TERMINAL CONFIGURED VEHICLE PROGRAM
RESEARCH HAVING POTENTIAL FOR FUEL SAVINGS

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The National Aeronautics and Space Administration Langley Research Center Terminal Configured Vehicle Program, in cooperation with the Federal Aviation Administration, is pursuing research and technology concept development for airborne systems, operations and procedures that can provide needed improvements and solutions to air transportation problems for conventional civil aircraft particularly for the 1980-2000 time period. Specifically, it is to provide the airborne systems capability which can lead to increased airport and runway capacity, increased air traffic controller productivity, energy efficient terminal area operations, reduced weather dependence with safety and reduced community noise by use of improved procedures. This paper describes the research activities and present results of the TCV Program. Emphasis is placed on those aspects of the program that have a direct or potential effect on fuel savings for terminal area operations.
INTRODUCTION

The National Aeronautics and Space Administration (NASA), Langley Research Center, Terminal Configured Vehicle (TCV) Program has been established to conduct research necessary to identify, evaluate, and demonstrate flight systems and flight management technology concepts that will improve the efficiency of conventional takeoff and landing (CTOL) aircraft operations in high density terminal areas with reduced weather minima. The urgency for improvement in terminal area operations is illustrated by the air fleet growth projections shown in figure 1 (ref. 1). One of the major constraints on capacity is the delay and congestion in the terminal area, and this situation will only worsen if the fleet growth occurs as shown in the figure. An actual data point is shown on the chart which indicates a larger fleet than predicted in the 1970 forecast. Conservative estimates indicate a doubling of the air fleet by 1995.

Terminal area problems addressed in the TCV Program include safety; weather effects; congestion and resulting loss in productivity caused by delays, diversions, and schedule stretchouts; energy management; and noise. The exposure of inhabited areas near airports to high noise level was one of the first problems to cause an impact on aircraft operations. Operations in a number of terminal areas are now restricted by procedures designed to reduce noise exposure. More recently, fuel conservation has rapidly climbed to a place of high national priority in all aircraft operations and this must be a dominant concern in evaluating methods for solving terminal area problems (ref. 2).

The deleterious effects of air traffic congestion on operations during peak traffic hours at some terminals, and the near-paralysis of the system that can be caused by weather-induced delays, diversions, or closure of only a few terminals are well known to air travelers. The effects of reduced visibility on safety occur predominantly in the terminal area.

It is recognized that some of the methods available for solving the terminal area problems can lead to conflicting results. For example, engine acoustic treatment to reduce source noise and arbitrary noise abatement procedures will cause increased fuel consumption (ref. 3). Thus, some hard choices must be made, and for maximum effectiveness the solutions for terminal area problems must ultimately be considered and evaluated in an integrated manner.

The relationship of delay and fuel costs can be implied through examination of the close agreement between delay and direct operating costs (DOC). Withington of Boeing (ref. 4) estimates that a 5 percent reduction in delay (or flight time) is equivalent, in terms of DOC, to a 5 percent reduction in drag. Figure 2 illustrates this point, with an approximate 3.5 percent change in DOC associated with drag and a 3.2 percent change in DOC associated with flight time reduction.
Considering the cost of delays, let us examine the lower part of figure 3, which is discussed in more detail in reference 5. The schedule time of an airline flight of average length is shown, including the various components (shaded) that add to the time required for a direct flight with no delays. Although the passenger is not aware of any delays, the average delays due to non-direct routing (current airway routes versus direct routes), holding and path stretching to obtain aircraft separation, non-optimum altitudes, weather delays, etc., are included in the airline scheduled flight times. In this particular case, 25 percent of the time is built-in for delays. It is estimated that a 20 percent reduction in scheduled time of a Boeing 727 for the stage length illustrated could be realized through improvement in airspace utilization of the type the TCV Program is investigating. This equates to approximately a 13 percent reduction in DOC. A more disturbing illustration of deteriorating airspace usage is presented in the upper part of figure 3 where a current jet time schedule is compared with an earlier turboprop flight time. The schedule time for the jet, which always follows Instrument Flight Rules (IFR) and procedures, is 42 percent greater than the slower Lockheed Electra using a direct routing under Visual Flight Rules (VFR). An objective of the TCV Program is to improve future systems to approach the VFR-type of operation in Instrument Meteorological Conditions (IMC).

