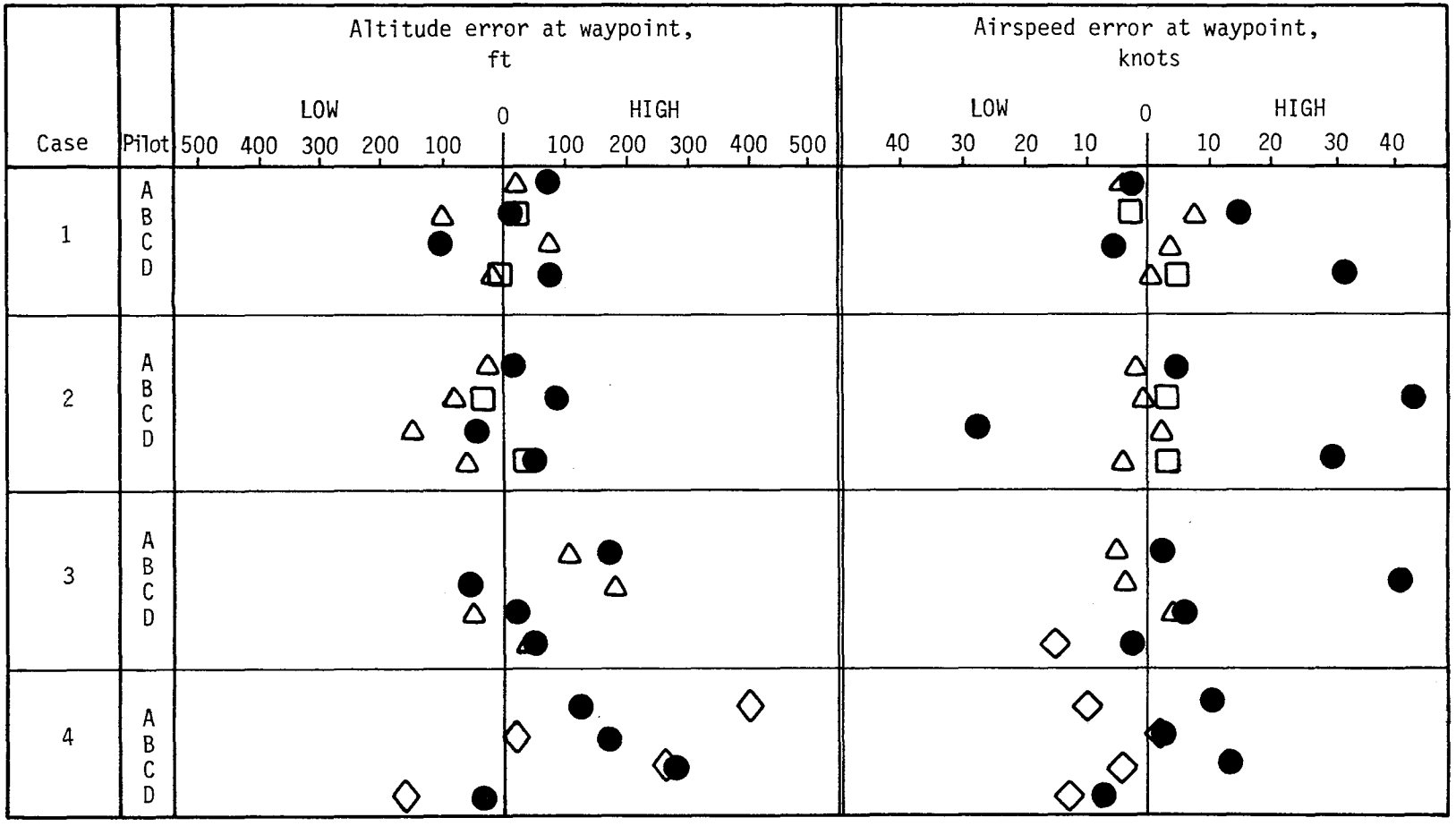
Figure 5.- Altitude, calibrated airspeed, and energy-altitude error for pilot A, during test case 2.



○ = Same descent speed, with and without guidance

△ = 250-knot descent speed with guidance, 280-knot descent speed without guidance

Figure 6.- Comparison of fuel usage with and without guidance.



