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FUEL PENALTIES AND TIME FLEXIBILITY OF 4D FLIGHT PROFILES UNDER MISMODELED WIND CONDITIONS

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SUMMARY

A parametric sensitivity study was conducted to evaluate time flexibility and fuel penalties associated with 4D operations in the presence of mismodeled wind. The final cruise and descent segments of a flight in an advanced time-metered air traffic control environment were considered. Optimal performance of a B-737-100 airplane in known, constant winds was determined. Performance in mismodeled wind was obtained by tracking no-wind reference profiles in the presence of actual winds. The results of the analysis are presented in terms of loss of time flexibility and fuel penalties compared to the optimal performance in modeled winds.

Mismodeled tailwinds were found to penalize the airplane to a greater extent than mismodeled headwinds. Higher cruise altitudes further reduced time flexibility and increased fuel penalties compared to lower cruise altitudes.

INTRODUCTION

Current Air Traffic Control (ATC) operations at several major Air Route Traffic Control Centers (ARTCC) incorporate a metering process to assist in the sequencing of aircraft for arrival into terminal areas. Estimated runway arrival times are calculated for aircraft while in cruise based on filed flight plan information. Times are then calculated for crossing an enroute metering fix, which is typically located approximately 35 nautical miles from the airport at the transition between enroute and terminal control sectors. The metering fix times are then used by enroute controllers to assist in manual sequencing of approach aircraft for handoff to the terminal controllers. Certain approximations and procedures (such as the use of flight plan speeds and positions for aircraft) limit the utility of the current metering process. Advanced time-based metering systems are being developed which should provide more accurate time calculations through improved airplane performance modeling and the use of actual tracked airplane position and speed. Aircraft capable of time-controlled (4D) flight may well be required to meet assigned crossing times at one or more metering fixes with a relatively high accuracy. The time accuracy needed, while still very much an open research issue, is on the order of 30 seconds at an enroute metering fix and 5 seconds at runway threshold.

Variations in wind speed and direction have a primary effect on the flight time of an airplane over a given range. Uncertainty in the wind is a primary obstacle to successful and cost effective time-based management of air traffic. Airplanes in the system must be able to consistently achieve accurate arrival times at pre-defined metering points. Further, individual aircraft fuel penalties incurred while correcting for unknown winds must be outweighed by the benefits of reduced delays provided by the time-based air traffic control system. The time-flexibility of a typical jet-transport aircraft and magnitude of fuel penalties associated with increasing levels of wind error are the subjects of this report.

This study was conducted to provide specific data on single airplane time flexibility and fuel penalties associated with 4D operations in the presence of mismodeled wind. An optimal vertical profile generation algorithm, representative of the next generation of onboard flight management system capability, was utilized to calculate reference vertical profiles with various levels of constant wind. The profiles were then tracked both with and without accurately modeled wind using a simple point mass airplane performance simulation. Detailed airplane performance models, including drag polar, engine and speedbrake functions, were incorporated in the tracking program in order to determine the maximum capabilities of the airplane in the wind and also to determine realistic fuel usage.

SCENARIO DESCRIPTION

A 200 nautical mile final cruise and descent flight segment was used as the basic scenario for this study. This flight phase is consistent with the region of active arrival time selection in advanced time-based air traffic control system concepts being developed. Initial conditions were selected to correspond to the reference profile cruise altitude and airspeed based on modeled wind for a given cost of time and fuel. End conditions were chosen to be 250 knots calibrated airspeed at 10 000 feet altitude.

TRAJECTORY GENERATION

A vertical trajectory computation algorithm designed to minimize operating costs was utilized to generate the reference profiles for the test scenario. This algorithm generates a speed and altitude profile for the aircraft to follow as a function of range in order to minimize overall cost for given time and fuel costs. A description of the formulation of the algorithm may be found in Appendix A. References 1 through 3 provide additional background information on the optimization technique used in this algorithm. Included in the algorithm are detailed airplane performance models as well as atmospheric effects of wind and temperature on the equations of motion. Constraints imposed on the algorithm were fixed altitude cruise until top of descent, followed by an idle thrust descent at optimal airspeed. Experience has shown that the benefits of cruise-climb and variable thrust descent are minimal, accounting for less than one percent lower costs than the constrained profiles (ref. 4).

REFERENCE PROFILE TRACKING

A vertical profile tracking program was used to track the reference profile and provide actual fuel and time required to fly the profile under both modeled and mismodeled wind conditions. Included in the tracking program were the same airplane performance models and equations of motion as in the trajectory generation program. In addition, speedbrake limits were modeled in order to limit airplane tracking of mismodeled wind profiles to the actual capabilities of the airplane. A description of the tracking program may be found in Appendix B.

The philosophy used in tracking the reference profiles was to match groundspeed exactly in cruise and attempt to fly both the groundspeed and inertial flight path angle of the reference during descent. With wind modeled exactly, the tracking program flew the reference at the same true airspeeds and thrust settings and arrived at the proper time while burning the same amount of fuel. For mismodeled wind, the tracking program adjusted true airspeed to match groundspeed of the reference. Thrust (above idle) or speedbrake would be used to maintain the reference inertial flight path angle during descent. When airplane speed, thrust or speedbrake limits were encountered, the airplane would fly at the limit and accumulate time error. When time errors exceeded 2 seconds, groundspeed increments would be added to the reference profile groundspeed to recapture the reference time. A maximum of 10 knots speed adjustment above or below the reference profile groundspeed was found to be adequate for the constant wind error profiles in this study.

RESULTS AND DISCUSSION

A parametric sensitivity analysis was conducted using the trajectory generation and profile tracking computer programs to determine the time-flexibility and fuel penalties associated with mismodeled wind. First, optimal performance of the airplane was determined in the form of minimum fuel versus flight time for a series of constant wind conditions. Next, fuel versus time performance for mismodeled wind was calculated by tracking the no-wind reference profiles under actual wind conditions. The following sections will discuss the optimal performance of the airplane in wind followed by performance in mismodeled wind.

Optimal Performance in Wind

Time cost. - The optimal trajectory generation algorithm described in Appendix A computes a 3D vertical trajectory which minimizes operating cost over a given range for specified time and fuel costs. For fixed fuel costs, a direct relationship exists between time cost and flight time for any given flight segment. Figure 1 presents time cost versus flight time of the baseline scenario for a series of constant wind conditions. For a given wind, minimum flight time corresponds to maximum time cost and maximum flight time occurs at the minimum time cost. A vertical profile which satisfies a specified flight time is determined by iterating on time cost until flight time converges on the desired value. Wind has the effect of shifting in time the curve of time cost versus flight time, as shown in figure 1. A fixed flight time will therefore occur at a different time cost for different wind conditions.

Fuel use. - Reference 3 has shown that the vertical profile generated by optimizing operating costs results in a minimum fuel profile for the resulting flight time. Plotting the fuel required versus flight time for a series of time costs with fixed fuel cost therefore provides an optimal fuel performance spectrum for a given scenario. Figure 2 presents the optimal fuel performance for the baseline scenario generated using the time cost values shown in figure 1. As seen in the figure, wind has the effect of shifting the fuel versus time curve both in fuel used as well as in time required. Reference lines of constant time cost have been drawn on the figure to illustrate the difference in wind effects between cost-optimal 3D and fuel-optimal 4D situations. For given time and fuel costs, optimal 3D performance will be a tradeoff between time and fuel which minimizes combined cost. Optimal 4D is simply a shift in fuel required for a fixed flight time.

Flight profile characteristics. - The flight profiles created by the trajectory generation algorithm consist of a constant altitude cruise segment followed by an idle thrust descent. The two parameters of primary interest to this study are cruise speed and descent range. Optimum cruise Mach numbers versus flight time for the baseline scenario are presented in figure 3. Lines of constant time cost are shown in the figure to illustrate the minimal effect of wind on cruise speed for optimum 3D operation. Fixed time operations, however, require a significant change in cruise Mach in order to achieve the same flight time in different winds. Similarly, descent range versus flight time is presented in figure 4. Here, wind also affects 4D operations to a greater extent than 3D operations, but not to the same degree as cruise Mach.

Cruise altitude effects. - Choice of cruise altitude will affect the time and fuel performance of the airplane. The baseline scenario in this study included a fixed cruise altitude of 33 000 ft. Optimal cruise altitude versus flight time for a 90 000 lb B-737-100 airplane is shown in figure 5. As seen in the figure, optimal cruise altitude is relatively constant at approximately 36 000 ft for middle values of flight time, dropping to lower altitudes at the extremes of flight time. Wind has the effect of shifting the optimal altitude curve in time while maintaining the shape. Since aircraft are currently restricted to flying fixed cruise altitudes or flight levels, it is useful to explore optimal performance at these fixed altitudes. Figure 6 presents the optimal fuel versus time performance for the 200 nautical mile scenario for optimal cruise altitude and four fixed flight level cruise altitudes with no wind. As would be expected, the minimum fuel occurs at optimal altitude, with fuel increasing at the lower cruise flight levels. Figure 7 presents the same information for the constant wind conditions included in this study. It should be noted that the fuel data do not reflect climb fuel required to achieve the various cruise altitudes and therefore do not accurately present overall mission fuel required. Time capabilities, in terms of maximum, minimum, and resultant time windows, are summarized in Table I for the cruise altitude and wind combinations considered in this study. The fuel and time data are presented as a basis for obtaining penalties under mismodeled wind conditions.

Performance In Mismodeled Winds

Tracking requirements. - Mismodeled winds force the airplane to fly non-optimal speeds and descent flight path angles in order to match the reference profile time. Figure 8 illustrates the cruise Mach number required for mismodeled 50 knot headwind and tailwind compared to the optimal Mach under modeled wind conditions. For a given flight time, there is a significant shift in cruise Mach required to track the 4D reference profile due to mismodeled wind. This shift in cruise Mach is approximately twice the change in optimal Mach when winds are accurately modeled. The time difference in cruise between modeled wind and mismodeled wind profiles is compensated in descent such that arrival times are the same. Under modeled conditions, the descent range increases in a tailwind and decreases in a headwind (as seen in figure 4), while the airplane maintains an idle thrust setting. The mismodeled case forces the airplane to fly the same inertial flight path angle, regardless of wind, requiring throttle or speedbrake compensation.