The NASA - Langley Research Center TCV Program, in cooperation with the Federal Aviation Administration (FAA), is pursuing research and technology concept development for airborne systems, operations, and procedures that can provide needed improvements and solutions to air transportation problems for conventional civil aircraft particularly for the 1980-2000 time period. Specifically, it is to provide the airborne systems capability which can lead to increased airport and runway capacity, increased air traffic controller productivity, energy efficient terminal area operations, reduced weather dependence with safety, and reduced community noise by use of improved procedures. This paper describes the research activities and presents results of the TCV Program with emphasis placed on those aspects of the program that have a direct or potential effect on fuel savings for terminal area operations.

TCV PROGRAM OVERVIEW

It is recognized that new or modified air traffic control systems or procedures cannot solve the problems they are intended to solve unless similar advances in the airborne systems and flight procedure capability are achieved. The airborne system is considered to be the basic airframe and equipment, the flight control systems (automatic and piloted modes), the displays for pilot monitoring or control, and the crew as manager and operator of the system. The purpose of the TCV Program, first described in reference 6, is to identify aircraft system and flight management technology that will benefit terminal area operations of conventional aircraft. The major research objectives to achieve this goal are:
(1) Improve Terminal Area Capacity and Efficiency
   a. Systems and procedures for ATC evolution
   b. Systems and procedures for runway capacity
   c. Profiles and procedures for fuel conservation

(2) Improve Approach and Landing Capability in Adverse Weather
   a. Human factor elements for effective flight management
   b. Systems and information to minimize wind shear hazard
   c. Airborne sensors for weather penetration

(3) Reduce Noise Impact through Operating Procedures (Profiles and Configurations for Noise Reduction)

In order to accomplish the program objectives and goal, balanced research activities are being conducted in navigation, guidance, displays, and automatic and pilot control. Displays and controls are considered essential for full participation of the pilot in the navigation and control of the aircraft in the terminal area environment. Automatic control is considered as augmenting the piloting functions in the execution of safe and efficient flight.

Operational goals of the TCV program are illustrated in figure 4. A microwave landing system providing precision navigation signals throughout a large volume of airspace is considered an important element of the advanced airspace system. As seen in this figure, operations in the MLS environment can, with proper controls, displays, and airframe characteristics, provide more effective airspace utilization. This can lead to alleviation of noise over heavily populated areas, and to a reduction in flight time and fuel consumption. Also, onboard precision navigation and guidance systems, with displays, will allow 2-dimensional (2-D), 3-dimensional (3-D), and 4-dimensional (4-D) control for closer sequencing and lateral runway spacing for simultaneous instrument approaches. Finally, precision landing with reduced touchdown dispersion combined with programmed turnoffs at relatively high speeds are required to clear the runway to allow operations to proceed with perhaps 40 to 45 seconds between aircraft, assuming alleviation of vortex wake problems. Research on displays and control is under way with the intent of achieving more efficient operations in lower visibility conditions with sufficient confidence that they become routine.

The primary facility (ref. 7) used in flight research phases of the program is a highly modified Boeing 737 aircraft shown in figure 5. This aircraft is equipped with all-digital, integrated navigation, guidance, control, and display systems which can be readily reprogrammed for research purposes.
THE TCV B-737 AIRCRAFT

The research capabilities of the TCV B-737 are described in detail in reference 7. A cut-away view of the aircraft, shown in figure 6, illustrates the palletized installation of the avionics, and depicts a second cockpit for research (aft flight deck, AFD). A simplified block diagram of the experimental avionics system used for flight research is shown in figure 7. Research in this aircraft is enhanced by several notable design features:

(1) The system functions are controllable and variable through software.

(2) The hardware is easily removed, modified, repaired, and installed.

(3) Flight station changes are readily accomplished in the research cockpit, which has a fly-by-wire implementation for control of the aircraft.

