APPLICATION OF FUEL/TIME MINIMIZATION TECHNIQUES TO ROUTE PLANNING AND TRAJECTORY OPTIMIZATION

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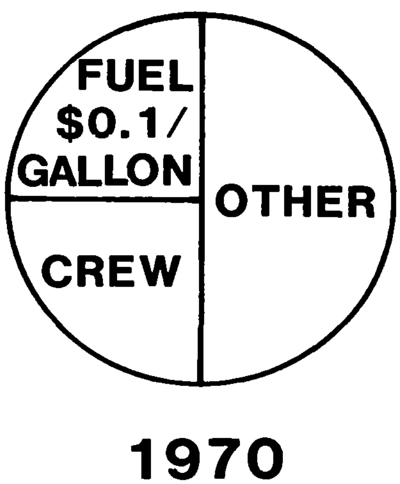
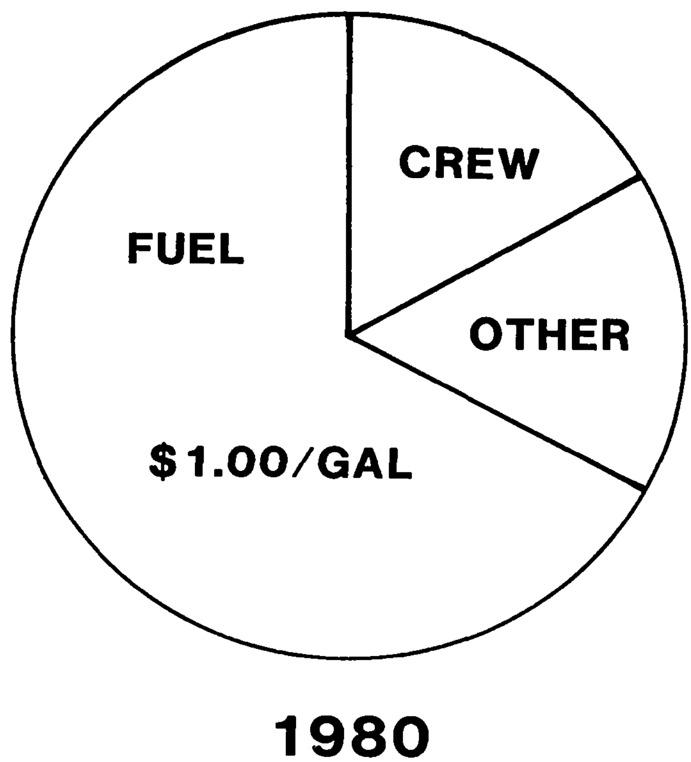
ABSTRACT

Rising fuel costs combined with other economic pressures have resulted in industry requirements for more efficient air traffic control and airborne operations. NASA has responded with an on-going research program to investigate the requirements and benefits of using new airborne guidance and pilot procedures that are compatible with advanced air traffic control systems and that will result in more fuel efficient flight. This paper summarizes the results of flight testing an airborne computer algorithm designed to provide either open-loop or closed-loop guidance for fuel efficient descents while satisfying time constraints imposed by the air traffic control system. The paper will also describe some of the potential cost and fuel savings that could be obtained with sophisticated vertical path optimization capabilities.

DIRECT OPERATING COST

Between 1970 and 1980, the average price paid by airlines for fuel rose approximately 1000%. In 1970, fuel costs represented about 25% of the flights' direct operating costs. In 1980, this percentage rose to between 60 and 70 percent. In addition, inflation has caused crew costs and other non-fuel airline operating costs to increase. These increased operating costs combined with lower revenue levels arising from recessionary trends in the economy have led to an emphasis on achieving more economical operations through changes in procedures, flight operations, airborne equipment capability, and in air traffic control (ATC) operations.