Time flexibility. - Tracking the reference profiles generated under mismodeled wind conditions results in a loss of time flexibility compared to optimal performance in modeled winds. Two factors contribute to this loss in time flexibility. First, the reference profile time window (minimum to maximum flight times) does not consider the shift in available flight times as seen in figure 1. Therefore, the longer flight times in a headwind and shorter flight times in a tailwind are not considered. Second, the airplane will be unable to achieve flight times associated with reference profiles that command speeds and/or descent flight path angles beyond the capabilities of the airplane. Figure 8 illustrates the second situation for a 50 knot mismodeled wind. Required cruise Mach numbers for the mismodeled winds are clearly seen to exceed the maximum or minimum speed capabilities of the airplane for a significant range of desired flight times. The resulting time capability for the baseline scenario is presented in figure 9 in terms of time error versus desired flight time.

Given a maximum acceptable time error, the loss in time flexibility can be computed. For example, the time window for a modeled 50 knot headwind (from Table I) is 13.62 minutes. It can be seen from figure 9 that a 50 knot headwind error increases the minimum flight time to 31.2 minutes while decreasing the maximum flight time to 37.5 minutes resulting in a time window of 6.3 minutes. This represents a loss in time flexibility of 7.32 minutes or 54 percent. An allowable 30 second time error reduces this loss in time flexibility to 43 percent (a 7.8 minute time window from figure 9).

The effect of wind errors at different reference cruise altitudes on time flexibility is presented in figure 10. As seen in the figure, time errors occur sooner at higher cruise altitudes for a given wind error condition, resulting in smaller time windows at the higher altitudes. The modeled wind time windows also decrease at higher altitudes as seen in Table I. The change in time windows for modeled and mismodeled winds as a function of cruise altitudes is illustrated in figure 11 for the 50 knot headwind condition. The change in time window is seen to be a linear decrease with increasing cruise altitude for both the modeled and mismodeled winds. The result is an increasing percentage of lost time flexibility with increasing cruise altitude. Similar results are observed for the other wind error conditions. A summary plot of lost time flexibility versus wind error is presented in figure 12.

Fuel penalties. - In addition to losing time flexibility, mismodeled wind results in fuel penalties to the airplane. These penalties arise principally from the improper descent range being computed, therefore requiring throttle or speedbrake compensation to maintain reference flight path. In a mismodeled headwind, the descent range is longer than optimal, requiring additional throttle during descent. In addition, the required cruise Mach is higher than optimal cruise Mach in order to achieve the same time with a longer descent. In a mismodeled tailwind, the descent range is shorter than optimal, requiring speedbrake compensation to maintain the same inertial flight path. As a result, a significant additional time is spent at cruise throttle rather than idle throttle resulting in additional fuel usage. The fuel versus time performance spectrum for the baseline scenario under mismodeled wind conditions is presented in figure 13. Fuel penalties were obtained by subtracting the fuel required for a given flight time and wind condition in figure 1 (optimal performance) from the fuel required for the same time and wind condition in figure 13 (mismodeled performance). The resulting fuel penalties are presented in figure 14. Fuel penalties for different cruise altitudes are given in figure 15. A summary plot of average fuel penalties versus wind error is presented in figure 16.

Several interesting trends are evident in the fuel penalty results. Tailwind errors are seen to produce essentially linear fuel penalties with increasing wind errors for a given flight time. In addition, higher cruise altitudes result in fairly consistent increases in fuel penalties for both 25 and 50 knot tailwinds. Headwind errors, however, exhibit non-linear fuel penalties with both increasing wind errors and increasing cruise altitude. The basic factor responsible for the non-linear behavior of fuel penalties in headwinds is the drag characteristic of the airplane. The drag increase associated with increasing Mach (compressibility drag) demands considerable thrust requirements in mismodeled headwinds. This in turn results in higher fuel penalties at high Mach and high altitude conditions. This situation would be more or less pronounced depending on the Mach drag rise characteristics of different airplane types.

CONCLUDING REMARKS

This report has presented specific time flexibility and fuel penalty data for the B-737-100 jet transport airplane flying 4D flight trajectories in the presence of constant wind errors. The 200 nautical mile cruise/descent scenario evaluated is a typical example of the 4D situation likely to be encountered by an airplane in an advanced time-metered air traffic control system. While the numerical results are specific to the B-737-100 airplane, some general comments and conclusions are deemed appropriate.

Variations in wind shift the optimal fuel versus time performance spectrum of an airplane both in time and fuel. Cruise speed and descent range required to achieve a specific flight time are similarly shifted due to wind. Mismodeled wind neglects these shifts in time, speed and descent range, forcing the airplane to fly off-optimal flight trajectories. The resulting loss in time flexibility affects the ability of the airplane to achieve a desired arrival time. The fuel penalties incurred while correcting for wind errors affect the economy of time-based air traffic control operations.

Mismodeled tailwinds affect the airplane differently than mismodeled headwinds. In general, a mismodeled tailwind will penalize the airplane to a greater extent than a headwind. The reference descent range in a mismodeled tailwind is less than optimal, resulting in more time spent at cruise altitude. The higher true airspeeds during cruise limit the slow speed capability of the airplane thus reducing the time flexibility. The airplane must also maintain higher average throttle settings resulting in substantial fuel penalties. In mismodeled headwinds, however, the airplane will descend early and fuel penalties will be small until the airplane approaches maximum speed and encounters high levels of drag. The point where headwinds become as costly as tailwinds is dependent on the airplane drag characteristics.

Cruise altitude also affects both time flexibility and fuel penalties in mismodeled winds. Higher cruise altitudes result in reduced time flexibility and increased fuel penalty. Optimal cruise altitudes are found to produce the greatest penalties. The tradeoff between efficiency gained at higher cruise altitudes versus penalties due to mismodeled wind should be assessed for individual airplane types. It may prove advantageous to fly lower cruise altitudes when operating under time-based air traffic control situations.

APPENDIX A - TRAJECTORY GENERATION ALGORITHM DESCRIPTION

The algorithm utilized to generate reference trajectories for this study was adapted from the computer program described in reference 5. This program, developed by Boeing Commercial Airplane Company, utilized singular perturbation theory in conjunction with the energy-state approximation to the vertical equations of motion to compute near-optimum vertical flight trajectories. The formulation of the algorithm, as adapted from reference 1, is presented in this appendix. Included are descriptions of specific modifications made to the algorithm for this study.

Equations of Motion

The energy-state approximation of the longitudinal model of the airplane was taken in reference 1 to be as follows:

$$\frac{dx}{dt} = (V + Vw) \tag{A.1}$$

$$\frac{dm}{dt} = -f \tag{A.2}$$

$$\varepsilon \frac{dE}{dt} = \frac{(V + Vw)\ (T - D)}{mg} - Vw\ \gamma \tag{A.3}$$

$$E = h + (V + Vw)^2/2g \tag{A.4}$$

where x was the range, V the airspeed, Vw the windspeed, m the mass, f the fuel flow rate, E the energy height, T the thrust, D the drag, γ the flight path angle, and h the altitude. ε is a small "singular perturbation" parameter that arises as a consequence of the particular airplane dynamics and an appropriate choice of scaling the equations of motion.

The computer implementation of the algorithm (ref 5) did not include the second term on the right hand size of equation A.3, assuming it to be negligible. Since energy change and energy rate were utilized in the program to calculate time and distance during climb and descent, significant errors in the reference trajectory were computed in the presence of wind. To alleviate the problem, equations A.3 and A.4 were reformulated to represent airmass-based energy and energy rate as follows:

$$\varepsilon \frac{dE}{dt} = \frac{V\ (T - D)}{mg} \tag{A.5}$$

$$E = h + V^2/2g \tag{A.6}$$

This reformulation was found to be preferable to including the wind terms in equation A.3 since flight path angle, γ , could not be explicitly known when dE/dt was computed. Equations A.1 and A.2 remained unchanged.

The airspeed V and thrust T were the control variables, varying within the limits:

$$Tmin \leq T \leq Tmax \tag{A.7}$$

$$Vmin \leq V \leq Vmax \tag{A.8}$$

Both Vmin and Vmax were functions of altitude and represented the controllability, structural, and performance limitations on the airplane. The airplane model also included fuel flow rate f(h,M,T), the drag polar $C_D(C_L,M)$, and minimum and maximum thrusts Tmin(M,h), Tmax(M,h). M denotes Mach number, C_D the drag coefficient, and C_L the lift coefficient.

It should be noted that the limits on thrust and airspeed were not included in the following formulation of the optimization equations. Climb or descent trajectories which encounter solutions at these limits must be considered sub-optimal.

Performance Index

The optimization problem was to steer the system, equations A.1, A.2, and A.5 from an initial state (x_1,m_1,E_1) at t_1 to a final state (x_f,m_f,E_f) at fixed final time t_f so that the fuel spent is minimized. Equivalently, the expression

$$J = \int_{t_1}^{t_f} C_f dt \tag{A.9}$$

was minimized where C_f was the cost of fuel.

Pontryagin's Minimum Principle

The Hamiltonian for equations A.1, A.2, A.5, and A.9 was

$$H_1 = C_f f + \lambda_x (V + Vw) - \lambda_m f + \lambda_E \frac{V (T - D)}{mg} \tag{A.10}$$

where λ_x, λ_m, and λ_E were the range, mass, and energy adjoint variables respectively. Pontryagins's minimum principle states that the Hamiltonian is minimum along an optimal trajectory. Furthermore, since the final time is fixed, and H_1 is not an explicit function of time, H_1 is constant along the optimal trajectory and given by

$$\min_{T,V} \{H_1\} = K \tag{A.11}$$

K has the units of cost per unit time, and if C_t = -K is selected, equation A.11 may be rewritten

$$\min_{T,V} [C_t + (C_f - \lambda_m)f + \lambda_x(V + Vw) + \lambda_E \frac{V (T - D)}{mg}] = 0 \tag{A.12}$$

along the optimal trajectory. It, therefore, reduces to a direct operating cost (DOC) optimization with free terminal time and cost parameters C_f and C_t. The 4D optimization problem was solved by iterating on C_t with fixed C_f until desired flight time was computed.

Cruise Cost Function

As $\varepsilon \to$ o, the outer solution (according to singular perturbation theory) was reduced to

$$\min_{\substack{h,v \\ (T=D)}} [C_t + (C_f - \lambda_m)f + \lambda_x(V + Vw)] = 0. \tag{A.13}$$

Using Pontryagin's minimum principle, we further get

$$-\lambda_x = \min_{h,v} [\frac{C_t + (C_f - \lambda_m)f}{(V + Vw)}]_{T = D}. \tag{A.14}$$

The ratio to be minimized in A.14 is referred to as the cruise cost function.

