FLIGHT MANAGEMENT CONCEPTS COMPATIBLE WITH AIR TRAFFIC CONTROL

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ABSTRACT

With the advent of airline deregulation and increased competition, the need for cost efficient airline operations is critical. This paper summarizes past research efforts and planned research thrusts toward the development of compatible flight management and air traffic control systems that promise increased operational effectiveness and efficiency. Potential capacity improvements resulting from a time-based ATC simulation (fast-time) are presented. Advanced display concepts with time guidance and velocity vector information to allow the flight crew to play an important role in the future ATC environment are discussed. Results of parametric sensitivity analyses are also presented that quantify the fuel/cost penalties for idle-thrust mismodeling and wind-modeling errors.

INTRODUCTION

As air traffic at the major airports continues to increase as forecasted, achieving a corresponding increase in capacity will become critical to minimizing intolerable delays. Since building either new airports or adding runways at existing terminals is generally not feasible for a variety of environmental reasons, other methods of increasing airport capacity are needed. The Federal Aviation Aministration's (FAA) National Airspace System (NAS) Plan and the Research Engineering, and Development (R, E&D) Plan outline several principal efforts being planned to improve capacity: (1) improved use of runway configurations, both existing and new, (2) traffic management improvements, (3) integrated control of major terminal airspace comprising several major and reliever airports, (4) use of time-based air traffic control (ATC) techniques to further improve terminal area capacity, (5) airport surface traffic automation, (6) improved weather services, (7) special use airspace (such as restricted airspace or military operations areas), and (8) Oceanic airspace (improved oceanic ATC systems).

One effort, the use of time-based traffic management concepts not only shows potential for increasing capacity and reducing delays, but also for enabling more aircraft to use flexible, fuel-efficient, four-dimensional (4-D) flight management capability. In a time-based ATC systems concept, a time is assigned for each aircraft inbound to the terminal area to cross a metering fix. This time is computed such that when aircraft cross the metering fix at their assigned times they may continue along a nominal path to the runway without conflicts from other arrival traffic. The time-based flow process, utilizing long-term planning, attempts to maximize airport throughput (or acceptance rate) by reducing the interarrival buffer, and also tries to absorb the essential delay at higher altitudes by early metering of the traffic to the terminal. Cruise speed-control and time-derived, fuel efficient descents are permitted practically all the way to the runway. Advanced air traffic control (ATC) procedures and systems are being designed to reduce traffic delays in the terminal area by metering and sequencing arrival and departure aircraft. Two of these air traffic control system concepts, one being designed for Eurocontrol[1], and one on an operational basis in the United States[2], utilize time control to meter arriving traffic.

Several major concerns and technology issues from both the ATC and aircraft perspective must be addressed in order to achieve improved delivery precision with increased operating efficiency. One of the primary concerns within this area of research has been the development of adaptable flow control algorithms and the ability of the controller to understand and transfer automated advisories that will enable aircraft to meet and adjust to the time schedule desired. The flow control algorithms being developed must be robust and adaptable to various ATC environments. They must provide instructions and information (controller aids) that are meaningful and useful. Also, the contribution of 4-D equipped aircraft in aiding the overall system improvements must be further determined.

This paper will discuss the challenges and opportunities of developing an integrated time-based aircraft/ATC system concept aimed at reducing delays and fuel-usage. A brief discussion of past efforts in this area will be presented, along with current and planned research activities that attempt to bring together evolving traffic flow control concepts with advanced on-board flight management concepts.