The photograph of figure 8 shows the arrangement of the AFD. The center area of the cockpit is seen to resemble a conventional B-737 cockpit, whereas the area immediately in front of the pilot and co-pilot have been opened up by removing the wheel and column and replacing them with panel mounted controllers. The placement of these controllers permits full view of the flight displays. Both pilots are similarly equipped with electronic vertical and horizontal situation displays (EADI, EHSI) and the Navigation Control and Display Unit (NCDU), which includes navigation data displays and a keyboard for communication with the navigation computer system. The pilot has display mode panels to call stored airport or other information from computer memory to be put on the map. He can similarly reject or erase information depending on its importance during each phase of his flight. The other facet of research flight deck operations is the Control Mode Panel located in the center of the glare shield. In this system either pilot can operate the airplane through either of two computer augmented manual control modes or five automatic modes. The EADI instrument provides basic attitude and vertical path information to control the aircraft. The EADI symbology is explained in figure 9. The EHSI, illustrated in figure 10, is a pictorial navigation display to provide the pilot with accurate aircraft situation information relative to the guidance path desired (either INS or MLS RNAV derived), flight plan waypoints, and geographic points of interest such as airfields, mountains, and VORTACs. The dotted track select line is a tentative new track and becomes solid when acquired in manual flight or accepted through the NCDU for automatic flight. In the illustration the desired horizontal flight path is displayed as a solid line connecting waypoints. The curved trend vector shown emanating from the nose of the aircraft symbol consists of three dashes indicating future position at 30-, 60-, and 90-second intervals. Only a 30-second trend vector is displayed with the 1 nautical mile scale. A rectangular box, just beyond the waypoint SOUND, indicates the scheduled along-path position during 4-D operations, with the dots ahead of it indicating future scheduled positions at 30, 60, and 90 seconds. The time box location of figure 10 provides the pilot with an indication of his scheduled time and flight path position errors.
## TCV Test/Demonstration Summary

### Through July 1979

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* Computer Generated Imagery

** Television Imagery
Magnetic track is indicated at the top of the EHSI. The operating modes of the two EHSIs (pilot and first officer) are independent; i.e., one may be operated in the north-up mode (for route visualization) and the other in track-up (preferred for navigation). The EHSIs may also be operated with different map scales or options. The six map scales provided are 1, 2, 4, 8, 16, and 32 nautical mile/inch, and the one selected is displayed in the lower left corner of the EHSI. The altitude/range symbol, an option when in the track-up mode, consists of an arc some distance ahead of the aircraft symbol and represents that location at which the aircraft would reach the reference altitude, selected via the control mode select panel, if the current flight path angle is maintained. In the lower right corner of the EHSI are displayed the ground speed (GS) in knots, the mode of navigation (in this case inertial with single DME update, IDX), and the wind velocity and direction. When in the MLS RNAV mode the letters AMX (for air data, MLS update) would appear in the lower right corner.

Complete flight from takeoff through landing can be accomplished from the AFD.

TCV PROGRAM RESEARCH ELEMENTS RELATED TO FUEL SAVINGS

Many of the TCV program goals illustrated in figure 4 have a direct or potential application to fuel savings. Several of the program research efforts related to these goals have been carried forward to flight tests and experiments on the TCV B-737. The results of these flight tests and experiments give promise of increased productivity in an operational environment.

MICROWAVE LANDING SYSTEM (MLS) OPERATIONS

Early in the TCV program, a joint NASA/FAA agreement recognized the long-term objectives of the NASA program, and NASA agreed to provide use of the TCV aircraft for support of specific FAA system evaluations, including that of the MLS. In July 1975, at the request of the FAA, NASA agreed to participate in a flight test/demonstration of the U.S. MLS capabilities to the All Weather Operations Panel (AWOP) of the International Civil Aviation Organization (ICAO) at the FAA's National Aviation Facilities Experimental Center (NAFEC) in May 1976. The ground rules adopted for the demonstration were:

1. Fly 3-D, automatic, curved, descending approaches using the originally implemented navigation control laws for the curved path portions and using MLS guidance instead of inertial platform (INS) guidance when within the MLS coverage.

2. Make transition from curved path portions to short, straight final approaches and land with the original autoland laws modified to use MLS guidance substituted for INS and ILS guidance.
(3) Perform flares using the MLS flare antenna (EL 2) and/or radio altimeter signals.

(4) Perform rollout using MLS guidance.

(5) Modify the electronic displays to accept MLS derived information. These displays include (a) horizontal situation, (b) curved trend vector, (c) centerline and glide path deviations.