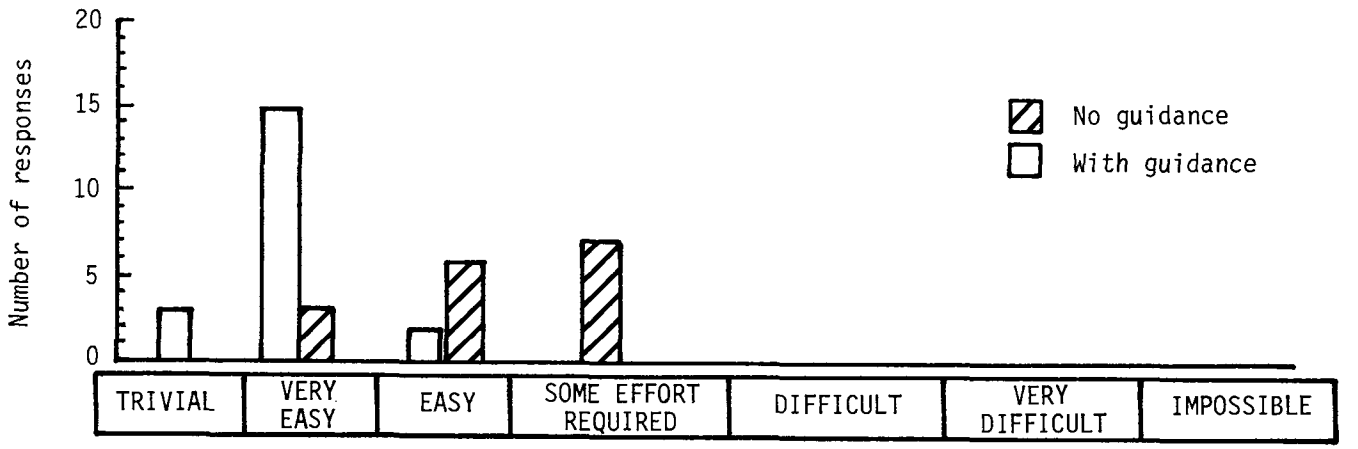
● = No guidance

□ = 280-knot descent with guidance

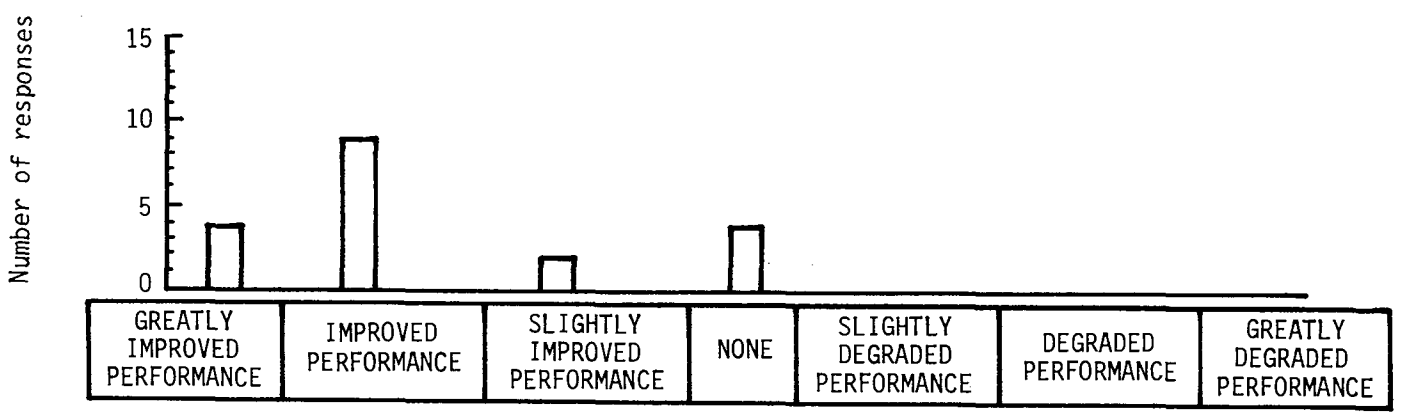
△ = 250-knot descent with guidance

◇ = 300-knot descent with guidance

Figure 7.- Altitude and airspeed errors at reference waypoint.