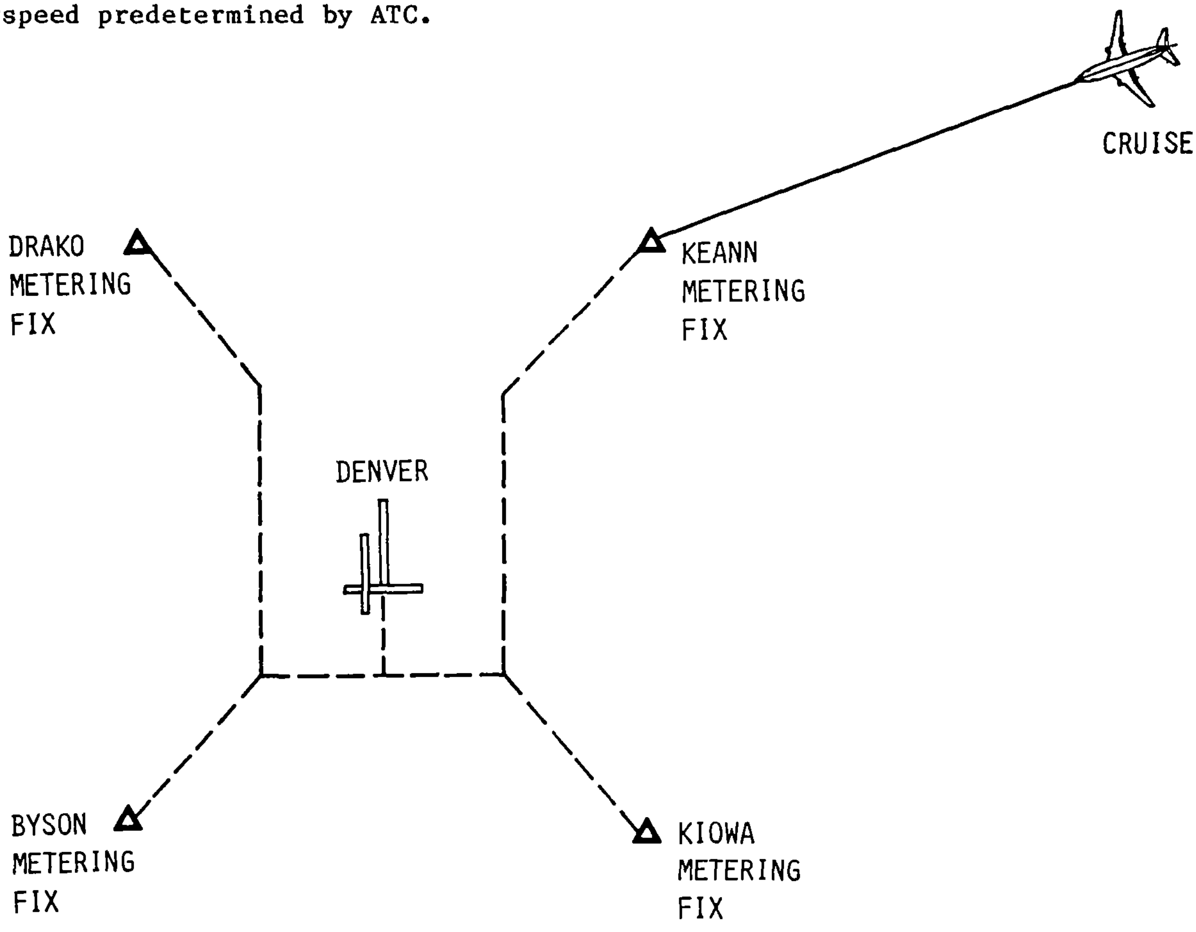




TIME-BASED METERING PROCEDURES

In response to the fuel crisis, the Federal Aviation Administration developed several programs to save fuel including an automated time-based metering (TMB) form of air traffic control for arrivals into the terminal area. This TBM concept provides fleet-wide (all users) fuel savings through time control by matching the airplane arrival rate into the terminal area to the airport's arrival acceptance rate. This procedure reduces the need for holding and for low-altitude vectoring for sequencing to land. Fuel savings are also achieved on an individual airplane basis by permitting the pilot to descend at his discretion from cruise altitude to a designated metering fix in a fuel-efficient manner. Substantial fuel savings have resulted but air traffic control workload is high since the radar controller maintains time management for each airplane through either speed commands or path stretching with radar vectors. Pilot workload is increased since the pilot must plan for a fuel-efficient descent usually by using various rules of thumb.

NASA has flight-tested in its Transportation System Research Vehicle (TSRV) Boeing B-737 airplane a flight management descent algorithm designed to increase fuel savings by reducing the time dispersion of airplanes crossing the metering fix at an ATC-designated time by transferring the responsibility of time navigation from the radar controller to the flight crew. Time and path (4-D) closed-loop guidance were provided to the pilot for an idle-thrust, clean-configured, constant Mach descent with transition to a constant airspeed descent to arrive at the metering fix at a time, altitude, and airspeed predetermined by ATC.



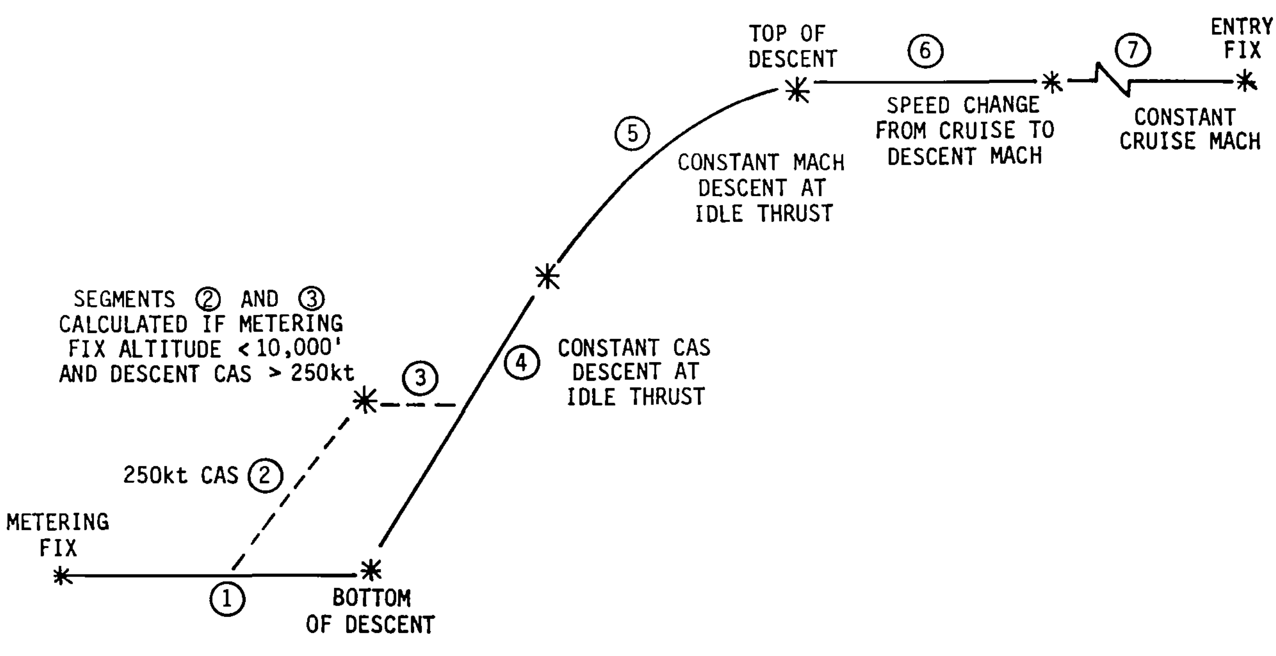
AIRBORNE COMPUTED DESCENT PATH

The NASA airborne flight management descent algorithm computes the parameters required to describe a seven-segment cruise and descent profile between an arbitrarily located entry fix to an ATC-defined metering fix. (Segments 2 and 3 are computed if the flight will be restricted by the ATC 250 knot airspeed limit below 10,000 feet.) The computed parameters are then used by the airplane's navigation and display systems to present guidance to the pilot and/or autopilot.

The descent profile is based on linear approximations of airplane performance for an idle-thrust, clean-configured descent. Airplane gross weight, wind, and nonstandard temperature and pressure effects are also considered in these calculations. To be compatible with standard airline operating practices, the path is calculated based upon the descent being flown at a constant Mach number with transition to a constant calibrated airspeed and speed changes being flown at a constant altitude.