PAST RESEARCH EFFORTS

Numerous research activities, such as the early metering and spacing concept development, illustrated that various levels of metering and spacing, including closed-loop time control, have the potential of improving the threshold interarrival precision to 5 seconds and thereby increasing throughput[3-7]. Figure 1 presents the variation of capacity with delivery precision and illustrates the capacity improvement possible if a closed-loop ATC time control process were successfully implemented[6]. It should also be noted that there is great capacity payoff in the concurrent reduction of IFR in-trail separation along with improved delivery accuracy. To further explore the potential capacity benefits that might be realized through increased aircraft delivery precision, a fast-time simulation has been run using the Langley Terminal Area Air Traffic Management (TAATM) model. This simulation contained a mix of air carrier aircraft (9 percent heavy and 91 percent large) and various conditions approximating real-world conditions (metering-fix time errors, wind and pilot errors were among the random variables). The aircraft were automatically scheduled, rescheduled, and sequenced to the runway in an adaptive manner, including interchanging landings times as dictated by events[8]. The results of this simulation are shown in figure 2. As can be seen, reducing the interarrival error from 20 seconds (typically quoted as achieved with current manual vectoring procedures) to 7 seconds yields an increase of 20 percent in throughput for the single runway, arrivals-only case simulated. It should be noted that even with a metering-fix time error of 30 seconds (σ), the system's robustness allowed capacity to be maintained at a high level. Piloted simulation research on the precise control of air traffic into the terminal via a time-based process has also shown that this concept holds great promise[9]. Interarrival time errors of 6 to 10 seconds recorded during this initial simulation study with piloted cockpits illustrates that proper use of an automated ATC process may well lead to achieving some or most of the potential gains envisioned. The study also demonstrated that most of the terminal area holding is transferred to more fuel-efficient, higher altitude en route delay when the en route time-base metering is coupled to the terminal scheduling and spacing process in the M & S system. A reduction in terminal delay not only saves fuel but increases safety by reducing congestion and lowering the work load of both pilots and controllers.

NASA and ONERA/CERT conducted a joint study of a ground-based time guidance algorithm which can enhance aircraft sequencing and improve fuel savings at busy terminal areas. The guidance algorithm computed airspeed and heading commands, which, if followed by the pilots, would result in airplanes crossing the metering fix at preassigned times. These airspeed and heading commands were based on time errors determined at intermediate time-check points located along a nominal path to the airport as illustrated in figure 3. A real-time, piloted simulation was used to study and evaluate the effects that various operational constraints had on time-control capability of the guidance algorithm. A metering fix was established at the outer marker of an Instrument Landing System approach. As the pilot flew along a nominal path towards the airport, heading and speed command corrections were computed by the algorithm and relayed to the pilot through radio communications so that a time objective for crossing the metering-fix would be met. Evaluations were made to determine the effects of an initial time-error, the ATC-imposed 250-knot airspeed limit, and wind-modeling inaccuracy on the capability of the guidance algorithm to null the time error. Test runs along the path, without initial time errors or wind-modeling inaccuracies, showed that use of the time guidance resulted in a mean time error and standard deviation at the metering fix of 1 sec and 17 sec, respectively. The variability of the time error occurred primarily on the path segment between the last time-check point and the metering fix where small flight path errors, such as heading and wind errors, could cause large time errors. It is believed that this variability could be reduced by including another time-check point before the metering fix. Tests showed that the guidance algorithm could accommodate maximum initial time errors at the beginning of the path of 72 sec late and 76 sec early. The 250-knot airspeed limit imposed by ATC reduced the maximum initial time error that could be nulled by the algorithm to 39 sec. A ten-knot wind bias error resulted in mean time errors at the metering fix of between 28 and 36 sec. The magnitudes of these errors will also be affected by the design of the nominal path. The subject pilots reported the speed and heading commands generated by the time guidance algorithm were easy to follow and did not increase their workload above normal levels[10].

The above simulations were conducted considering conventionally equipped aircraft. A real-time air traffic control simulation was conducted to assess mixing aircraft equipped with time-controlled guidance systems and unequipped aircraft in the terminal area[11]. Results indicated a substantial reduction in controller workload and an increase in orderliness when more than 25 percent of the aircraft were equipped with 4-D guidance systems.

Flight test results in the Denver time-based metering ATC environment illustrated the feasibility and potential benefits of having closed-loop time control capability in the airplane[12]. Flight test data were obtained on idle-thrust descent test runs to the metering fix, where the standard deviation of metering-fix arrival time error was 12 seconds. These flight tests included the descent phase only and were aimed at gaining an initial understanding of 4-D equipped aircraft-ATC compatibility issues. Figure 4 is an illustration of the Navigation Display format flown in the NASA Transport Systems Research Vehicle (TSRV) during these tests. Most importantly, the results of these tests began to define the display information necessary for the pilot/airborne system to play an important role in a future air traffic control environment. A similar set of flight tests was also conducted to evaluate the feasibility of open-loop time guidance (hand-held calculator) onboard the airplane[13]. The standard deviation of the metering fix arrival time error from this set of tests was 35 seconds. Although important results have been obtained, further research is required to develop a robust/flexible/ATC-compatible FMS concept that will ensure operational improvements throughout all flight phases (climb, cruise, and descent).