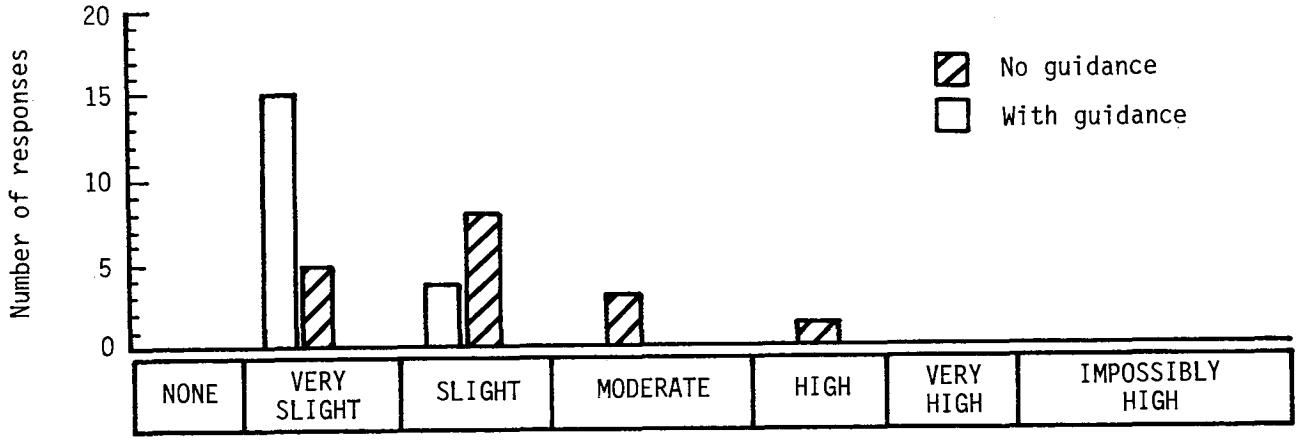


Question 1. Rate the difficulty of the task of arriving at the waypoint on altitude and airspeed.

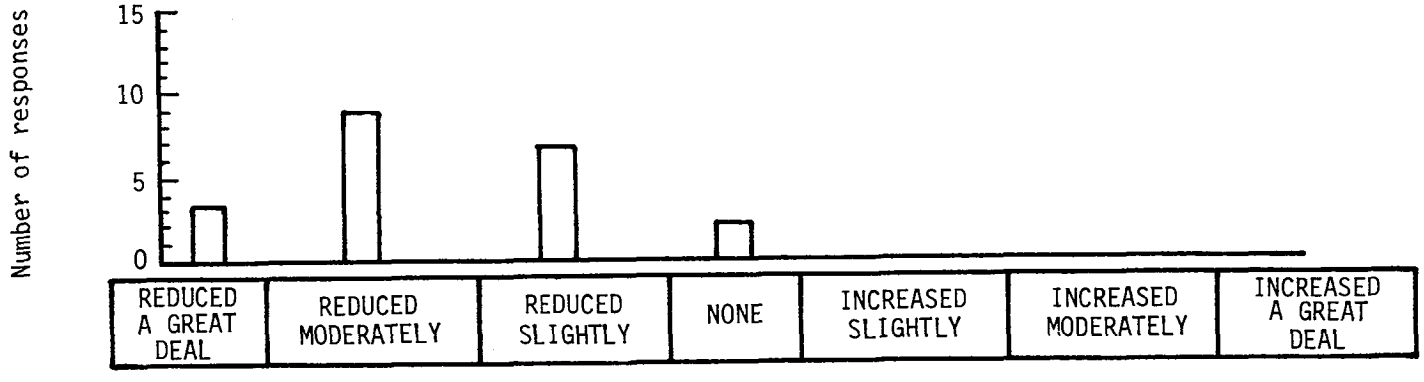


Question 5. Relative to no guidance, what effect did the guidance have on your ability to arrive at the waypoint on altitude and airspeed?

Figure 8.- Summary of responses to questionnaire.