Climb/Descent Cost Function

During climb/descent, the independent variable was redefined as $\gamma = t/\varepsilon$ for climb and $\sigma = (t - t_f)/\varepsilon$ for descent such that $\varepsilon \to 0$, γ, and σ were finite over climb and descent, respectively. Equation A.12 was therefore transformed into

$$\min_{T,V} \left[C_t + (C_f - \lambda_{mc})f + \lambda_{xc}(V + Vw) + \lambda_E \frac{V\ (T - D)}{mg} \right] = 0 \tag{A.15}$$

where λ_{mc} and λ_{xc} correspond to the values during cruise. To minimize equation A. 15, the energy adjoint

$$\lambda_e = - \begin{array}{c} \min \\ V, D<T\leq Tmax \\ \\ \max \\ V, Tmin\leq T\leq D \end{array} \left[\frac{C_t + (C_f - \lambda_{mc})f + \lambda_{xc}(V + Vw)}{(T - D)\ V\ /mg} \right]_E. \tag{A.16}$$

The minimization was done to get the climb solution, and the maximization to get the descent solution. The ratio in equation A.16 to be optimized at current energy E, was called the climb/descent cost function.

The computer implementation of the algorithm (ref. 5) was found to actually perform this climb/descent optimization at fixed altitude rather than fixed energy conditions. This technique simplified the program and improved computation speed by eliminating atmospheric subroutine calls during the Fibonacci search for optimum speed at each climb/descent step. The resulting climb/descent trajectories were found to be sub-optimal compared to using fixed energy steps. The difference in fuel between the fixed altitude and fixed energy techniques for the cruise/descent segments used in this study was quite small, and it was deemed unnecessary to modify the Boeing program for this application.

APPENDIX B - TRAJECTORY TRACKING PROGRAM DESCRIPTION

A tracking program was developed to provide fuel and time required to fly reference vertical profiles under arbitrary atmospheric conditions. The program utilized equations based on a point-mass energy state approximation to vertical motion, with provisions for both non-standard atmospheric temperature and wind effects. Full airplane performance modeling was provided, including fuel flow, drag, and appropriate constraints on thrust, speed, and speedbrake capabilities. This appendix describes the equations and methodology utilized in this tracking program.

Equations of Motion

The energy state approximation to the longitudinal point-mass equations of motion was used to determine time and fuel used between waypoints on a reference vertical trajectory. The fundamental equations are:

$$E = h + V^2/2g \tag{B.1}$$

$$\dot{E} = V\,(T - D)/mg \tag{B.2}$$

$$\dot{x} = V + Vw \tag{B.3}$$

$$\dot{m} = -f \tag{B.4}$$

where E is specific total energy relative to the airmass, x is range, m is airplane mass, h is true geopotential altitude, V is airspeed, Vw is windspeed, T is thrust, D is drag, and f is fuel flow rate. The airplane performance model provides thrust $T(h_p,M)$, fuel flow rate $f(T,h_p,M,T_k)$, lift coefficient $C_L(m,M,h_p,\delta_{sb})$, drag coefficient $C_D(C_L,M,\delta_{sb})$, and appropriate limits on airspeed, thrust, and speedbrake δ_{sb}. M denotes Mach number, h_p is pressure altitude, and T_k is atmospheric temperature.

Energy change between two points on the trajectory was determined by:

$$\Delta E = \Delta h + \Delta(V^2/2g). \tag{B.5}$$

Time between waypoints, from B.2 and B.5 was:

$$\Delta t = \Delta E/\dot{E} = \frac{\Delta h + \Delta(V^2/2g)}{V\,(T - D)/mg}. \tag{B.6}$$

Distance and fuel between waypoints then become:

$$\Delta x = (V + Vw)/\Delta t \tag{B.7}$$

$$\Delta F = -\Delta m = f/\Delta t \qquad \text{(B.8)}$$

where F is the fuel used.

Non-standard atmosphere. - The true geopotential altitude h, in equation B.1, is the same as pressure altitude h_p, used in the airplane performance functions, only under standard atmospheric conditions. Altimeter settings for airplanes flying above 18 000 feet are required to be pressure altitude. For non-standard temperature conditions, corrections must be applied to the indicated pressure altitude in order to obtain true altitude for the equations of motion. Since true altitude is only used to determine time between waypoints in equation B.6, it is only necessary to calculate the change in true altitude Δh, and not absolute true altitude h. From reference 6, this correction is:

$$\Delta h = \Delta h_p (T_k / T_{k,s}) \qquad \text{(B.9)}$$

where $T_{k,s}$ is the average standard day temperature at the given pressure altitude. The equation for time between waypoints for non-standard day conditions then becomes:

$$\Delta t = \frac{\Delta h_p (T_k / T_{k,s}) + \Delta (V^2/2g)}{V\,(T - D)/mg} \qquad \text{(B.10)}$$

Tracking Methodology

Cruise. - Fuel required for a fixed time, fixed range cruise segment was determined by calculating the required average airspeed over the segment. If the airspeed was within the capabilities of the airplane, fuel used was calculated using the average fuel flow at the midpoint of the segment for thrust equal to drag. Required airspeeds beyond the capabilities of the airplane were limited to the maximum or minimum speeds. Time was recalculated at the restricted speed and fuel then determined at the revised conditions. At the conclusion of all cruise segments, a time error was computed as the actual time minus the desired time. This time error was passed to the subsequent descent segment.

Descent. - The descent tracking assumed the reference profile was computed at idle thrust. For each consecutive waypoint, the program would first determine the airspeed required to match the groundspeed of the reference profile. The speed was adjusted to reduce an existing time error by adding or subtracting a speed increment of 2 ft/sec for each second of time error up to a maximum of adjustment of 10 ft/sec. As in cruise, the airspeed was limited to the capabilities of the airplane. Time and distance between waypoints was then calculated using equations B.10 and B.7. If actual distance was more or less than desired distance, additional thrust or speedbrake was used to achieve the desired distance. If required thrust or drag exceeded the airplane capabilities, distance errors would continue to accumulate. The final conditions would always match the reference profile altitude; however, time, groundspeed, and range could vary depending on the level of mismodeling in the reference profile and the capabilities of the airplane.

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TABLE I - TIME CAPABILITIES FOR REFERENCE SCENARIOS

Cruise Altitude (ft)	Wind	Minimum Time	Maximum Time	Time Window
29 000	50 knot tailwind	24.05	33.86	9.81
"	25 knot tailwind	24.25	36.29	12.04
"	no wind	26.56	39.10	12.54
"	25 knot headwind	28.02	42.38	14.36
"	50 knot headwind	29.66	46.26	16.66
31 000	50 knot tailwind	24.21	33.30	9.09
"	25 knot tailwind	25.43	35.62	10.19
"	no wind	26.77	38.28	11.51
"	25 knot headwind	28.28	41.37	13.09
"	50 knot headwind	29.92	45.01	15.09
33 000	50 knot tailwind	24.40	32.79	8.39
"	25 knot tailwind	25.65	35.00	9.35
"	no wind	27.00	37.53	10.53
"	25 knot headwind	28.54	40.44	11.90
"	50 knot headwind	30.23	43.85	13.62
35 000	50 knot tailwind	24.61	32.33	7.72
"	25 knot tailwind	25.88	34.44	8.56
"	no wind	27.26	36.84	9.58
"	25 knot headwind	28.85	39.59	10.74
"	50 knot headwind	30.62	42.79	12.17
Optimal	50 knot tailwind	24.21	33.91	9.70
"	25 knot tailwind	25.39	36.40	11.01
"	no wind	26.69	39.28	12.59
"	25 knot headwind	28.14	42.67	14.53
"	50 knot headwind	29.72	46.71	16.99

NOTE: Times are for 90 000 lb B-737-100, 200 nautical mile cruise/descent with winds accurately modeled.

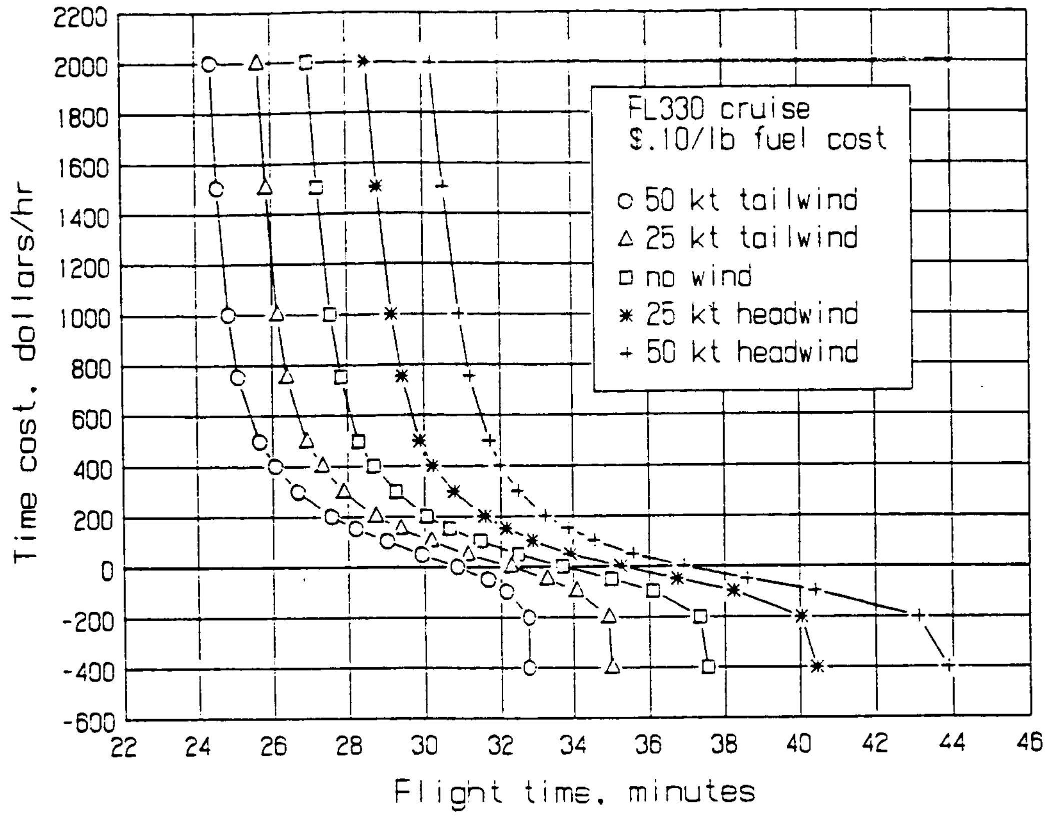


Figure 1.- Time cost versus flight time for constant winds.
90 000 lb B-737-100, 200 nautical mile cruise/descent.