TECHNICAL ISSUES AND RESEARCH THRUSTS

If we examine both the successes and the "lessons learned" from the past research efforts, the definition of remaining issues and the required research to address those issues become clearer. Although the future aircraft and ATC system development should and will be undertaken in an integrated manner (the NASA and FAA are in the process of defining an integrated program), the next two sections will discuss issues and either ongoing or planned research on both the aircraft and ATC side. None of the issues can be separately addressed and some of the issues, particularly information transfer (data-link) requirements, certainly span a critical gap between the airborne and ground systems.

ATC Perspective

One of the primary concerns within this area of research has been the need to develop flow control algorithms that begin the planning and sequencing process early, but do not issue delay instructions until absolutely necessary, thereby assuring that no empty slots in the arrival stream go unused. The necessary robustness to numerous real-world occurences such as piloting errors, time errors at metering fixes, and wind errors must be inherent in the algorithms. From the airborne user perspective, the ground-based algorithms must also have aircraft efficiency considerations embedded, and be able to handle aircraft with minimum to full 4-D system levels of avionics equippage.

Another important concern is the ability of the controller/automation to generate, understand, and transmit instructions and clearances that will enable aircraft to meet and adjust to the time schedule desired. The robustness of the automated process to human (controller) interaction will be critical. The manner in which the human controller plans, sequences, spaces, and merges aircraft must be embedded within the decision logic, so that the automated instructions are natural and help to maintain full situational awareness.

At the Langley Research Center, a primary objective of this area of research is to define, develop, and evaluate an evolutionary ATC concept which would improve the capacity, reliability, and economy of extended terminal flow operations (en route approach, transition, and terminal flight to the runway) when used with projected ground and avionic hardware. The concept would perform the task of assisting the air traffic controller with traffic management in the extended terminal area. It is a ground-centered, time-based process which integrates en route flow control, runway sequencing, scheduling, rescheduling and ATC flight management together with fuel efficiency. It is evolutionary in nature, accommodating today's aircraft, as well as 4-D equipped advanced technology aircraft. The algorithm generates ground-derived speed and profile descent instructions to aircraft without 4-D capability, but only metering fix and runway time objectives to 4-D equipped aircraft. The algorithm, employing simplified models, is designed for integration into the manual, voice-linked ATC system and will accommodate NAS upgrade features such as data link capability and further ground automation. As the concept develops toward the end goal of reduced separation with precision, interarrival time separations may be flexible (function of wake vortex dissipation) as well as fixed.

The extended terminal, time-based flow control concept has been developed and incorporated in the TAATM (Terminal Area Air Traffic Model) simulation. A fast-time parametric sensitivity evaluation of the basic extended terminal area flow control concept with non 4-D traffic is underway using TAATM in a four corner-post, Denver runway 26L configuration with IFR arrival commercial traffic. Initial results show the effects of such variables as metering-fix time error, aircraft separation requirements, traffic density, and delay discounting.

To begin testing for robustness to controller interaction, real-time simulation studies are being defined that will include preprogrammed aircraft along with a piloted-simulation airplane. The initial study would also investigate and document the delivery precision achieved with a piloted simulator representing a conventional aircraft. Of great concern will be the man/machine interface issues within this effort. Improvements in the controller instructions/aids will be made to assure that situational awareness is maintained and delivery precision is achieved.

Another required technical activity in this research area is to define and explore information transfer concepts, message content, display formats, procedures, interface requirements, and crew/controller interaction as needed in the extended terminal area operations. An initial effort has concentrated on defining the message set to enable exchanging present-day ATC information via data link between aircraft and ground facilities.