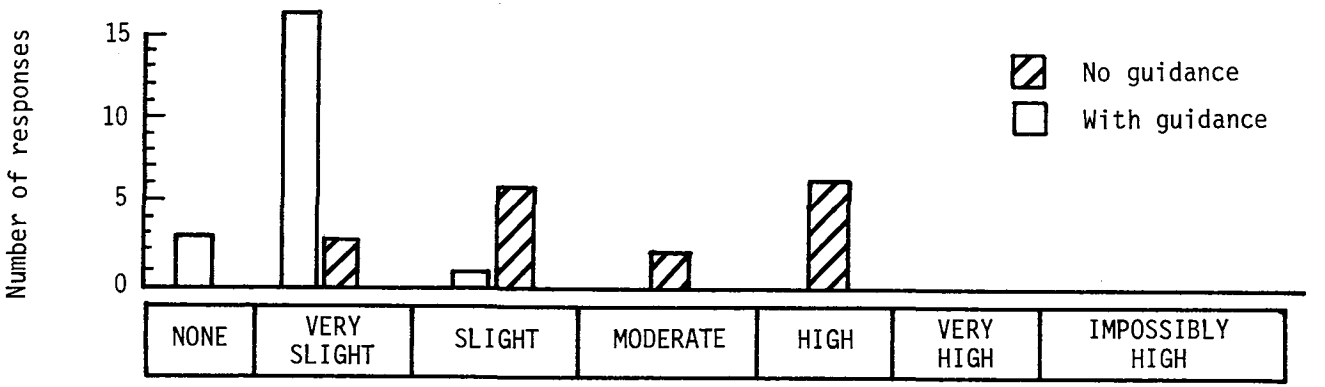


Question 2. Rate the level of physical work load.

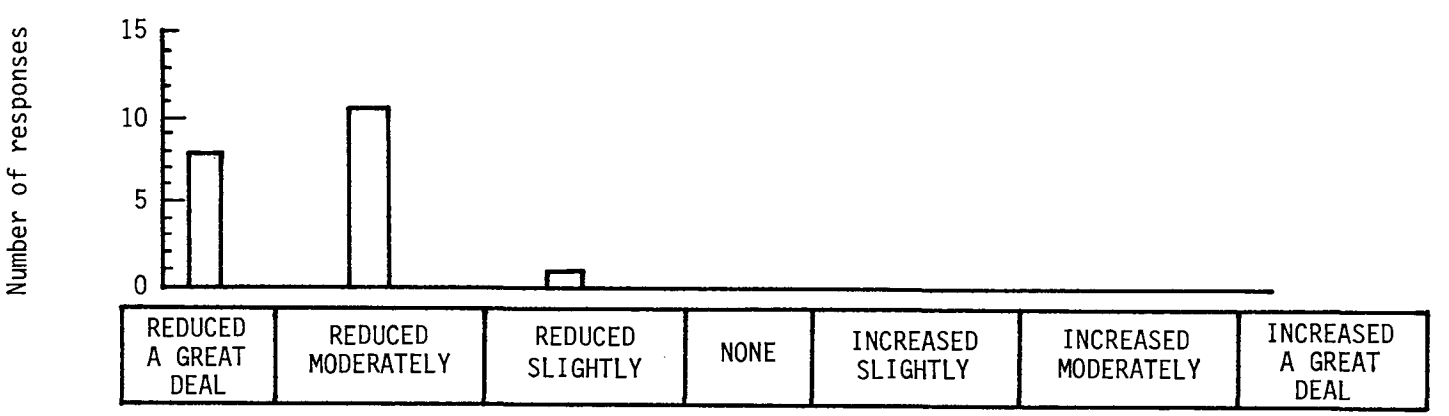


Question 6. What effect did use of the guidance have on physical work load?

Figure 8. Continued.