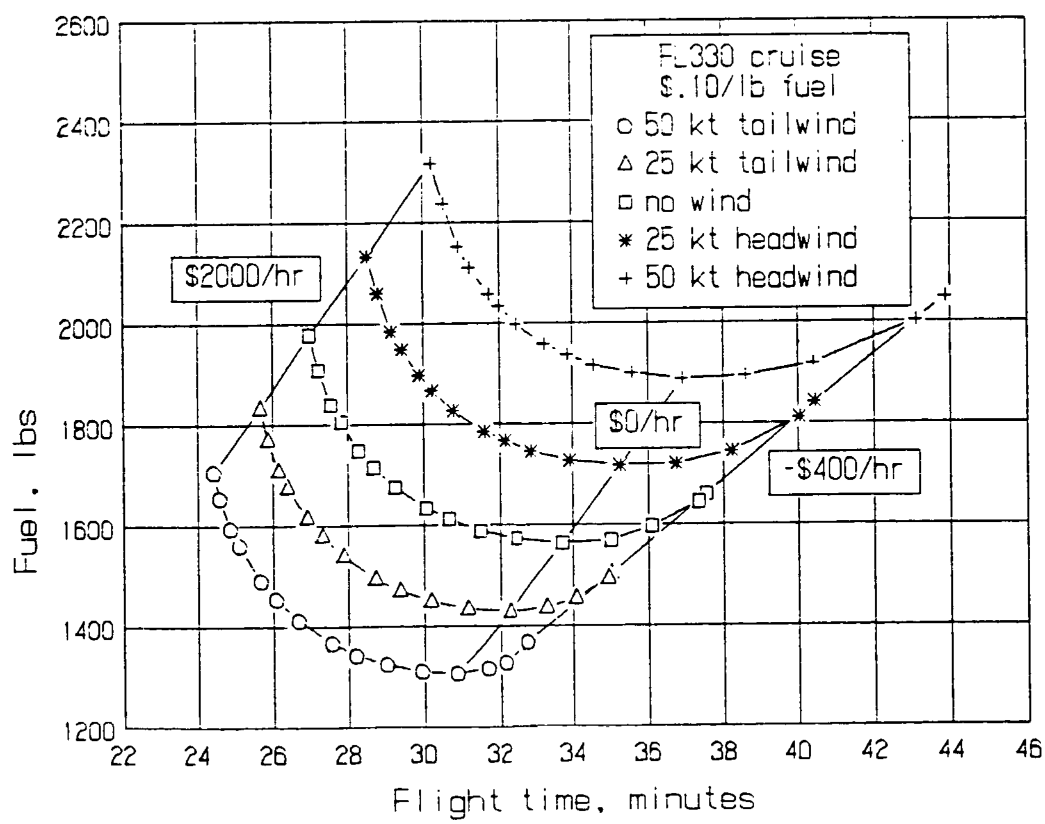


Figure 2.- Optimal fuel versus time for constant winds.
90 000 lb B-737-100, 200 nautical mile cruise/descent.

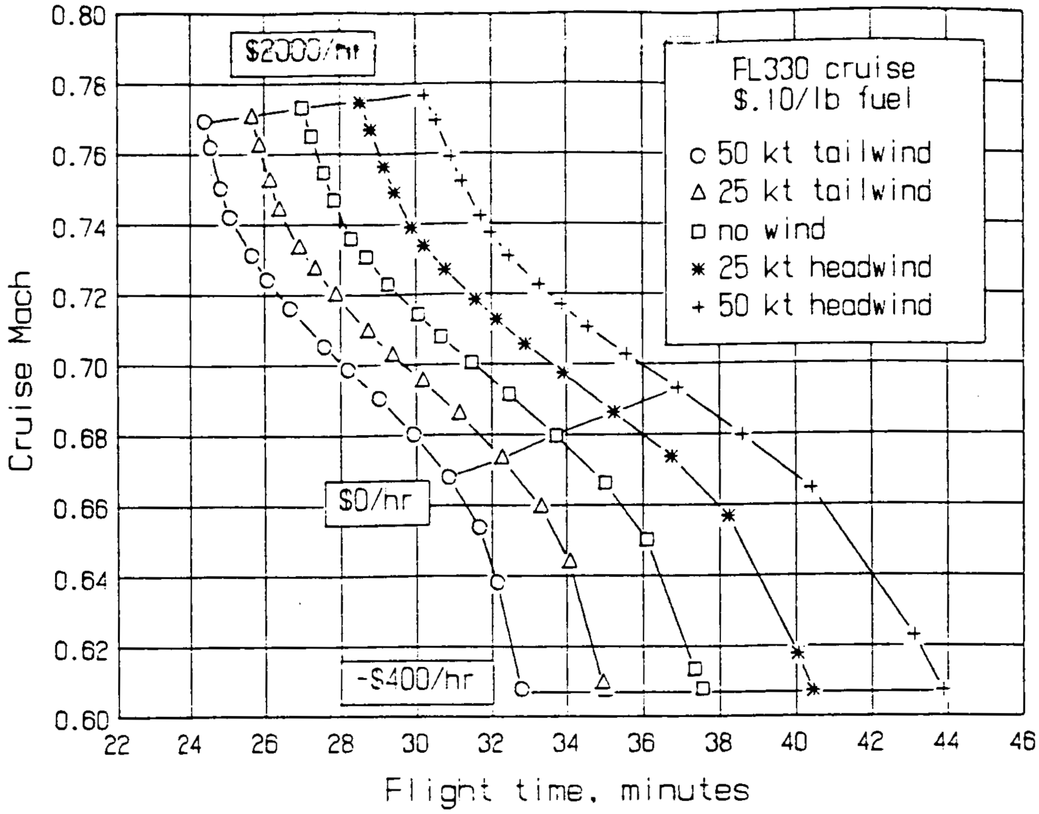


Figure 3.- Optimal cruise Mach for constant winds.
90 000 lb B-737-100, 200 nautical mile cruise/descent.

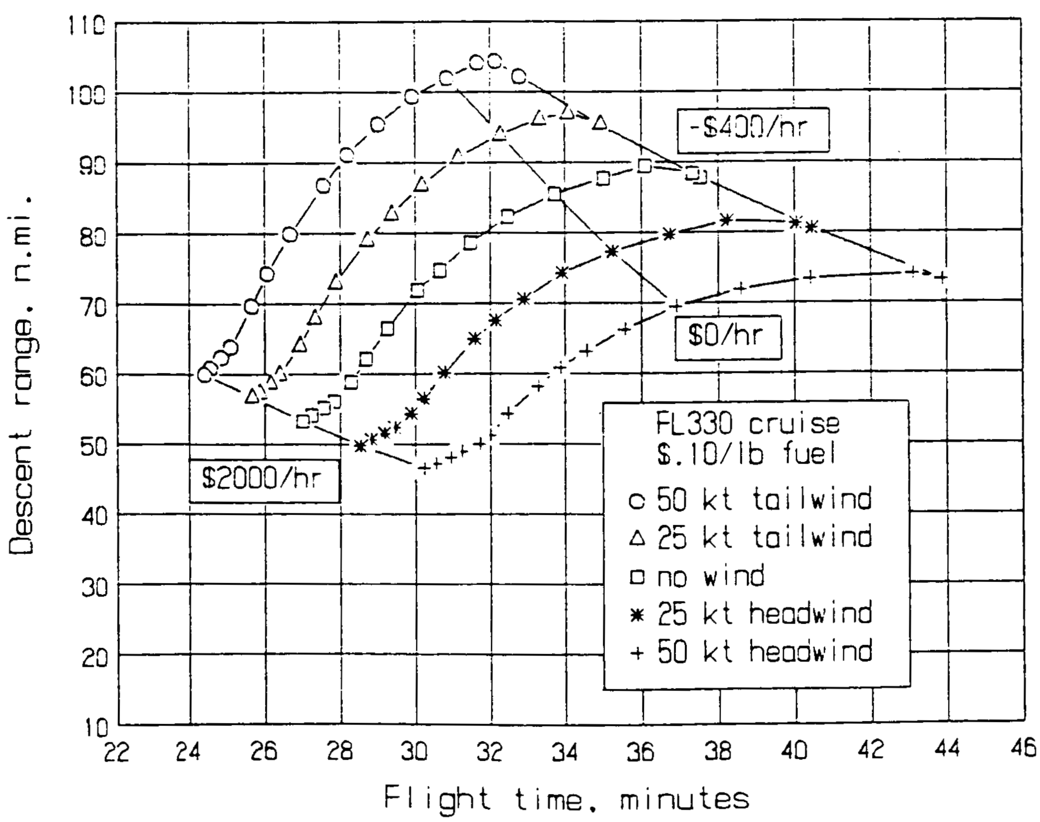


Figure 4.- Optimal descent range for constant winds.
90 000 lb B-737-100, 200 nautical mile cruise/descent.