The initial simulation test has as its objective to evaluate an in-house-developed data link message exchange concept implemented on a modified version of the TSRV Navigation Control/Display Unit (NCDU) shown in figure 5. The NCDU has an additional capability included through modifications to the key labels and supporting software to provide a data-link interface. Messages are compiled using the NCDU's keyboard and displayed on its Cathode Ray Tube (CRT). The concept includes the use of a data-link capability along with voice message exchange during descent and approach into the Denver Stapleton Terminal Area. This process will be compared to today's conventional voice communication with ground-based ATC facilities. The TSRV simulator and Mission Oriented Terminal Area Simulation (MOTAS) environment will provide comparisons of this baseline concept with more optimal crew and controller interface concepts which will evolve. To emulate today's newer aircraft the simulator's display panel will include the standard primary flight display, an airspeed indicator, altimeter, and clock. Engine status information will be provided on the center-panel electronic displays. Velocity-vector control-wheel steering and automatic control features such as altitude hold, flight path angle select, and auto-throttle will also be utilized.

Research pilots' opinion and expertise of researchers in the area of flight systems, human factors, and the ATC system are being used to guide the research and development. This study will address such questions as (1) how to appropriately alert the crew of incoming messages and their urgency, (2) which data exchanges are appropriate for data link and which should continue to be transmitted via voice, and (3) what initial software and hardware assistance should be provided in the cockpit to enable efficient message exchange. Using well-designed interfaces, tests on the MOTAS/TSRV facility will determine effects of information transfer concepts on interarrival error, throughput, operator workload, fuel savings, and safety through more efficient air-ground communications.

Aircraft Perspective

For several years a research effort has been underway to explore and develop advanced flight management system concepts that would enable the flight crew to more effectively function in today's and tomorrow's evolving air traffic control environment. Considerable development of onboard flight management systems has taken place, but research is required to provide more robust flight management algorithms and pilot interfaces that will permit the flight crew to be an effective/compatible partner in the ATC process.

Research will be conducted that is aimed at developing ATC compatible flight management algorithms that are both flexible and fuel-efficient. The goal of increased capacity gains, while realizing reductions in direct operating costs, will be achieved only if a systems approach is taken. Early research was motivated by the fact that the flight management computer in airplanes provided cost-optimal flight profiles and fostered the development of several profile optimization algorithms. The trajectories that are generated by the onboard algorithms are characterized by different profiles than conventional handbook ones in that they are constantly varying in both flight path angle and airspeed.

Considering the dynamic nature of the pilot's control task, various guidance concepts were tested to assure pilot acceptability with low workload levels. Three display configurations and four control modes were tested in the experiment to investigate their relative merits in flying climb and descent trajectories. The path tracking accuracy and the pilot's control activity were the quantitative measures used to evaluate the various display and guidance options. A subjective evaluation of the associated workload and situational awareness was provided through a pilot questionnaire. Although the number of tests subjects was small, the trends in the data and the pilot comments indicate that the current state-of-the-art flight director display and guidance, as well as the two more-advanced display and guidance configurations tested, were acceptable for flying these profiles.

Figure 6 is an illustration of the advanced primary and navigation display formats tested in the study. All the pilot test subjects agreed that the display of vertical path information was very helpful for situational awareness and that the vertical trend vector provided useful information. Most of the pilots felt that the least amount of guidance required to fly the reference profile would be a flight director. Some suggested that the flight director be energy referenced so as to provide guidance for nulling not only vertical and lateral errors but speed errors as well.

The fidelity of the aircraft performance and atmosphere models (wind and temperature) required to support 4-D flight profile optimization is another primary concern. An initial sensitivity study has focused on mismodeled idle engine performance which may result in off-optimal descent profiles that penalize potential cost savings. A flight profile optimization computer program was utilized in conjunction with a vertical trajectory simulation of the NASA TSRV for this analysis. Variations in idle power setting, thrust, and fuel flow were evaluated in a parametric manner for a cruise/descent flight segment. Flight data from the TSRV airplane complemented the analysis with engine parameters measured during idle descents.