All the capabilities implied by the ground rules were to be tested and demonstrated in an automatic mode without use of the inertial smoothing technique which is a basic part of the original configuration in the TCV aircraft. However, the FAA stated that the use of body-mounted accelerometers or direct measurement of INS acceleration signals were permissible if parameters of this type were needed for the basic control system. The FAA also stated that the use of attitude data from the INS was permissible, in lieu of attitude from additional high quality vertical and directional attitude reference systems, for control/display purposes. The philosophical approach taken by Langley Research Center for MLS tests and demonstrations was to make minimum modifications in the existing navigation, guidance, and control systems and to derive all necessary parameters from the MLS data for interface with these systems.

Following the NAFEC tests/demonstrations in May 1976, the FAA, in early September 1977 requested further test/demonstration support of NASA with the TCV aircraft. The tests/demonstrations were to be at Buenos Aires, Argentina, during October - November 1977; New York's Kennedy Airport in November - December 1977; Montreal, Canada, in March - April 1978; and NAFEC again on a more relaxed schedule during the summer of 1978. The latter was in the context of research experiments with the use of back azimuth and C-band flare antennas as new experiments.

Although improvements were made during the course of these tests/demonstrations to the automatic mode performance, and to the longitudinal control and EADI display for piloted Control Wheel Steering (CWS) operations, the basic avionics configuration for utilization of the MLS signals has remained the same.

The basic configuration of the TCV B-737 flight control system is shown in figure 7. The flight sensors and computers for the autoland system are triplicated for redundancy, similar to those that would be suitable for an operational system. Other components were intended to be dualized, but have not been in the current research system. The MLS integration with the TCV aircraft flight control system is illustrated in figure 11 (ref. 8). As noted, the original avionics system was not configured to use MLS data for navigation, guidance, or control.
The principal task to which NASA addressed its efforts was the integration of the MLS signals into the navigation, guidance, and control laws and display symbology of the original system that had been designed to use INS, DME, ILS, and radio altimeter data. The major development efforts involved with the configuration, as shown in figure 11, were directed at aircraft antenna design and location, interface of the MLS receiver with the experimental system, and design of the MLS guidance signal processor. Wherever possible, the functions of this signal processor were designed to permit integration of MLS derived navigation, guidance and control parameters with existing laws of the navigation and guidance computer and the flight control (autoland) computer with minimal modifications to these computers. Minor changes were made to the existing display formats with features added to indicate validity of MLS signal and to improve the perspective runway format.

NAFEC MLS Automatic Flight Demonstrations. - The flight profiles selected for the 1976 ICAO test/demonstrations are shown in figure 12 superimposed on a photograph of the NAFEC area. The two profiles shown in this figure are designated as a 130-degree and a 5-turn azimuth capture. A more detailed illustration of flight events along the demonstration profiles is shown in figures 13 and 14. Each flight profile contains a 3 nautical mile straight final approach representative of many VFR approaches being flown at the present time at congested airports near heavily populated areas. These profiles, which can be used to provide alleviation of noise over populated areas, are also illustrative of the types of curved paths that have potential for increasing airport capacity in an advanced ATC environment.

During the development, test/demonstration, and post-demonstration data-collection flights in the NAFEC MLS environment, 208 automatic approaches and 205 automatic flares were flown. These flares were terminated in touch-and-go maneuvers and full-stop landings that included automatic rollout operations. A comprehensive description of flight operations during these flights is given in references 8, 9, 10, and 11.

Statistical summary plots (ref. 10, 11) of vertical and horizontal errors for the final approach, measured by theodolite system for the 53 automatic approaches performed during the 1976 formal demonstration, are presented in figure 15. The errors at 5 to 6 km from touchdown are those incurred by the navigation system at the end of the final turn before capture by the autoland system. The "jump" in the data at 5 km is due to switching from radar tracking to theodolite tracking.