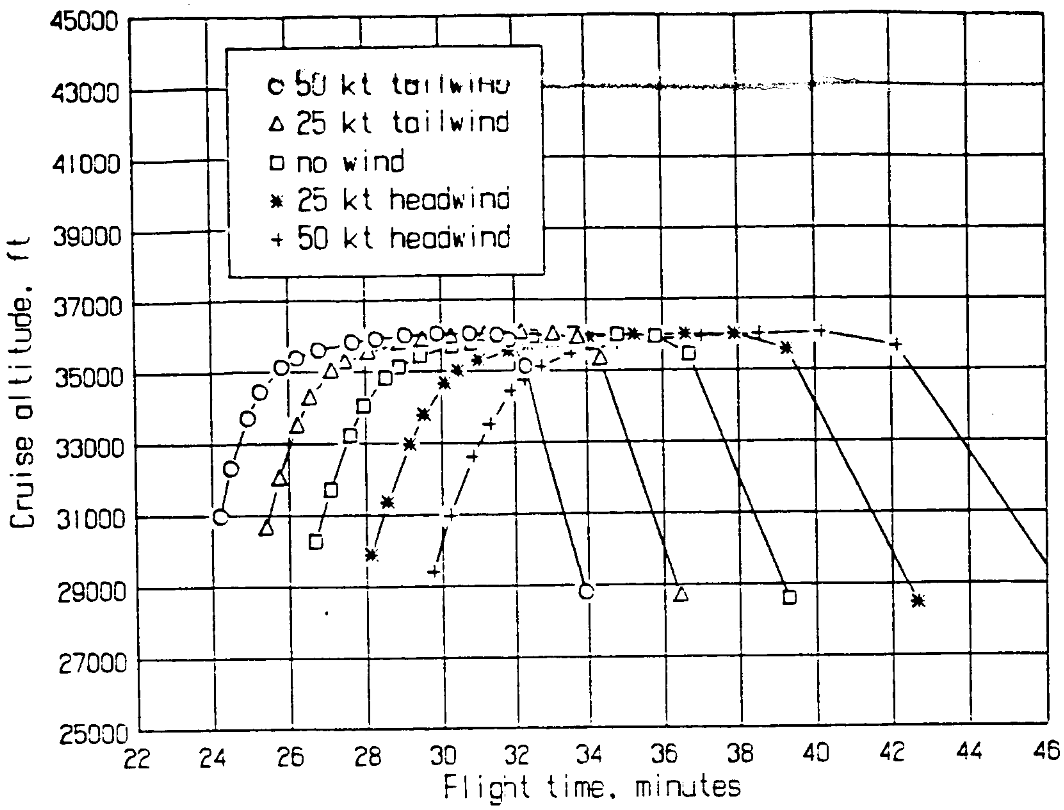


Figure 5.- Optimal cruise altitude for constant wind.
90 000 lb B-737-100, 200 nautical mile cruise/descent.

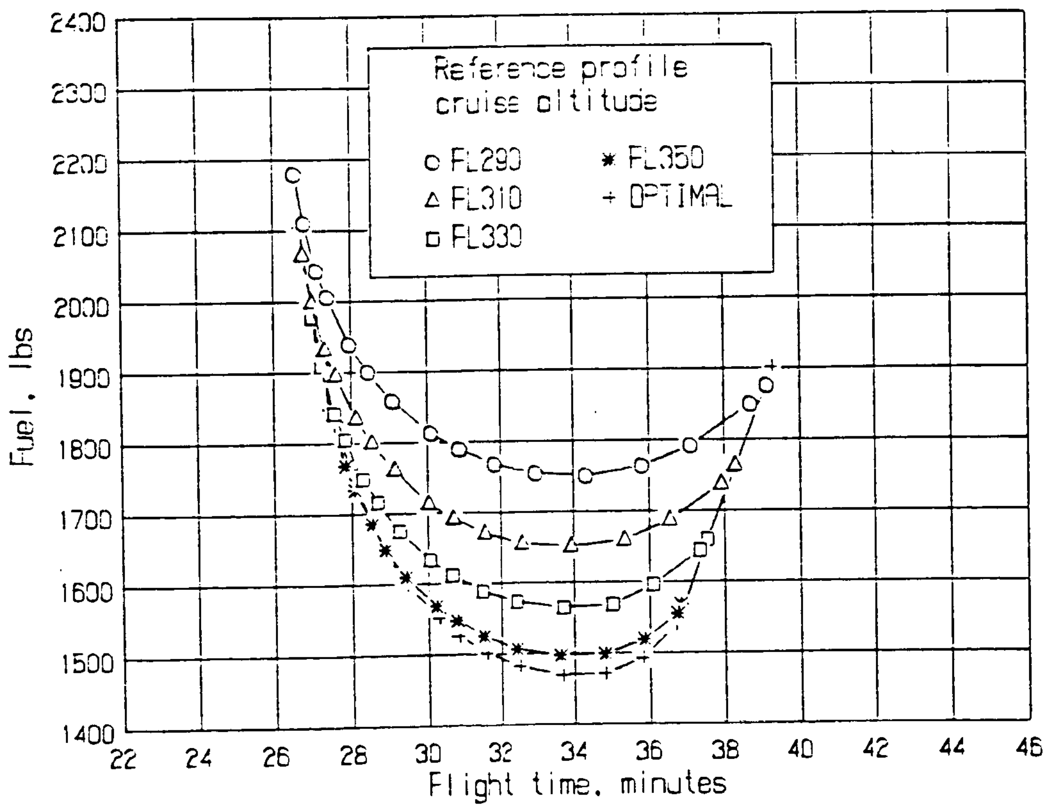
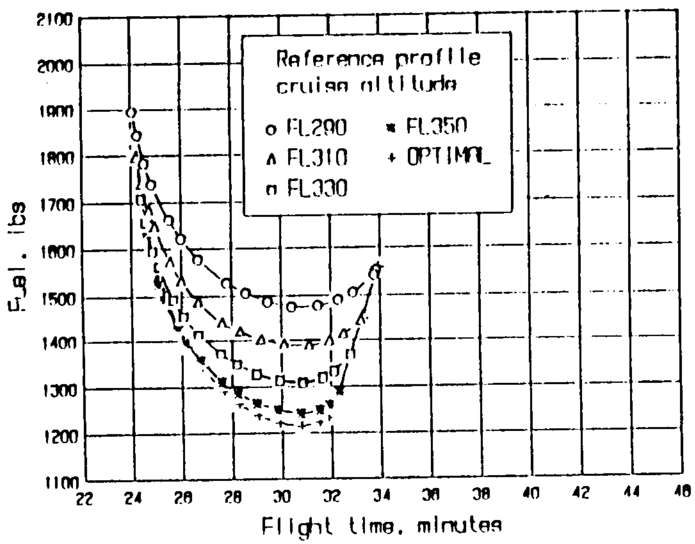
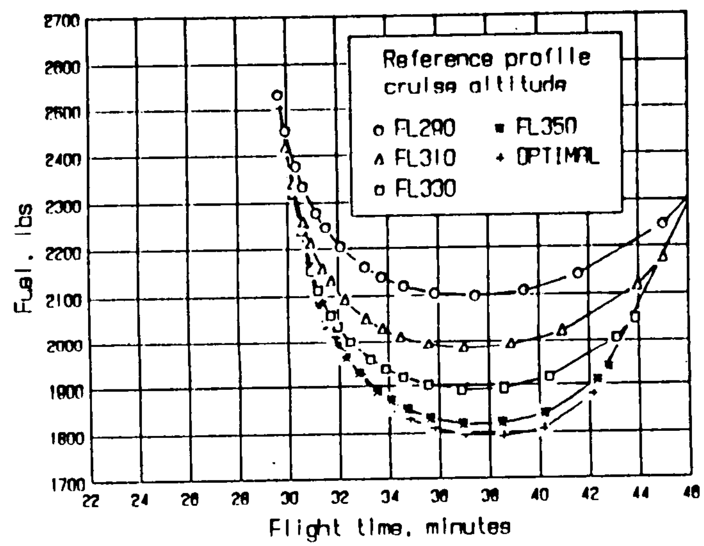


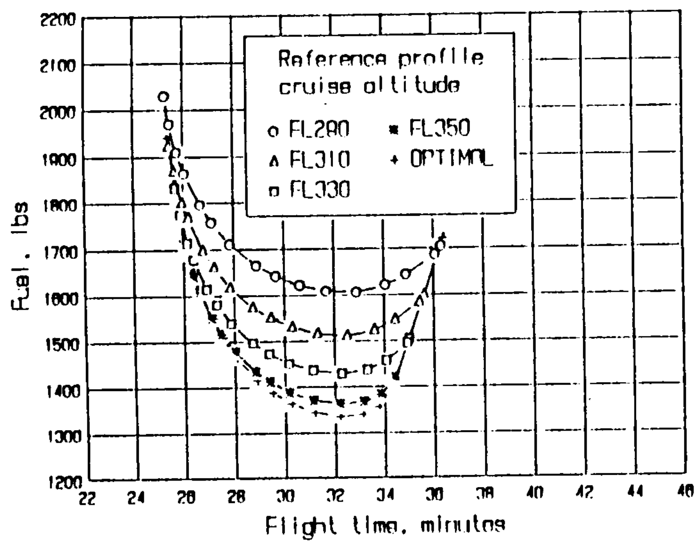
Figure 6.- Optimal fuel versus flight time for no wind.
90 000 lb B-737-100, 200 nautical mile cruise/descent.



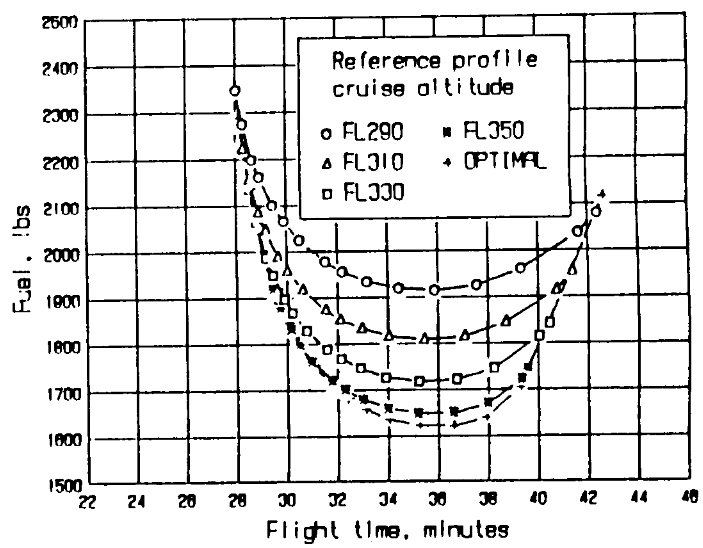
b) 50 knot modeled tailwind.



d) 50 knot modeled headwind.



a) 25 knot modeled tailwind.



c) 25 knot modeled headwind.

Figure 7.- Optimal fuel versus flight time for constant modeled wind.
90 000 lb B-737-100, 200 nautical mile cruise/descent.