A matrix of sensitivity test results for modeled and mismodeled idle engine parameters was obtained for a range of cost functions. An example of fuel increments and resulting fuel penalties associated with increasing and decreasing levels of corrected net thrust at idle is shown in figure 7. These results are useful both for determining the penalties for given engine parameter errors, as well as for providing guidance on modeling methods which minimize these penalties. Flight data from the TSRV airplane revealed engine modeling errors equivalent to approximately a 1 percent fuel penalty for a typical 400 nautical mile flight. Revised modeling of idle power setting reduced this penalty to less than .4 percent, while simultaneously reducing the complexity of the engine model.

One of the primary concerns for the successful implementation of an effective time-based flow management concept is the uncertainty in the winds aloft. Cost penalties incurred by individual aircraft correcting for unknown winds must be outweighed by the benefits of reduced delays provided by the time-based ATC process. Sensitivity tests have been conducted to assess the magnitude of the cost penalty as a function of mismodeled winds. The results are shown in figure 8. Data are presented for two flight strategies/wind modeling conditions. The 4-D condition is where the reference profile is generated to minimize fuel burn for a given flight time. The wind is accurately modeled, and, therefore, the cost penalties represent the effect of not adjusting flight time based on actual wind conditions. The 4-D (error) condition is where the reference profile is generated to minimize fuel burn for a given flight time, but the wind is not accurately modeled. The cost penalty, therefore, represents the effect of wind errors both in the selection of a flight time and generation of the reference profile. The cost penalties are presented as a percentage of the optimal 3-D cost for the same wind condition. As can be seen, wind errors can be costly in a 4-D flight mode, with both 20-kt headwind and tailwind errors causing the airplane to incur approximately a 2 percent cost penalty [14].

An important research thrust on the airborne side is the development of a flexible, fuel-efficient flight management system (FMS) concept that will be compatible and adjust to ATC considerations. A comparison of two cruise/descent strategies in terms of their fuel efficiency and guidance requirements is presented in reference 15. One strategy uses a full-optimized energy-referenced method; the other uses a suboptimal Mach/Calibrated Airspeed (CAS) method. The results indicate that the idle Mach/CAS descent strategy is easier to implement and fly and is less than 0.9 percent as costly. Also, as can be seen in figure 9, for a given time of flight, the range of Mach/CAS descent-speed combinations can be assessed for a 1 percent or less fuel penalty. This planning/replanning information may be very valuable to the flight crew who must quickly understand and respond to a speed change by the ATC. For the example shown in the figure, if the crew is requested to change cruise speed from .78 to .70 Mach, an intelligent decision can be made to keep fuel cost within the 1 percent (or any other) penalty chosen as a limit. Since the new speed is within the 1 percent boundary, acceptance of the speed would be in order. If the new speed were outside the boundary, the crew (with the aid of the onboard intelligence) would then know to request a new time slot from ATC. Intelligent aiding, display information concepts, and input devices that will allow the crew to effectively make decisions that assist the ATC process will be a focus of future research toward ATC-compatible FMS concepts.

CONCLUDING REMARKS

Time-based traffic management concepts are currently operational for en route metering and are expected to expand into the terminal area. Fast-time and real-time ATC simulation studies have documented potential reductions in delays, fuel usage, and controller workload that encourage further research.

On-board flight management capability for time-navigation (4-D) that functions cooperatively and effectively within the future air traffic control environment is essential. Piloted simulation and flight tests have shown that advanced display/control concepts play an important role in the crew's ability to be an effective partner in the future aircraft/ATC operational environment.

Parametric sensitivity studies have begun to document the fuel/cost penalties of idle-thrust mismodeling and wind-modeling errors and will help define on-board computational requirements. The assessment of various cruise/descent strategies has begun to illustrate the fuel efficiency and guidance tradeoffs between optimal and Mach/CAS descent methods.

A systematic, integrated approach to the development of the future airborne/air traffic control process must be taken to assure maximum efficiency of aircraft operations. The benefits to be achieved appear to be much greater than the research and development costs.