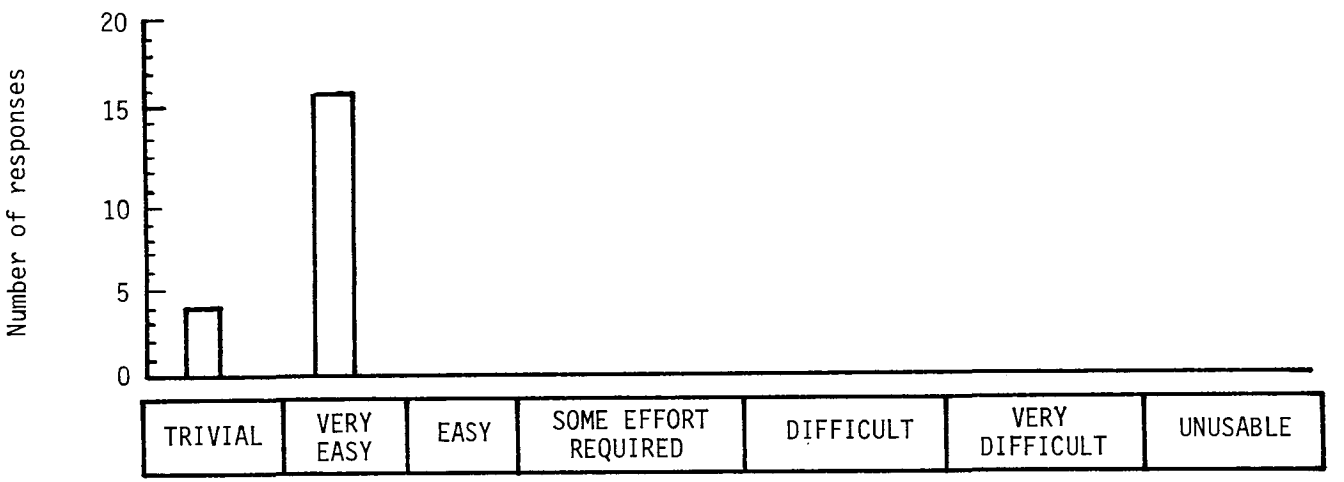


Question 3. Rate the level of mental work load.



Question 7. What effect did use of the guidance have on mental work load?

Figure 8.- Continued.



Question 8. Rate the ease of use of the information as presented.

Figure 8.- Concluded.

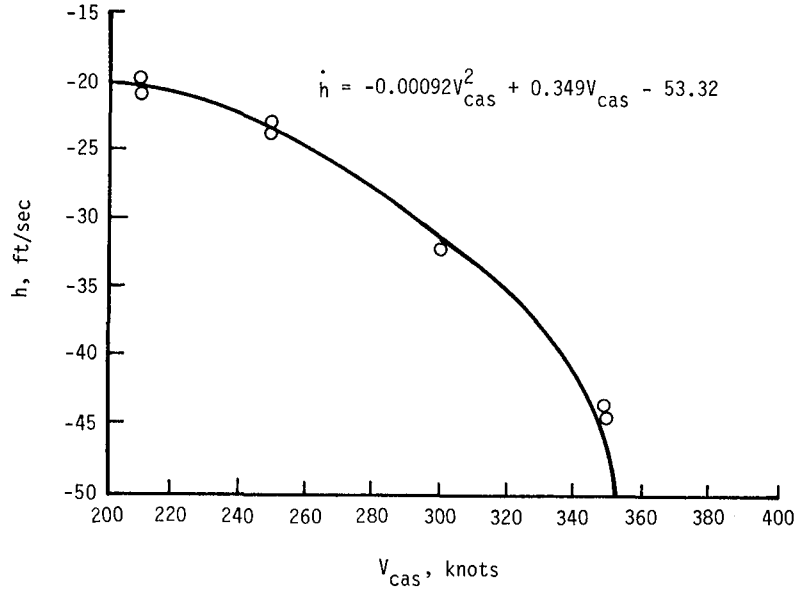


Figure 9.- Average descent speed and resulting model for NASA TSRV B-737 airplane simulation.