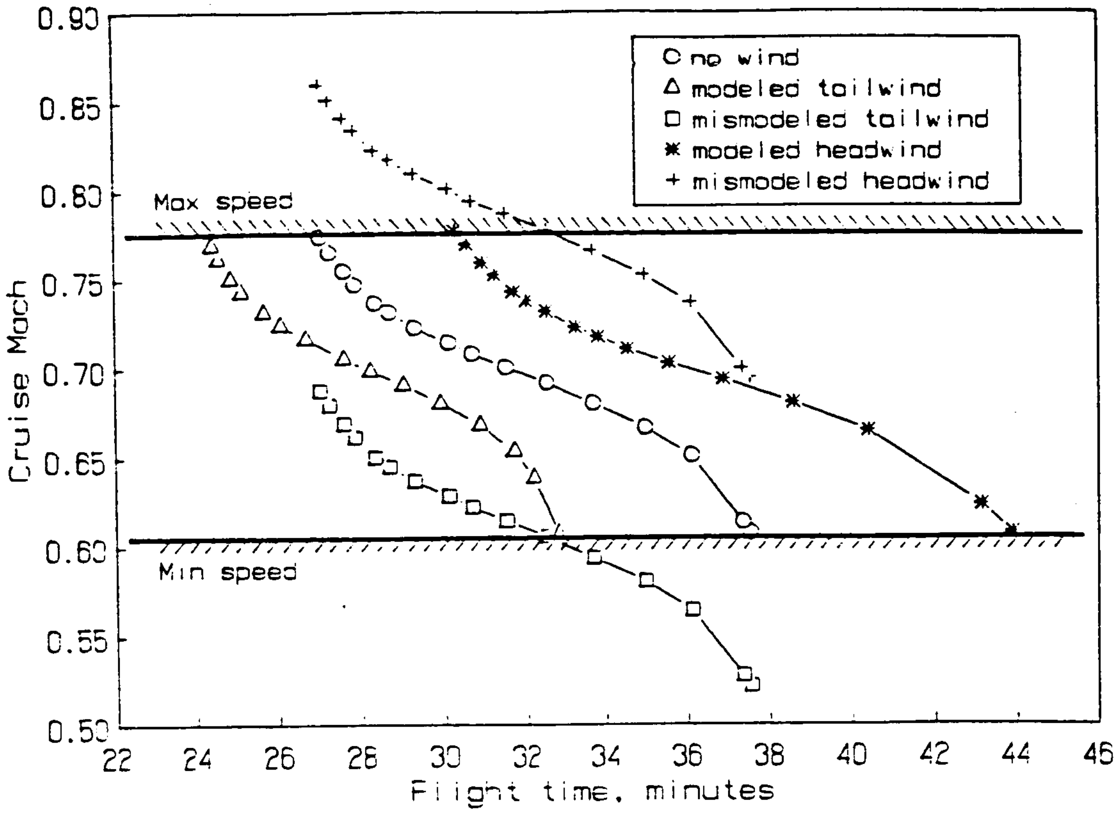


Figure 8.- Cruise Mach in modeled and mismodeled 50 knot wind. 90 000 lb B-737-100, 200 nautical mile cruise/descent.

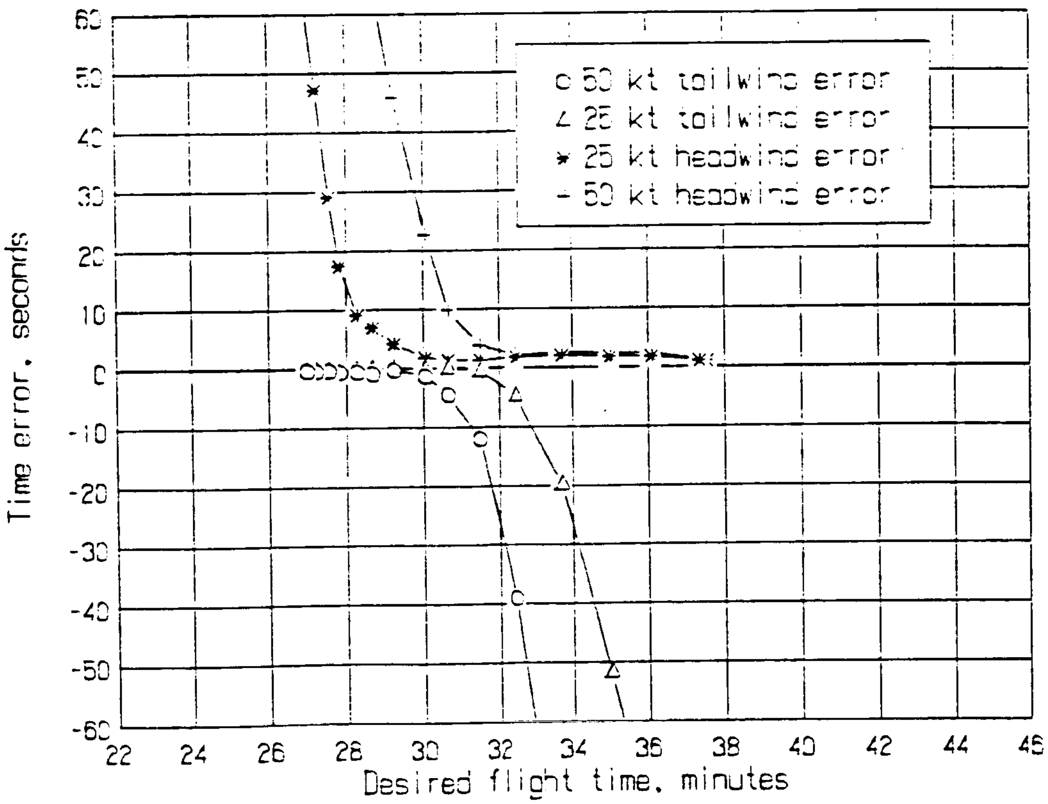
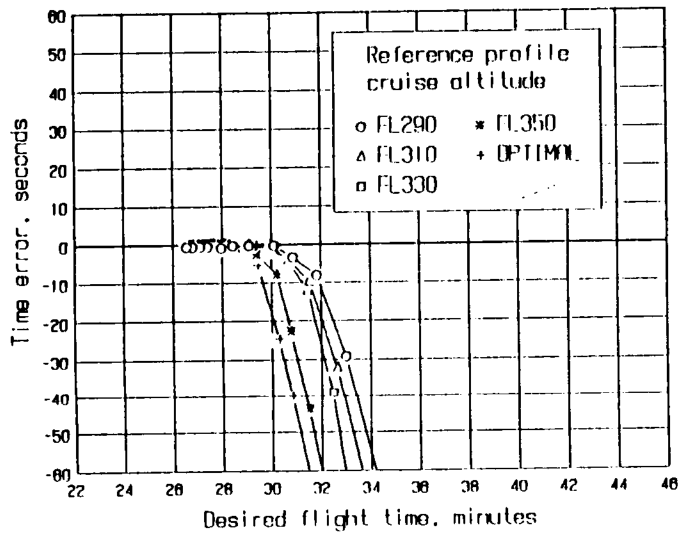
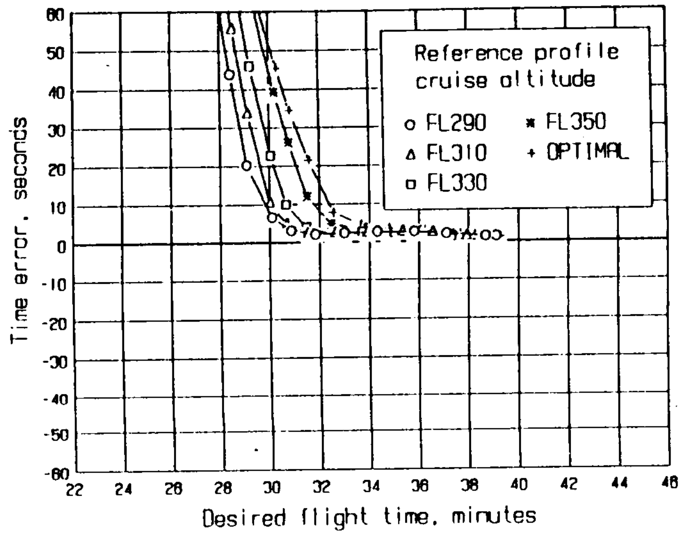


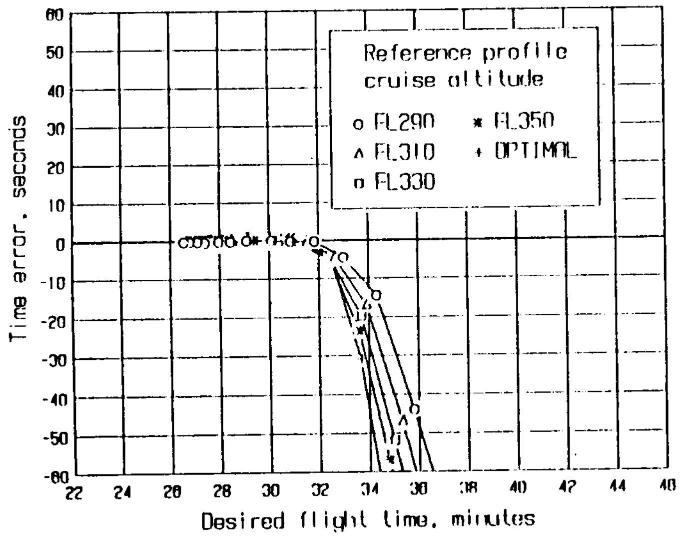
Figure 9.- Time error versus flight time for mismodeled wind. 90 000 lb B-737-100, 200 nautical mile cruise/descent.



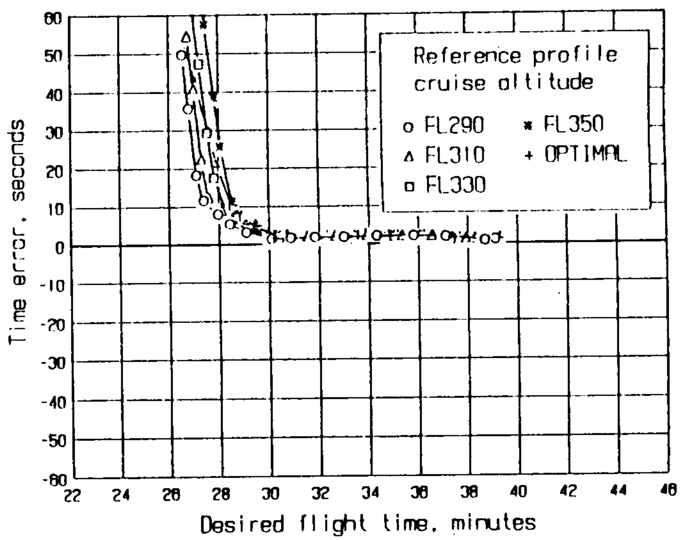
b) 50 knot tailwind error.



d) 50 knot headwind error.



a) 25 knot tailwind error.



c) 25 knot headwind.