The mean overshoot error on turning onto final was about 9 m, tapering down to about 3 m at 1 nautical mile. The mean vertical error at 1 nautical mile was less than 1.5 m. This accuracy of performance was achieved despite very adverse winds. The winds were strong and gusty and quartering from the left rear, thus providing strong crosswind and tailwind components that were larger than those considered in normal autoland certification. Very strong sneers were also experienced at times. A more detailed discussion of the flight performance during these 1976 flights is contained in references 10 and 11.
Buenos Aires MLS Automatic Flight Demonstrations.- The MLS tests/demonstrations in Buenos Aires from October 31 through November 7, 1977, were conducted at Aeroparque Jorge Newbery, a single strip downtown airport 4 km from city center, which handles a high volume of short haul and commuter traffic. This airport lies along the shore of the Rio de La Plata. The flight profiles selected for this demonstration are shown in figure 16 superimposed on a map of the area. The MLS configuration the FAA chose for the Aeroparque installation was the Basic Narrow (aperture) with ±40 degrees azimuth coverage. This was installed on runway 13. No flare antenna (EL 2) was provided. A more detailed illustration of flight events along these demonstration paths is shown in figures 17 and 18. During the development and test/demonstration flights in the Buenos Aires MLS environment 56 automatic approaches and flares were flown terminating in touch-and-go maneuvers and full-stop landings that included automatic rollout. A report (ref. 9) describing operations during these flights and a report (ref. 12) on the tracking performance of the aircraft in the automatic mode during these tests/demonstrations show that results of these flights were very similar to those achieved at NAFEC in 1976.

JFK MLS Automatic Flight Demonstrations.- Following the Buenos Aires operation, MLS tests/demonstrations were conducted at J.F. Kennedy (JFK) Airport in New York from December 5 through December 13, 1977. The MLS configuration provided at JFK was a Basic Wide (aperture) with ±60 degrees azimuth coverage. The MLS antennas were set up for runway 13L. No flare antenna was provided.

The test/demonstration profile chosen was an overlay of the published Canarsie approach to runway 13 L shown in figure 19. Figure 20 shows the MLS approach in detail from Canarsie VOR (CRI) inbound. A constant 3-degree glide was followed. The dashed line indicates the MLS azimuth coverage provided. The turn is a constant radius of 4,500 m and requires a very shallow average bank angle of 8 degrees. The straight-in portion was only 0.44 nautical mile to the displaced threshold.

It is of interest that, particularly during the development period prior to the demonstrations, local ATC controllers from the common IFR room and the tower at JFK were carried on each flight. The controllers, as a result, became enthusiastic in support of the advanced experiment. The displayed situation information, particularly, impressed the controllers. Having enlisted the participation of the local controllers, a departure/arrival RNAV pattern, shown in figure 21, was mutually agreed on that was expeditious and predictable in terms of time, and was specific and accurate in terms of track. The navigation after takeoff was thereafter left up to the NASA crew, with radar following. The aircraft capability and ATC cooperation, after the controllers became familiar with the program and equipment, greatly expedited the demonstration flights. Generally, because of traffic, landings were full stop with takeoff in the opposite direction on runway 31R.
Strong tailwinds of the order of 20 knots or more occurred on 5 of the 8 demonstration days. A total of 45 autolands was accomplished during the whole exercise. Thirty approaches performed during the formal demonstration flights resulted in successful autolands, which was considered very successful under the circumstances. Eight approaches required takeover for manual landings. These results are attributed to the strong northwest winds at 20-30 knots, changing from a crosswind to a tailwind during the final turn, combined with the narrow autoland capture limits very close to the threshold. This illustrates the limitations of the ILS-type capture techniques currently implemented. A more detailed discussion of operations during these flights is given in reference 9 and statistical data describing tracking performance of the aircraft during these flights is described in reference 13. The flight performance, again, was very similar to that achieved at NAFEC in 1976.

The Canarsie approach into JFK, an effective noise abatement procedure, shown in figure 19 is currently performed only under visual conditions with 244 m (800 ft) ceiling and 2 nautical mile visibility minima. The visual portion of this approach is defined by high intensity flashing lead-in lights on the ground which generally follow Shore Parkway. This approach avoids high density residential areas and saves airspace and time. This approach procedure makes an excellent case for an MLS volumetric coverage precision guidance system to allow similar approaches under instrument meteorological conditions. The significance of being able to perform such close-in patterns during instrument flight conditions is obvious from figure 22 showing the New York terminal area for a typical landing direction. The ILS patterns for the several airports overlie one another’s control zones (shown by dashed outlines). There is no usable airspace between the control zones in this case. If one could use Canarsie-type approach patterns as depicted, under IMC, the approach patterns could be contained within the individual control zones, thus freeing airspace shorthaul or other traffic use between control zones and alleviating some of the traffic conflict and capacity problems of the major airports.