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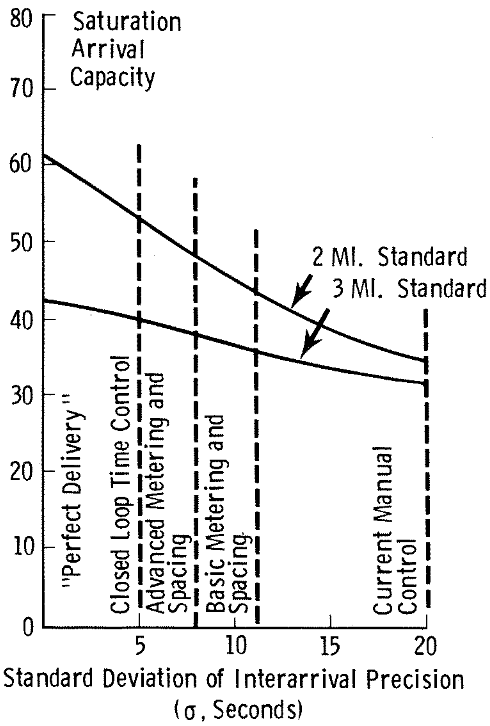

Figure 1. - Variation of Capacity with Delivery Precision (ref 6)

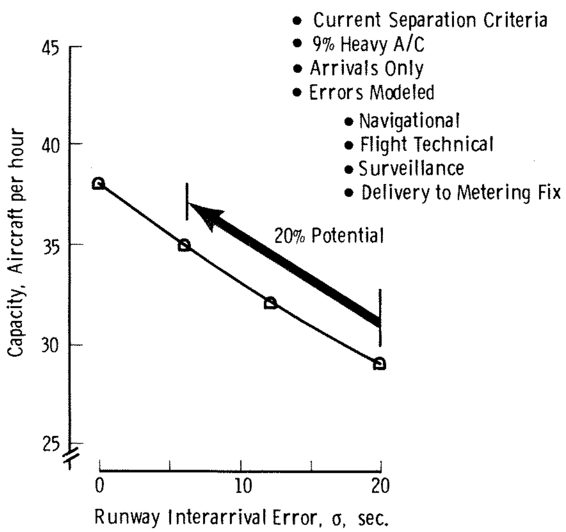

Figure 2.-ATC Simulation Result - Capacity vs Interarriual Error

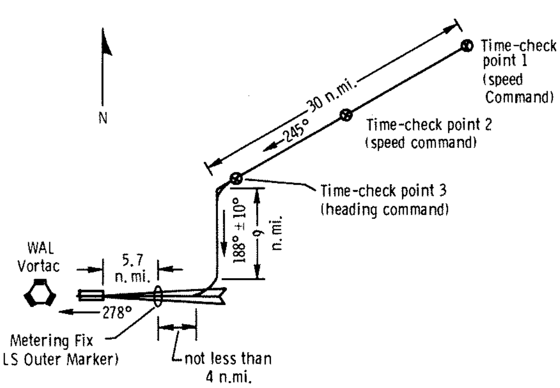

Figure 3.-Nominal Test Path

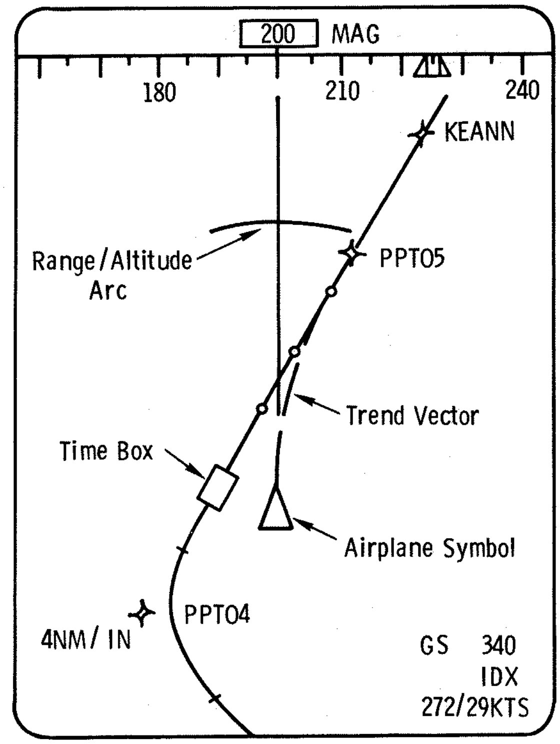

Figure 4. - Navigation display with vector, range/ altitude arc, and time guidance information