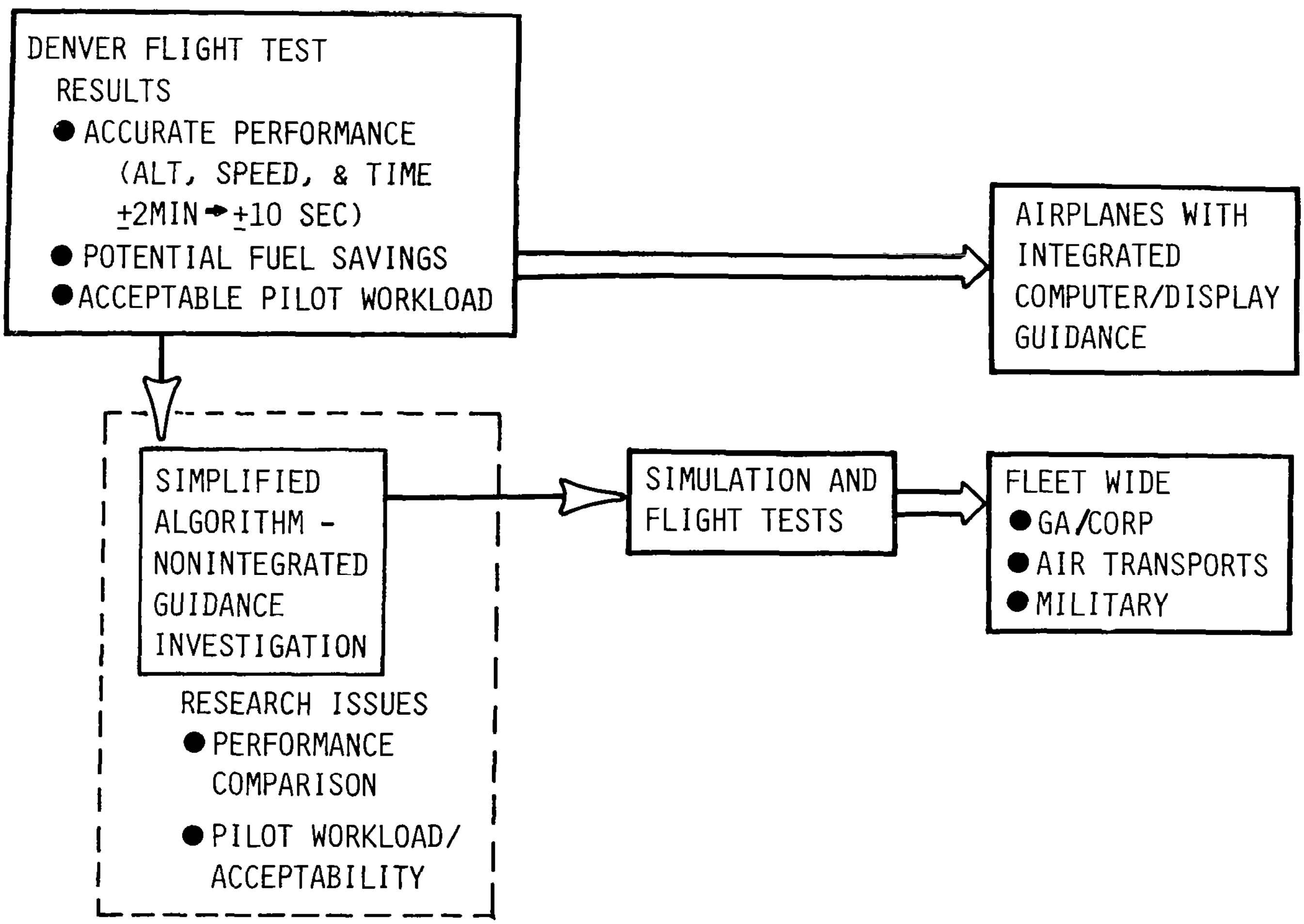
The flight management descent algorithm may be used in either of two modes. In the first mode, the pilot may input the Mach/airspeed descent schedule to be flown, and the descent profile is calculated independent of an assigned metering fix time. If a metering fix time is subsequently assigned, some time error, which must be nulled by the pilot, may result since an arbitrary specification of the descent speed schedule may not satisfy both the initial and final time boundary conditions.

The second mode was designed for time-metered operations. In this mode, pilot inputs include the estimated time of arrival to the entry fix and the ATC specified metering fix arrival time. The descent profile is then calculated based on a Mach/airspeed descent schedule, computed through an iterative process, that will closely satisfy the crossing times for both of these way points.



RESULTS AND FUTURE INVESTIGATION

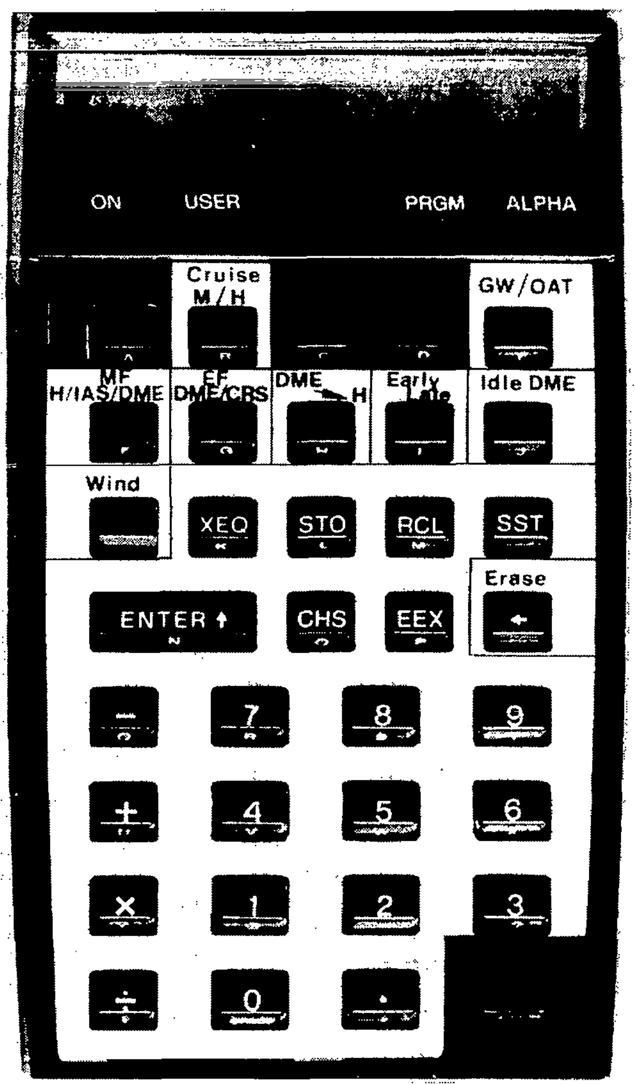
Research flight tests of the NASA flight management descent algorithm in the Denver Air Route Traffic Control Center time-based metered air traffic environment demonstrated that time guidance and control in the cockpit were acceptable to both the pilots and the ATC controllers. Descent guidance presented on the airborne CRT flight instrumentation allowed the test airplane to be flown across the metering fix at the proper altitude and speed and significantly reduced the time dispersion occurring with other airplanes at the metering fix. The concept of closed-loop guidance time control in the cockpit could be readily extended, with similar results, to other aircraft with integrated electronic navigation and guidance/display systems. However, many airplanes flying in the time-based metering ATC environment do not have these integrated electronic guidance and display systems. This research was then extended to provide the pilots of unequipped airplanes with simplified open-loop 4-D guidance. The issues in this research are a trade-off between performance and pilot workload and acceptance.



PROFILE DESCENT HAND-HELD CALCULATOR

To determine the feasibility of providing open-loop guidance to the flight crew to make fuel-conservative, time-constrained descents to the metering fix, the NASA descent algorithm was programmed on a small, hand-held programmable calculator. All inputs required by the algorithm are made by the pilot through the keyboard. All outputs are shown in the calculator display.

Flight tests conducted with NASA test pilots in a T-39A (Sabreline) airplane indicated that it was feasible to fly the descents with open-loop guidance provided to the pilot in the form of a DME indication to define the top-of-descent point and the appropriate Mach and airspeed indications to use during the descent. The resulting mean distance and time errors to actually achieve the predicted speed and altitude conditions at the end of the descent profile were 1.2 n. mi. long and 1.4 seconds early. A question remained, however, if open-loop guidance provided by a hand-held calculator would be pilot acceptable in an operational environment.