Figure 10.- Time error versus desired flight time for constant wind error. 90 000 lb B-737-100, 200 nautical mile cruise/descent.

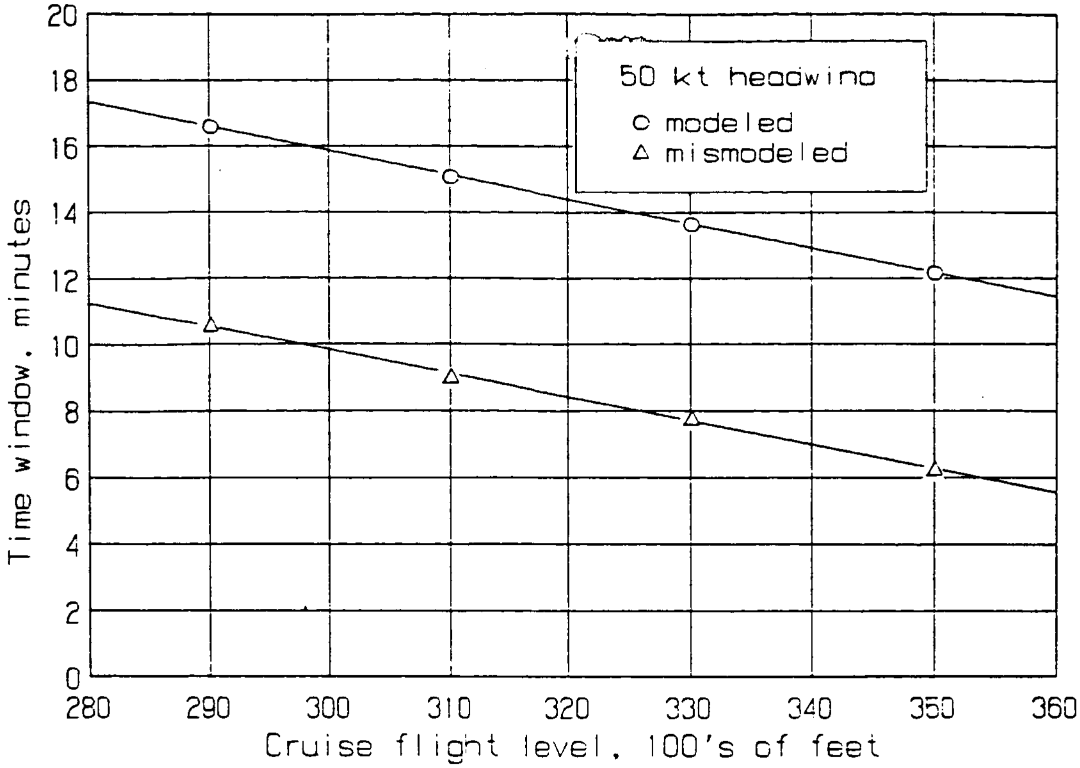


Figure 11.- Cruise altitude effect on available time window for modeled and mismodeled 50 kt headwind. 90 000 lb B-737-100, 200 nautical mile cruise/descent.

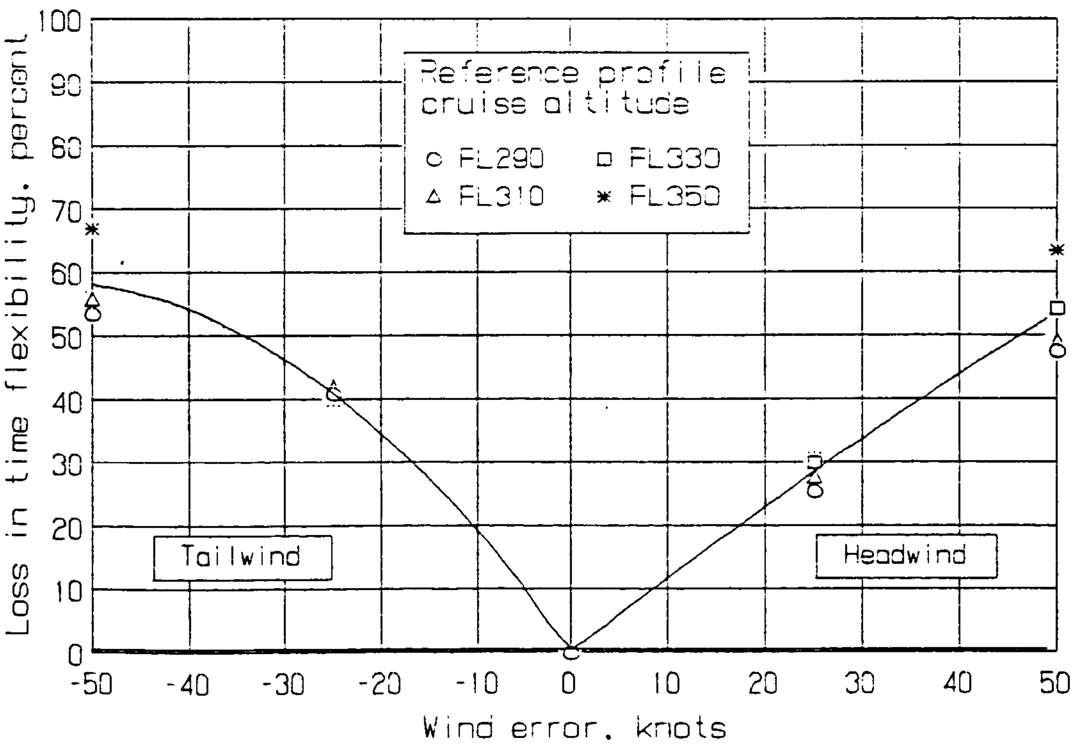


Figure 12.- Loss in time flexibility versus wind error. 90 000 lb B-737-100, 200 nautical mile cruise/descent.

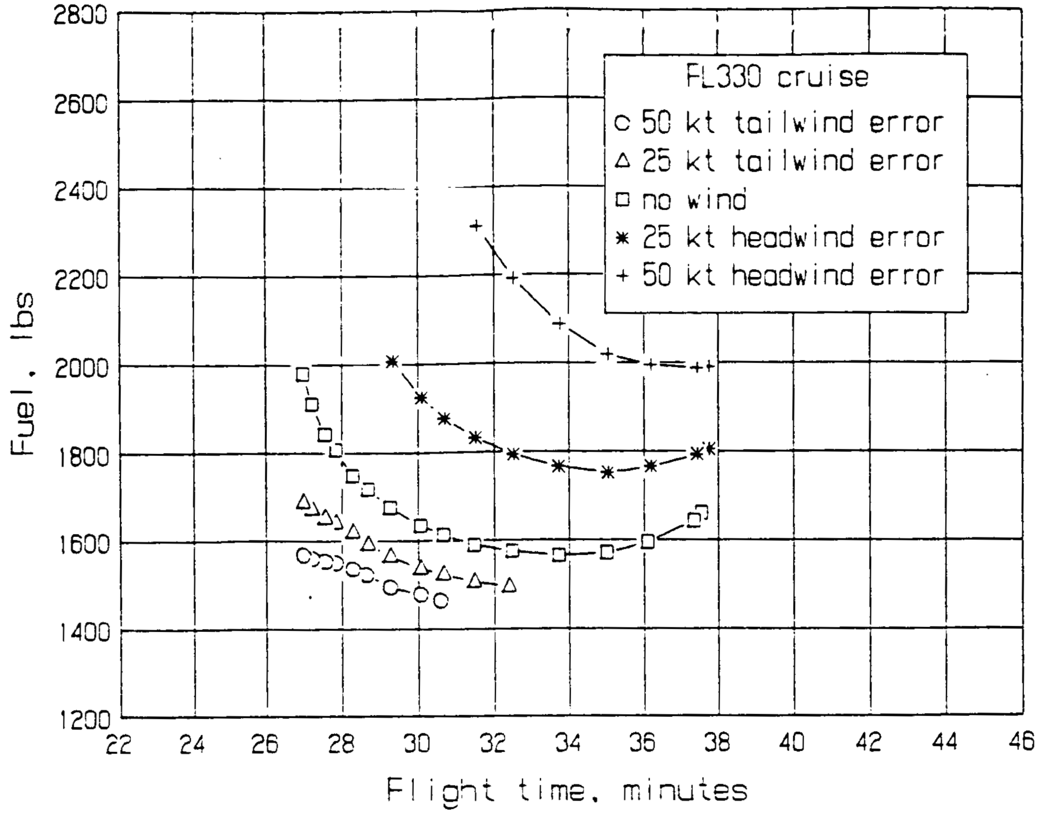


Figure 13.- Fuel versus flight time for mismodeled winds. 90 000 lb B-737-100, 200 nautical mile cruise/descent.