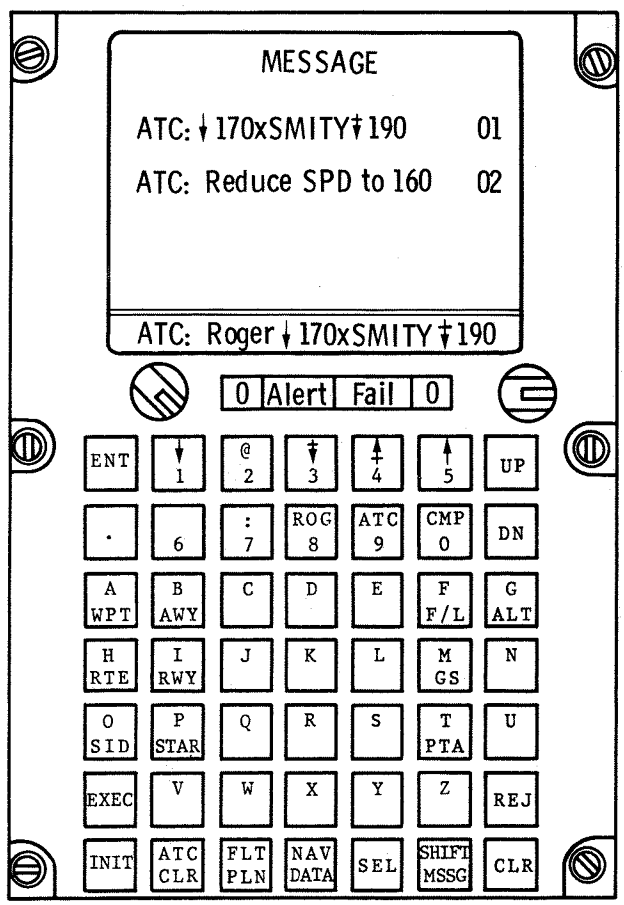

Figure 5. - Modified NCDU for Data-link Messages

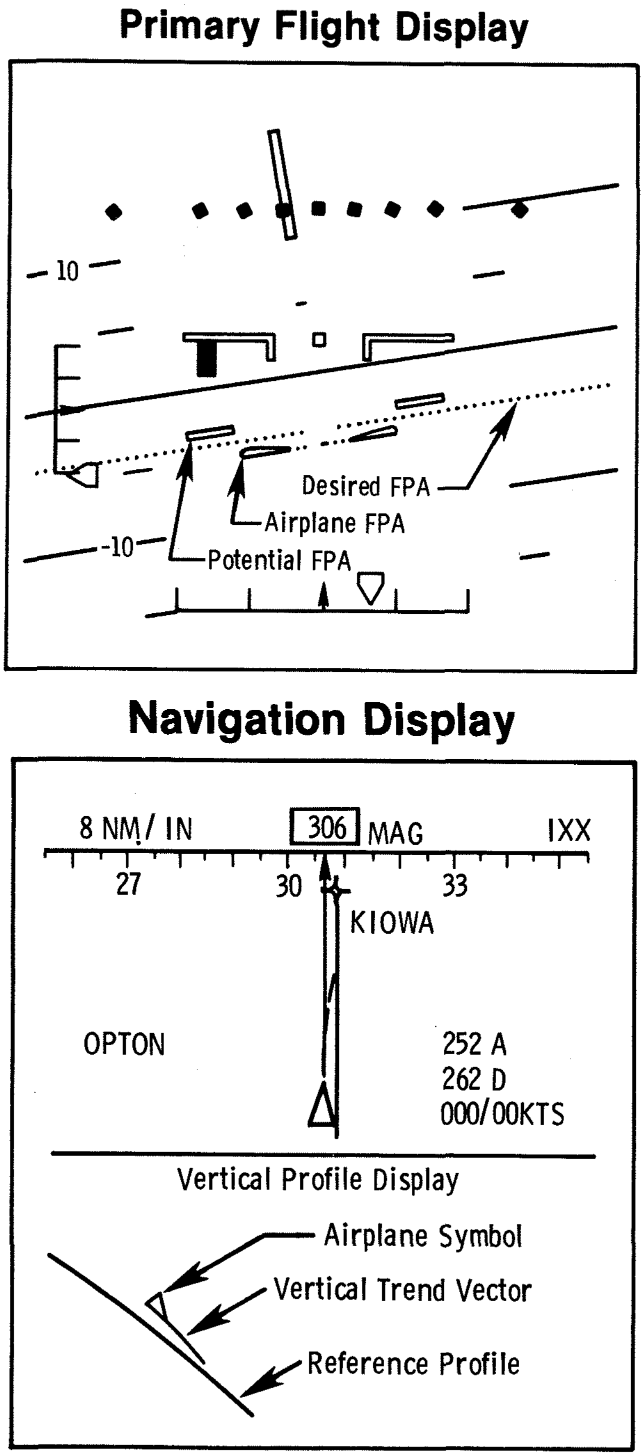

Figure 6. - An Adanced Display/Guidance Configuration

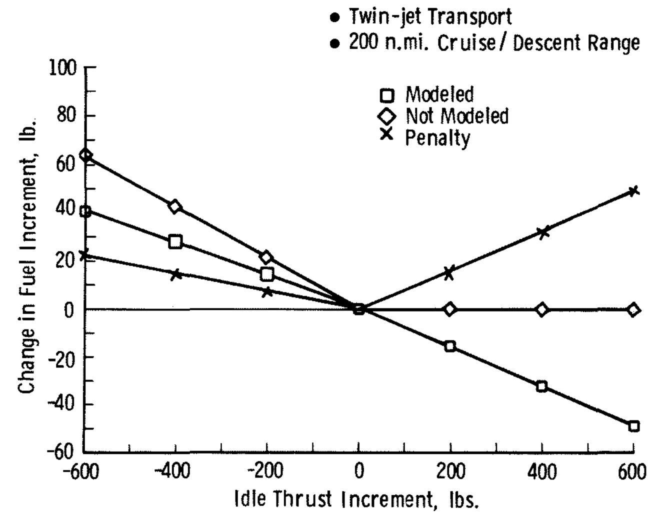