Montreal MLS Automatic Flight Demonstrations.- The flight profiles for the 1978 Montreal tests/demonstrations are shown in figure 23 superimposed on a map of the Dorval Airport area. The two paths were successfully and repeatedly flown. South of the river is the Caughnawaga Indian Reservation which was to be strictly avoided. The paths accomplish the objectives by bringing the airplane over the river, or alternatively far inland, then along a railroad-industrial area to the runway approach. The departure path was similarly constrained. Descent angles were over 4 degrees on one of these profiles. A preliminary review of the performance data collected for these flights indicates that the performance was very similar to that achieved during the previous demonstrations. This demonstration period was taken as an opportunity to collect touchdown dispersion data for evaluation of a new flare law developed as a part of the TCV program. Performance data collected during the Montreal tests/demonstrations is under final analysis and will be published in NASA reports in the near future.
Summary of MLS Automatic Flight Demonstrations.- A summary of the flight profiles flown under automatic control during the demonstrations as well as in manual control modes during the tests and development flight is shown in figure 24. The accuracy of the MLS was high, and the aircraft performance good, considering the unfavorable winds encountered and the lack of full development of the automatic control techniques and control laws for utilization of MLS.

During the course of the MLS development flights and demonstrations with the TCV B-737 aircraft over 595 automatic landings and rollouts from curved approach paths have been performed. Also, more than 900 observers have been carried during the actual demonstrations. The large majority of those coming off the flights appeared impressed and enthusiastic about the AFD displays in particular, and the observations of the profiles from the front cockpit as well as the cabin seats. The profiles flown have all been acceptable and comfortable from the pilots' and observers' standpoint and have drawn no unfavorable comments.

During the formal demonstrations, the ability to observe the position of the aircraft at all times and its tracking performance by means of the displays was as impressive as the automatic operation itself, as indicated in references 8 and 9. After takeoff, the displays permitted the AFD pilots to position the aircraft manually for a smooth, maneuverless transition to 3-D automatic flight into the first waypoint of the automatic profile. Also, during the development flights prior to the demonstration, numerous interruptions in flying the profiles were encountered such as diversions due to intrusion of traffic. The displays, in combination with control wheel steering, resulted in effortless navigation during reprogramming or redirected flight and facilitated expeditious maneuvering by the pilots to re-enter the desired patterns without the need for vectoring from the ground. The EADI symboloby provided an effective means of monitoring flight progress on final approach. In particular, the excellent registration of the computer generated image of the runway with the real runway (as shown by a superimposed TV image of the real runway) established confidence in the potential utility of computer generated runway symbology for monitoring landing operations.

The implications for the future are clear with respect to automatic flight. Advanced displays will have to be provided to:

(1) Maintain crew orientation.

(2) Permit manual maneuvering within constraints in airspace, fuel and time in order to cope with diversions due to traffic or weather, or loss of automatic capability.

(3) Permit continued controlled and accurate navigation when new clearances and/or flight profiles must be defined.
Approach and Landing Display Operations with MLS.- Upon completion of the automatic flights of the 1976 ICAO demonstration, additional flights were conducted to evaluate display effectiveness for manually controlled flights along the same profiles, since this is considered to be the best way to evaluate display information for monitoring purposes and takeover if necessary. This work is reported in references 14 and 15.

The velocity vector control mode was used during the approaches. In this mode the pilot commands pitch rate by pulling or pushing the panel mounted controllers. When the pilot perceives that the desired flight path angle has been reached, he releases the controllers and the system maintains the flight path angle regardless of changing winds or airspeed. The pilot also commands roll rate by rotating the panel mounted controllers. When he attains the desired track angle relative to the runway, he releases the controllers with wings level and that track angle is maintained until further inputs are made, regardless of varying winds.