PROFILE DESCENT HAND-HELD CALCULATOR
UNITED AIRLINES FLIGHT TESTS

Joint flight tests were conducted with United Airlines to determine if the concept of using open-loop guidance for fuel-conservative descents with a hand-held calculator during routine flight operations was acceptable to the pilots. The results of these tests showed that the majority of the pilots participating in the tests felt that the open-loop guidance concept of the calculator provided useful information. Several test subjects felt that they could mentally compute the top-of-descent point and would not save additional fuel through use of the calculator. However, all of the test subjects agreed that the computations necessary to satisfy the metering fix crossing time constraints were too difficult for mental calculation and would require other means (such as the calculator) to provide guidance. All subjects agreed that the workload associated with using the calculator was low and would not interfere with normal crew tasks.

All of the test subjects expressed a concern that the ATC system would not allow them to fly a preplanned descent without being interrupted and thus suffer a fuel penalty. This concern was realized during these flight tests: 68% of the descents were modified with altitude restrictions or speed restrictions by ATC and required recomputation of the descent profile. This statistic emphasizes the requirement that compatibility must exist between the airborne and ground systems to realize significant fuel conservation.

- TEST RESULTS:

  CONCEPT WAS ACCEPTABLE TO PILOTS

  - HELPFUL TO CREW FOR DESCENT PLANNING
  - WORKLOAD LOW--DID NOT INTERFERE WITH NORMAL CREW TASKS
  - INITIAL TRAINING REQUIRED LESS THAN ONE HOUR

- PERFORMANCE RESULTS--16 DESCENTS

TIME ERROR SEC.		DISTANCE ERROR N. MI.
1 EARLY	MEAN	1.7
20.8	σ	2.1
39 EARLY	MAX	6.4

ADVANCED FLIGHT MANAGEMENT CONCEPTS

The NASA flight management research activities also include defining the interface and guidance requirements necessary for practical implementation of sophisticated optimal path trajectory calculations. One of the corner stones of this research effort is the "OPTIM" computer program. This program generates a full vertical path profile including climb, cruise, and descent based upon one of three selectable objectives: minimum cost, minimum fuel, or fixed time/minimum fuel.

The OPTIM computed profile is generated from solutions of an energy state approach in which range and specific energy are used to describe aircraft state. A cost functional, which expresses the quantity (fuel or operating cost) which is to be minimized, is combined with the aircraft state equations to form a Hamiltonian with energy as the independent variable. As energy is incremented along the trajectory, airspeed and thrust are chosen to minimize the Hamiltonian. In this manner a complete vertical profile is generated along a pre-specified horizontal path.

This program presently is being used in a fast-time mode to examine parametric sensitivities and to define potential fuel and cost savings. The program has also been implemented into a real-time piloted simulation to define interface requirements between the pilot, the airborne guidance systems, and the ground-based ATC systems to ensure compatibility and efficiency.

"OPTIM" GENERATES VERTICAL FLIGHT PROFILES THAT MINIMIZE DOC AND SATISFY EXTERNALLY IMPOSED TIME CONSTRAINTS

- MINIMUM COST
- MINIMUM FUEL
- FIXED TIME, MINIMUM FUEL

- FAST-TIME ANALYSIS
  - PARAMETRIC SENSITIVITY
  - FLIGHT PLANNING TOOL
  - DEFINE POTENTIAL TRIP FUEL AND COST SAVINGS

- REAL-TIME SIMULATION
  - PILOT/AIRPLANE SYSTEMS INTERFACE REQUIREMENTS FOR PRACTICAL OPTIMAL FLIGHT PATHS
  - INTERFACE REQUIREMENTS TO ENSURE A/G COMPATIBILITY AND EFFICIENCY

DIRECT OPERATING COST MINIMIZATION

The direct operating cost (DOC) function used in the OPTIM program is a function of the cost of operation per hour K_1 and the cost per pound of fuel K_2. The geometry (speed, altitude, and flight path angle) of the trajectory is a function of the ratio of K_1 and K_2 rather than the absolute magnitudes. The selection of the value of fuel cost is relatively straightforward. However, the selection of the operating costs per hour is much more complex to establish. These costs must be truely time variant costs rather than cyclic costs (i.e., costs associated with take-off and landing are cyclic, not trip time variant). The magnitude of the operating cost may also be biased higher or lower to change trip times (changes airspeed and altitude) to reflect corporate policy. Airline management should select the proper values for K_1 and K_2 to reflect both optimal flight operations and corporate policy for each flight.

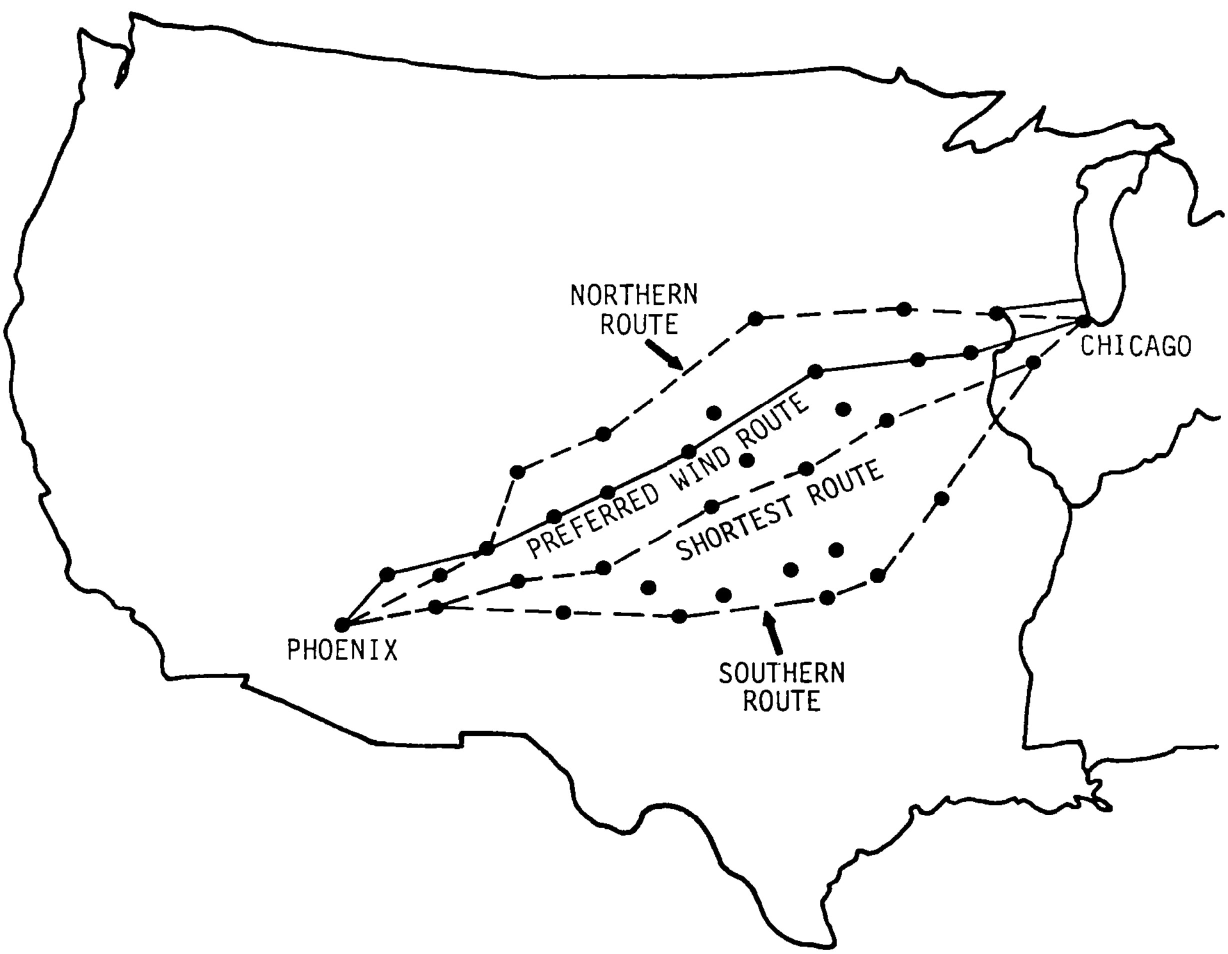
$$\text{DOC} = K_1\,(\text{HOURS}) + K_2\,(\text{FUEL USED})$$