Figure 7. - Fuel Sensitivity to Idle Thrust Variations

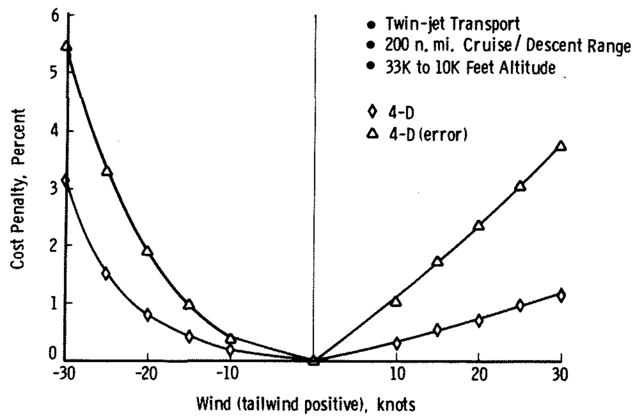

Figure 8. - Effect of Winds on 4-D Operations

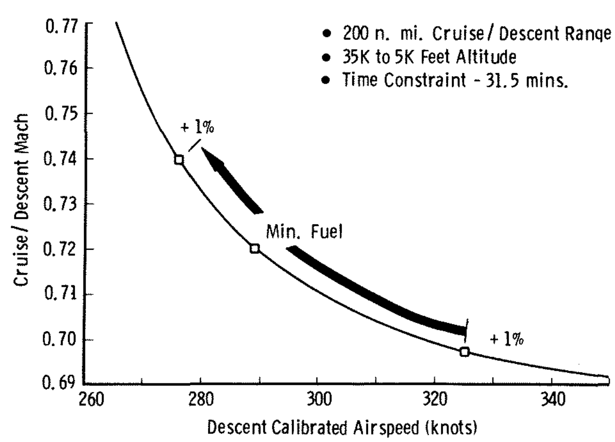

Figure 9. - 1 Percent Fuel Penalty for Various Cruise/Descent Speeds