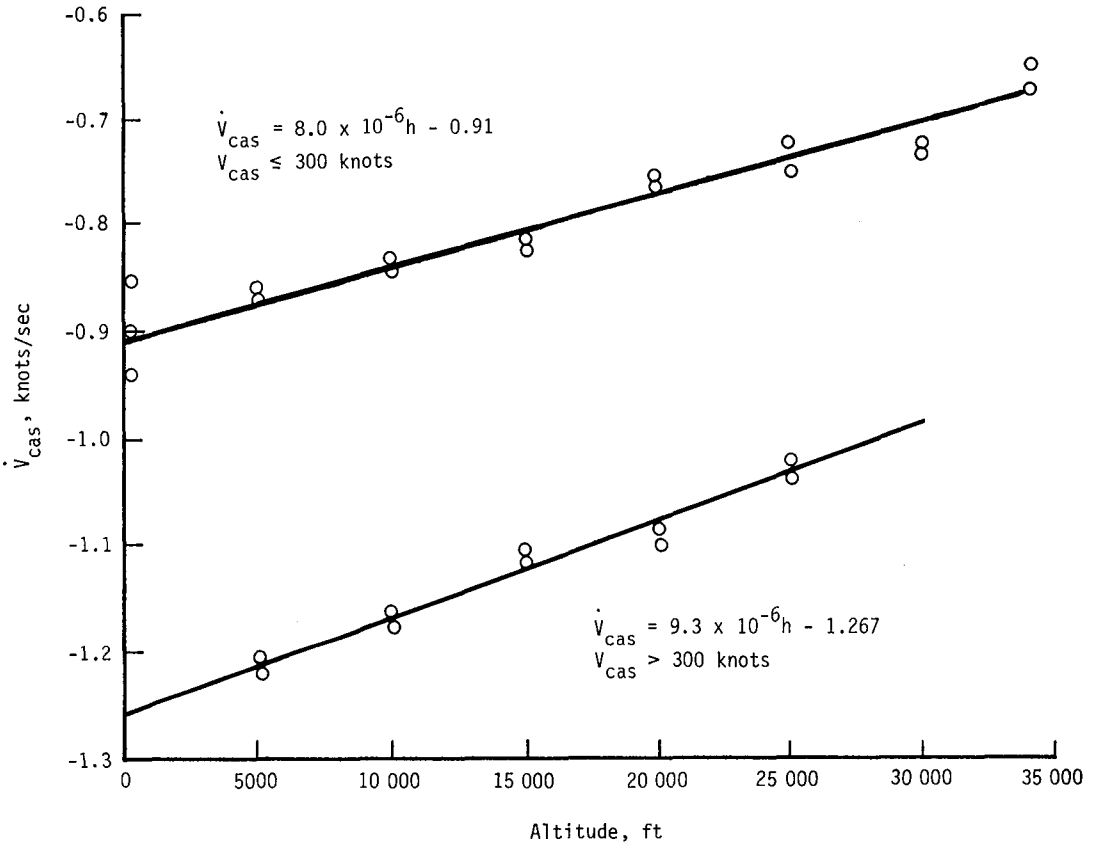


Figure 10.- Average deceleration and resulting model for NASA TSRV B-737 airplane simulation.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TP-2383		

4. Title and Subtitle	5. Report Date
REFERENCE ENERGY-ALTITUDE DESCENT GUIDANCE - SIMULATOR EVALUATION	January 1985
	6. Performing Organization Code: 505-45-33-03
7. Author(s): Kathy H. Abbott and Charles E. Knox	8. Performing Organization Report No.: L-15800
	10. Work Unit No.
9. Performing Organization Name and Address: NASA Langley Research Center, Hampton, VA 23665	11. Contract or Grant No.
	13. Type of Report and Period Covered: Technical Paper
12. Sponsoring Agency Name and Address: National Aeronautics and Space Administration, Washington, DC 20546	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Descent guidance was developed to provide a pilot with information to make a fuel-conservative descent and cross a designated waypoint at a preselected altitude and airspeed. The guidance was designed to reduce fuel usage during the descent and reduce the mental work load associated with planning a fuel-conservative descent. A piloted simulation was conducted to evaluate the operational use of this guidance concept. The results of the simulation tests showed that the use of the guidance reduced fuel usage and mental work load during the descent. Use of the guidance also decreased the airspeed error, but had no effect on the altitude error when the designated waypoint was crossed. Physical work load increased with the use of the guidance, but remained well within acceptable levels. The pilots found the guidance easy to use as presented and reported that it would be useful in an operational environment.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Fuel conservation Flight-management systems Aircraft Flight guidance Air traffic control	Unclassified - Unlimited Subject Category 06

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	37	A03

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