$$K_1 = \$/\text{HOUR} \qquad K_2 = \$/\text{POUND FUEL}$$

- DOC IS A FUNCTION OF K_1 AND K_2
- TRAJECTORY IS A FUNCTION OF THE RATIO OF K_1 AND K_2
- INTERACTIVE SELECTION OF K_1 AND K_2 IS DESIRABLE

An actual flight planning example will illustrate the potential fuel and cost savings that can be achieved by using an optimal path trajectory program like OPTIM. In this example, an airline has 11 different pre-specified routes between Chicago and Phoenix to allow the flight dispatcher to select the most favorable route considering winds and other atmospheric conditions. Typically, a flight dispatcher will choose the highest cruise altitude possible, for the given airplane gross weight and ambient temperature, that is consistent with ATC altitude constraints. For this flight, a route slightly north of the shortest route (designated ATC route) was chosen to take advantage of lower head winds. Even though this route is nine miles longer than the shortest route, the fuel required to complete the trip and the resulting trip cost were reduced since the time to complete the trip was reduced.

TYPICAL CHICAGO - PHOENIX ROUTE STRUCTURE



ORD - PHX ROUTE SELECTION

This figure shows the magnitude of trip time, fuel required, and cost to complete the Chicago to Phoenix trip using a generic commercial tri-jet transport airplane with time variant costs of $600 per hour and fuel costs of 15 cents per pound. The first two cases show a comparison of the trip flown at a cruise altitude of 35,000 feet (chosen by the flight dispatcher) for the shortest distance route and the preferred wind route. By flying the preferred wind route, the trip time was reduced by 3 minutes and 39 seconds resulting in a corresponding decrease of 404 pounds of fuel used and a reduction of $97.10 to the trip cost.

To illustrate how much further trip costs could be reduced, the OPTIM program was run in a minimum cost mode for the preferred wind routing. The results of this run, listed in the third case, indicate that a cruise altitude of 24,000 feet should be used. Even though this lower altitude resulted in more fuel used to complete the trip (742 pounds), the total trip cost was reduced by $147.55 due to a 25 minute 44 second reduction of trip time.

It should be stressed at this point that the trip profile (airspeed and cruise altitude) will change as the time cost and the fuel cost ratio is changed. As time costs are reduced or fuel costs increase, the trip profile will change towards a minimum fuel trajectory.

It was interesting to note that with the OPTIM program run in the minimum cost mode on the ATC preferred route, further trip time, fuel, and cost reductions were obtained. This illustrates the fact that to achieve truly optimal cost and fuel savings, both horizontal and vertical path optimization must be obtained together.