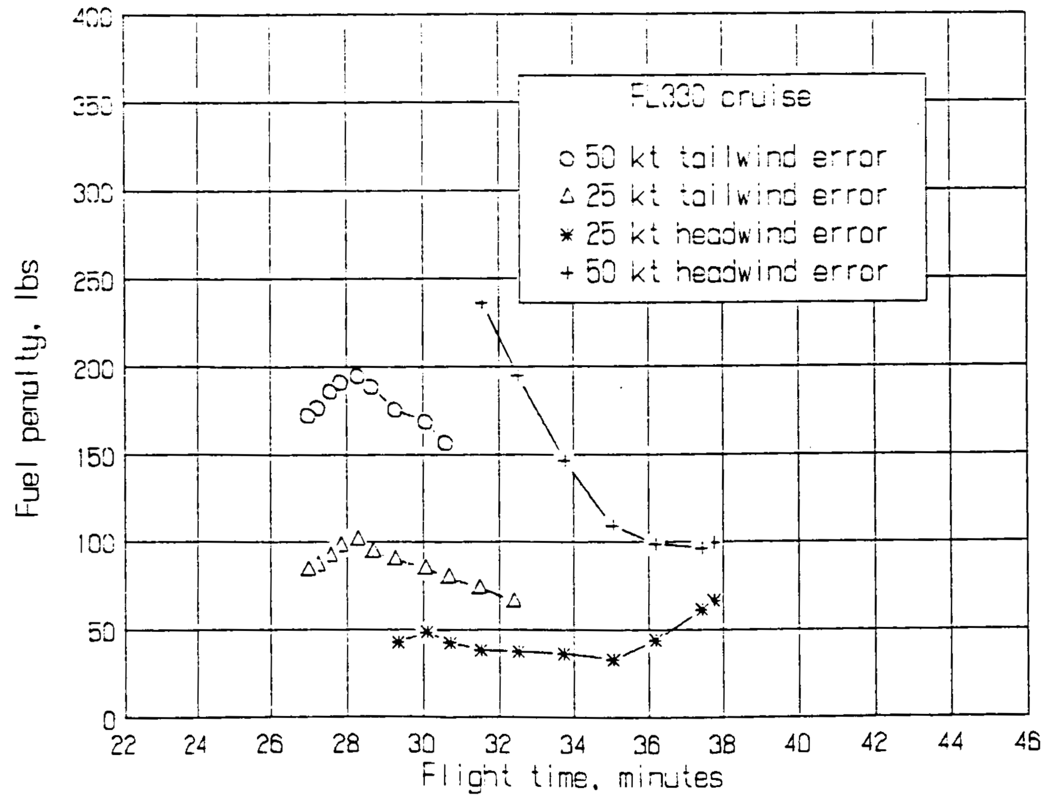
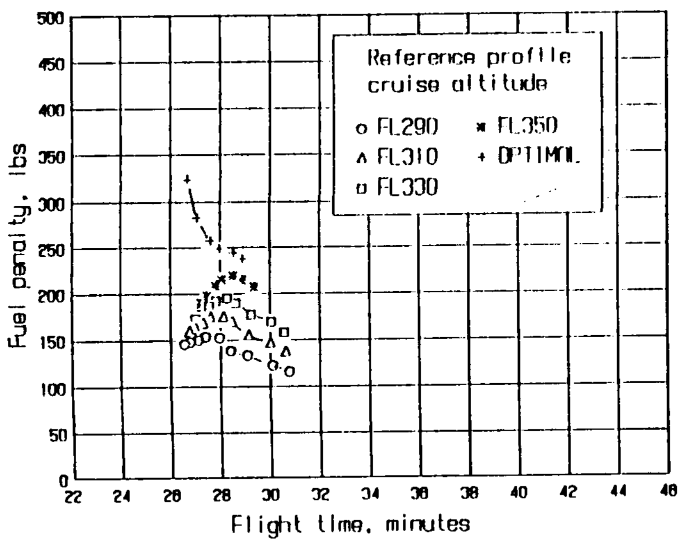
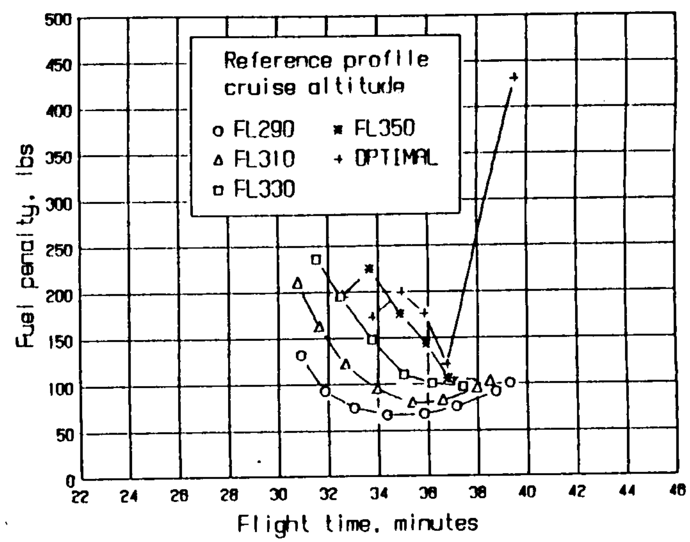


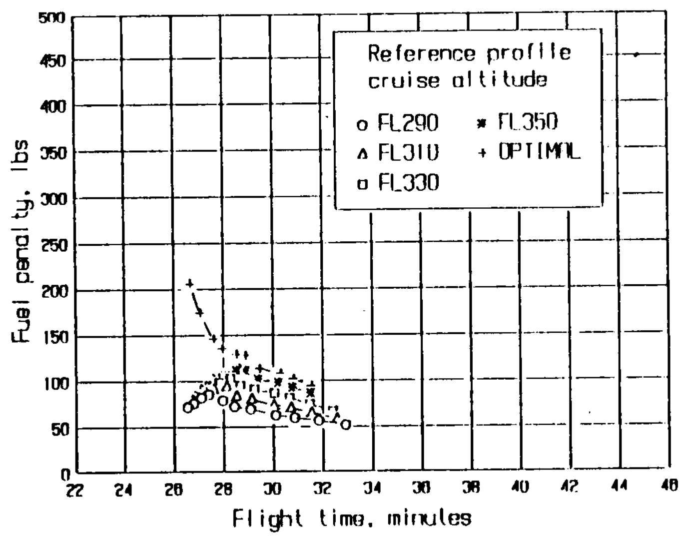
Figure 14.- Fuel penalty versus time for mismodeled wind. 90 000 lb B-737-100, 200 nautical mile cruise/descent.



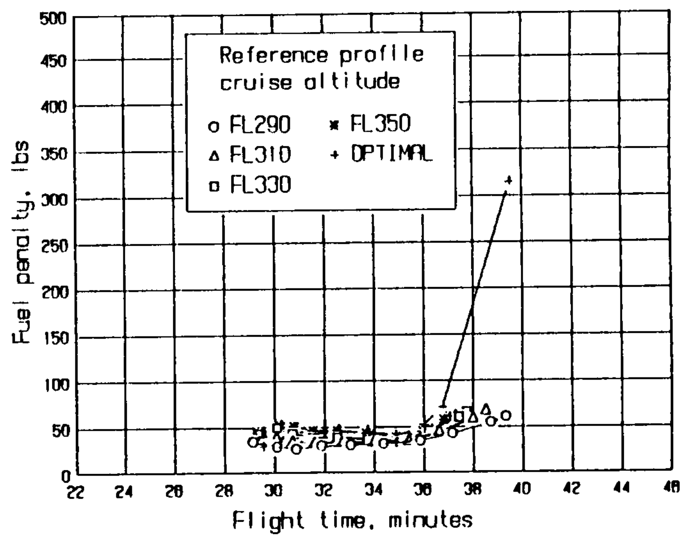
b) 50 knot tailwind error.



d) 50 knot headwind error.



a) 25 knot tailwind error.



c) 25 knot headwind error.

Figure 15.- Fuel penalty versus flight time for constant wind error.
90 000 lb B-737-100, 200 nautical mile cruise/descent.

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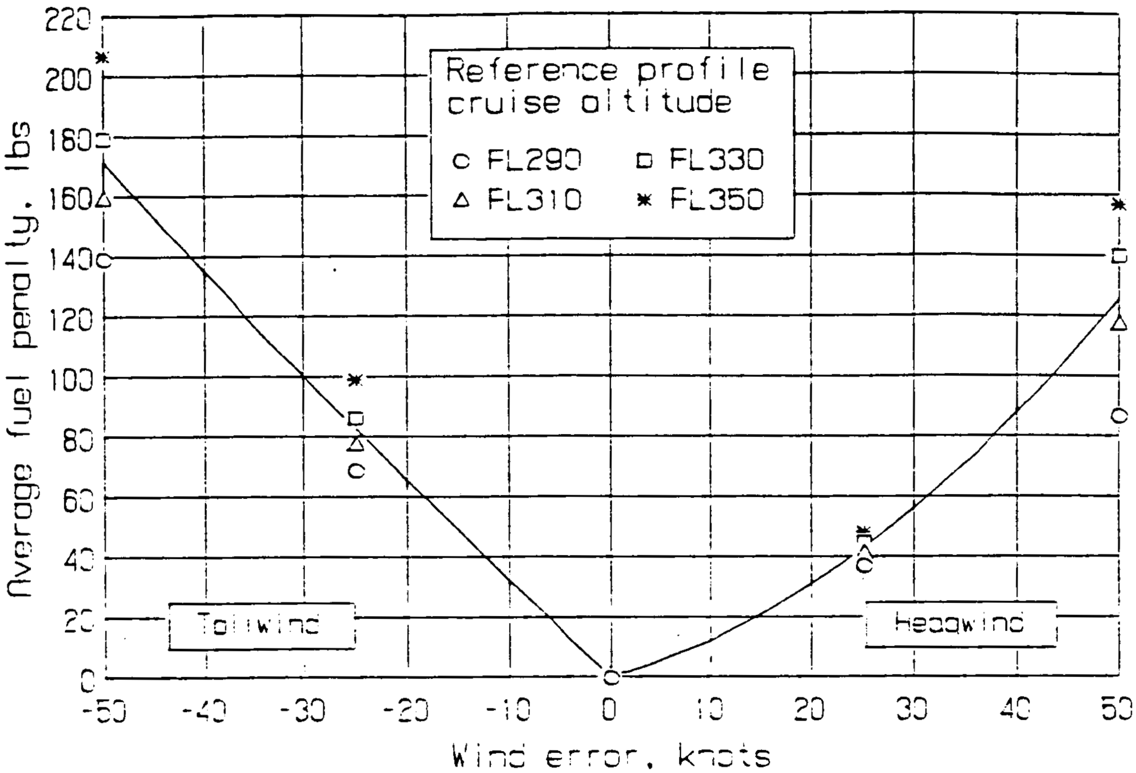

Figure 16.- Average fuel penalty versus wind error.
90 000 lb B-737-100, 200 nautical mile cruise/descent.

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16. Abstract

A parametric sensitivity study was conducted to evaluate time flexibility and fuel penalties associated with 4D operations in the presence of mismodeled wind. The final cruise and descent segments of a flight in an advanced time-metered air traffic control environment were considered. Optimal performance of a B-737-100 airplane in known, constant winds was determined. Performance in mismodeled wind was obtained by tracking no-wind reference profiles in the presence of actual winds. The results of the analysis are presented in terms of loss of time flexibility and fuel penalties compared to the optimal performance in modeled winds.

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