TRI-JET AIRPLANE

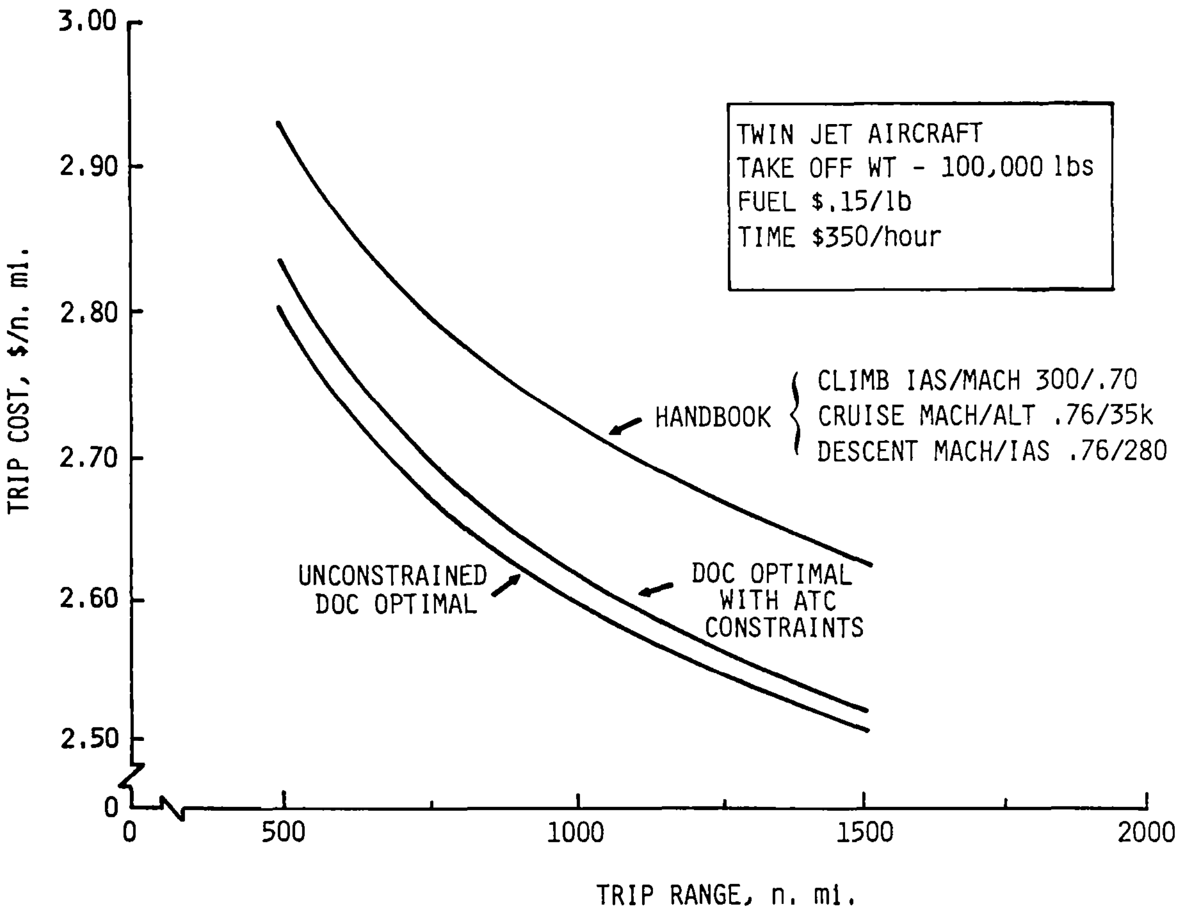
TIME COST $600/HR -- FUEL COST $.15/LB

ROUTE DESCRIPTION	TIME H:M:S	FUEL LB	COST $
1. SHORTEST GROUND DISTANCE (1263 nmi RANGE); CRUISE ALTITUDE 35,000 FT	3:46:04	29,100	6625.75
2. PREFERRED WIND ROUTE (1272 nmi RANGE); CRUISE ALTITUDE 35,000 FT	3:42:25	28,696	6528.65
3. PREFERRED WIND ROUTE (1272 nmi RANGE); CRUISE OPTIM PROFILE (~24,000 FT)	3:16:41	29,438	6381.10
4. SHORTEST GROUND DISTANCE (1263 nmi RANGE); CRUISE OPTIM PROFILE (~24,000 FT)	3:15:01	29,134	6320.37

TRIP COST COMPARISON

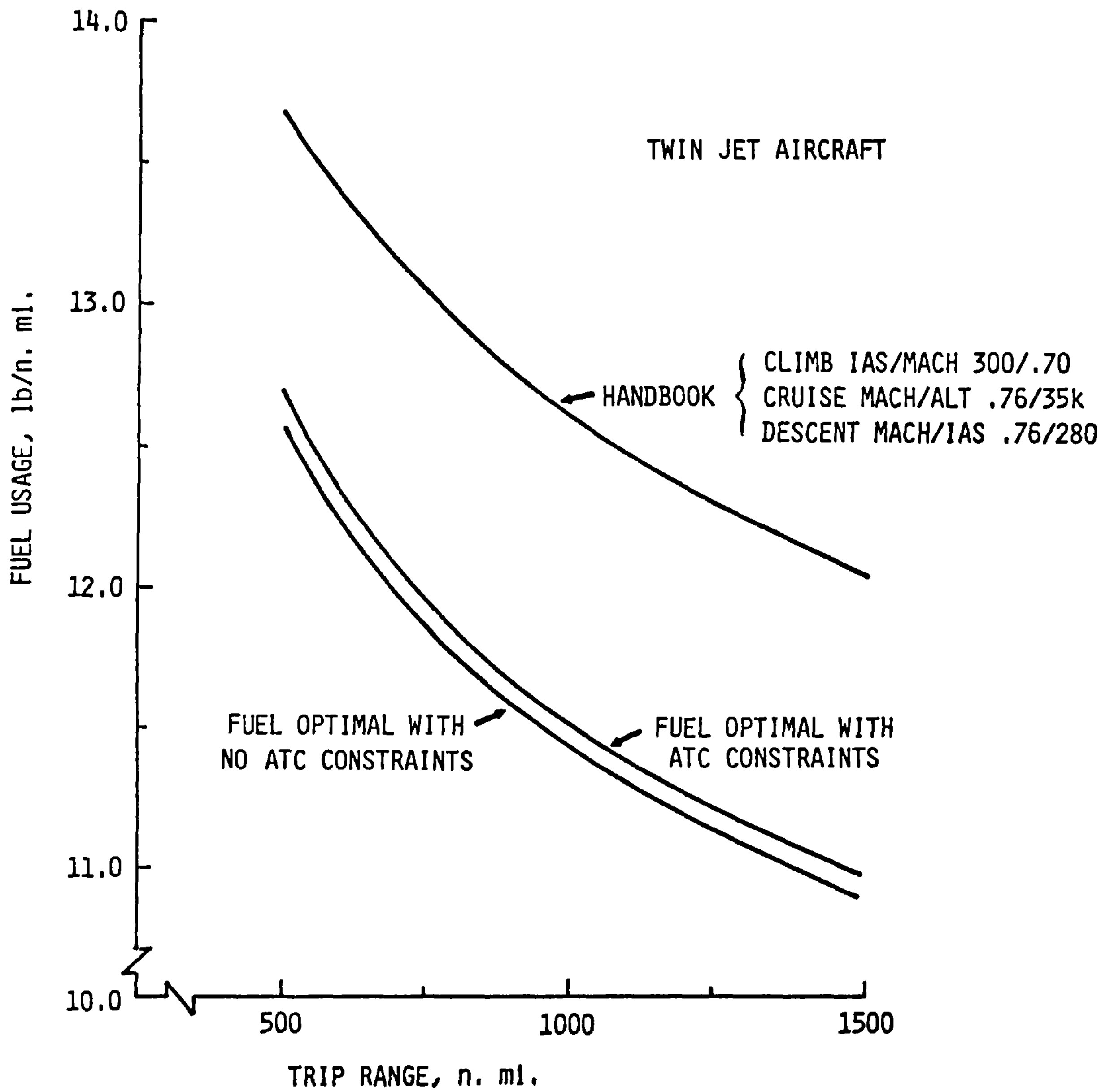
This figure shows trip cost expressed in \$/mile as a function of trip length for a generic commercial twin-jet transport airplane operating on three different vertical profiles. The three profiles presented are a standard handbook profile, a minimum cost profile which satisfies current ATC vertical path constraints, and an unconstrained minimum cost profile. The minimum cost profiles each represent a significant savings relative to the handbook profile which calls for a constant airspeed/Mach climb, cruise at a fixed altitude and Mach number, and a constant Mach/airspeed descent. The cost-optimized profile with ATC constraints complies with the ATC-imposed speed limit of 250 knots under 10,000 feet and maintains a fixed cruise altitude. The second cost-optimized profile does not comply with the 250-knot speed limit and gradually increases the cruise altitude as fuel is burned.

The difference in trip costs between the optimized profiles and the handbook profiles are significant — increasing from 3.1% to 3.8% as trip length increases from 500 to 1500 n. mi. for the ATC-constrained profile. For the unconstrained profile, the trip costs range from 4.3% to 4.5% less than handbook.



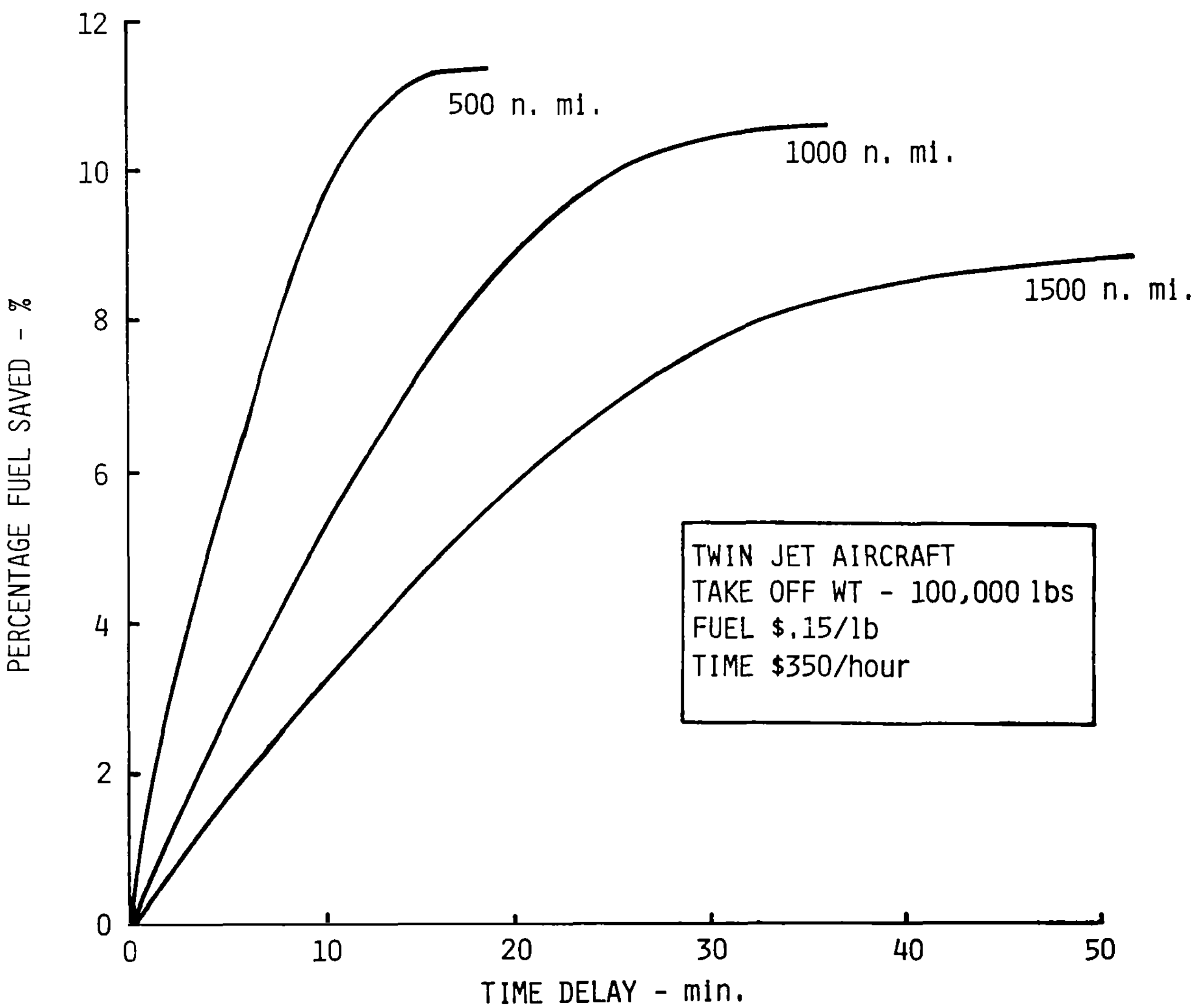
TRIP FUEL USAGE COMPARISON

This figure shows fuel used to complete the trip expressed as pounds/mile as a function of trip distance for the same generic commercial twin-jet used in the previous figure. The three profiles presented are the handbook profile and the optimized profiles, with and without the ATC vertical path constraints. However, the optimized paths were computed based on minimizing fuel usage rather than cost. The resulting fuel savings between the handbook profile and the minimum fuel profile with ATC constraints ranged between 7.4% for a 500-mile trip to 8.8% for a 1500-mile trip. If the ATC vertical profile and speed constraints were eliminated the total savings would range between 8% and 9.5%.



FUEL SAVED VIA FIXED-TIME OPTION

Another option in the OPTIM program is the minimum fuel, fixed-time mode. This mode will be used when a fixed trip time, for either airline or ATC purposes, is desired. This chart shows the percentage of fuel saved by absorbing known time delays through reduced speeds during the cruise and descent flight segments instead of maintaining normal cruise speeds and absorbing the delay in a holding pattern prior to descent. Curves for 500 n. mi., 1000 n. mi., and 1500 n. mi. trips are plotted to show the percentage of fuel saved for each trip as a function of the amount of time to absorb. The assumption is made that the delay is known at the beginning of the cruise segment, although the OPTIM program can reoptimize the profile later in the cruise to absorb the delay. However, the later in the flight that the pilot knows his delay, the smaller the delay that can be absorbed by using speed control. Significant fuel savings can be obtained with this capability, but may require modification of some ATC procedures and policies to obtain arrival time assignments early in the trip.

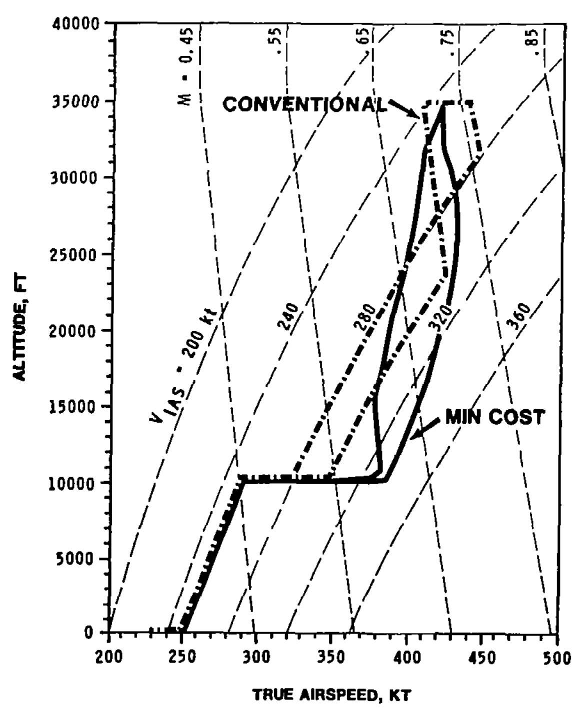


SPEED/ALTITUDE FOR CONVENTIONAL AND MINIMUM COST PROFILES

A significant problem that must be addressed in the practical implementation of the optimized flight paths is to provide adequate guidance for the pilot or autopilot to fly the vertical profiles computed by the optimization routines. This figure illustrates this problem by comparing the speed and altitude profiles of a conventional handbook climb, cruise, and descent with one computed for a minimum cost flight.

The piloting techniques employed on a conventional "handbook" profile are manageable by the pilot since thrust is generally set to a predetermined value and the vertical flight path controlled by adjusting the pitch attitude of the airplane in reference to maintaining a constant value in either the altimeter, airspeed indicator, or the Machmeter. As shown in this figure, during a conventional profile (heavy dashed line), the airplane is accelerated to 250 knots indicated airspeed (KIAS) shortly after take-off. A constant 250 KIAS climb is maintained until reaching 10,000 feet. Then the airplane is accelerated to 300 KIAS while remaining at approximately 10,000 feet. A constant 300-knot climb is maintained until the desired .70 Mach number is obtained. At this point a constant .70 Mach is flown until reaching cruise altitude. Then the airplane is accelerated at constant altitude to the cruise Mach number (.76 in this example). The descent is flown at a constant Mach number (.76) with a transition to a constant 280 KIAS between 23,000 and 24,000 feet. At 10,000 feet, a constant altitude is maintained until the airspeed is slowed to 250 KIAS. This speed is maintained until entering the terminal area for landing.

The minimum cost speed and altitude profile (heavy solid line) may be contrasted to the conventional profile. When unconstrained by the ATC-imposed 250-KIAS limit (above 10,000 feet) neither airspeed, Mach number, nor altitude is constant during the climb or descent. Conventional guidance and pilot techniques are not adequate to fly these profiles. These profiles may not be acceptable due to increased pilot workload and the uncomfortable feeling of not being in control of the airplane.

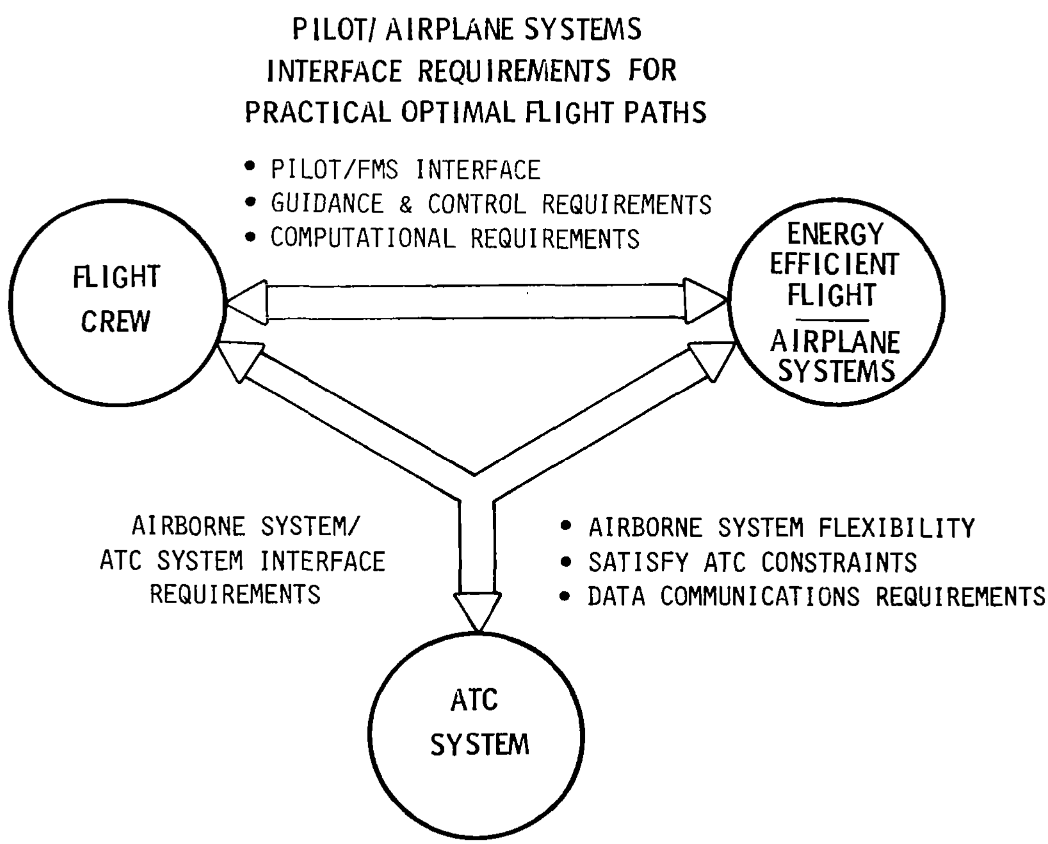


ADVANCED FLIGHT MANAGEMENT CONCEPTS RESEARCH

The flight path profiles of the optimized trajectories may differ significantly from conventional profiles as illustrated in the previous figure. Many questions arise about the interface required for the flight crew to fly the airplane along optimal trajectories, particularly, in an airline environment. There are additional concerns about obtaining the full benefits of optimal trajectories within an ATC environment with other air traffic.

NASA is engaged in an advanced flight management concepts research effort. This research will be conducted in two phases. The first phase will be aimed at defining the interface requirements between the flight crew and the airborne systems necessary for executing practical optimal flight paths. This will essentially be a single airplane problem with no external influences from ATC or adverse weather. The emphasis in this phase will be on guidance and control requirements and pilot and passenger acceptability from an airline operations point of view.

The second phase of this research will be aimed at defining the interface requirements between the airborne system (including the flight crew and airborne electronic systems) and the ATC system. This will be a systems problem in that additional constraints such as ATC requirements, other air traffic, or adverse weather will be considered. The emphasis in this phase of research will be an airborne system flexibility and air/ground communication requirements.



SUMMARY

Potential fuel savings and subsequent cost reductions have been demonstrated with the simplified computations of the programmable calculator with open-loop guidance. Additional savings may be obtained from closed-loop guidance and with the more complex trajectory computations that can be provided with an integrated flight system.

Regardless of the sophistication of the airborne system, however, compatibility must exist with the air traffic system. Airborne derived optimal trajectories must retain the profile qualities that produce the desired optimization, but also fit the path constraints necessary for safe air traffic control.

Flight crew response due to external influences, such as other air traffic or adverse weather, will be a key issue in the acceptance and usefulness of future flight optimization airborne systems. Attention must be paid to the air/ground communication interface and the airborne system flexibility to ensure a high degree of systems efficiency.

- POTENTIAL FUEL SAVINGS AND COST REDUCTIONS HAVE BEEN DEMONSTRATED WITH BOTH SIMPLIFIED AND COMPLEX TRAJECTORY COMPUTATIONS.

- INCREASED OPERATING COSTS HAVE NECESSITATED INCREASED EFFICIENCY AND COMPATIBILITY BETWEEN AIR TRAFFIC CONTROL AND FLIGHT OPERATIONS.

- PILOT AND AIRBORNE/GROUND SYSTEMS INTERFACE REQUIREMENTS RESULTING FROM FLIGHT ON NON-STANDARD, OPTIMIZED TRAJECTORIES MUST BE DEFINED.