First, in the evaluation of the display, comparative performance tests were made between a baseline display format, consisting of the EADI and EHSI, as shown in figure 25 and an integrated display format shown in figure 26. The integrated display concept has a computer generated perspective runway and relative track information added to the EADI symbology to bring horizontal situation up into one display. This improves the realism of the display format and reduces the scanning and mental integration required in the two-display arrangement. However, the pilots require two or three sessions using this display in simulation before learning how to use it effectively.

The task designed for the test consisted of flying a path offset 0.1 nautical mile inside the 130-degree turn approach, as shown in figure 27. At the end of the turn the offset was removed and the pilot had then to acquire and track alignment with the runway in the 3 nautical mile remaining to flare height. Three pilots took part in the test. Figure 28 shows the tracking performance with the baseline format. Note that the pilots did not, in this case, align or stabilize the flight path adequately with respect to the runway before crossing the threshold. Using the integrated display, adequately stabilized alignment was achieved at a comfortable distance from the threshold as shown in figure 29.

Evaluation of the integrated display format was continued with the task of performing the 130-degree profile with final approaches shortened to 1.5 and 1 nautical mile. Four pilots took part in these tests. These were the first such approaches flown by the pilots. Figure 30 shows tracks for a 1.5 nautical mile final and indicates stabilized alignment again at a comfortable distance from the threshold. The large overshoot of about 100 m on one approach was not of concern to the pilot because his situation was clear to him and he proceeded to acquire runway alignment without overshoot or undershoot. Figure 31,
for a 1 nautical mile final, indicates that the pilots did not do as well in stabilizing alignment as with longer finals, but probably did an adequate job for suitable landings to be accomplished with visual references. Throughout all MLS testing to date 75 manual landings (CWS) have been made from the AFD using the computer generated symboloby with the perspective runway.

Two additional requirements have been defined as a result of this test and both are currently under study. First, some clearly defined path to the runway must be identified in the EADI such as a path in the sky format (ref. 16). Second, predictive information must be provided so that the pilot can quickly correlate his controlling action with his future path requirements (ref. 5). A predictive vector format for the EADI is currently under evaluation to satisfy this second need.

4-D FLIGHT RESEARCH RESULTS

In the future, 4-D flights will be required for controlling the arrival and landing of traffic at major airports in a sequence that will expedite the flow of traffic for maximum capacity. It seems probable that 4-D control, the basis for strategic control concepts, will be exercised from takeoff through landing with adjustments to arrival times being made enroute and with fine tuning being applied in the metering and spacing to the runway threshold.

Limited flight tests have been made over a demanding 1-hour test pattern using radar tracking to determine the navigation system position and time errors. These tests and results for the automatic mode performance are described in reference 17. For the normal mode of navigation with the inertial system using dual DME update, the results indicate that the mean time error to be expected at any waypoint (where ground speed has been specified), including the outer marker on arrival (or equivalent), is 1.4 seconds with a 0.7 second standard deviation. Further, 4-D flights to landing have shown typical errors of 3 to 5 seconds. This difference in time errors is apparently due to the fact that the final approach, being controlled with respect to airspeed, is subjected to wind effects. Errors at low elevations may also increase due to loss of dual DME update in some areas.

In the summer of 1977 a 4-D flight demonstration was performed by the TCV Program. The flight originated at Langley Research Center with routing into North Carolina and terminated with an ILS landing at Norfolk, a total distance of 259 nautical miles. The flight had a scheduled landing time. Immediately after takeoff from Langley the aircraft was placed under 4-D automatic control. The major portion of the flight was accomplished automatically except for a maneuver to illustrate manual control capability in the 4-D mode as discussed in reference 18.
During the flight leg from waypoint LVL to RMT, as illustrated in figure 32, a 6-minute delay in scheduled arrival time was simulated. Using the velocity vector CWS mode (holds track and path angle) the pilot manually entered a holding pattern, shown in figure 33, then recalled the appropriate flight path page when on the "outbound" track and entered the new arrival time at RMT in the navigation computer. This change "rippled" backward and forward through all flight legs and reset the time box (current scheduled position). Since the EHSI shows only magnetic track it can be seen in figure 33 that the velocity vector CWS mode held track very well against the existing 90 kt direct crosswind from the west. It is obvious that during the turns considerable drift occurred, necessitating an intercept angle inbound. Although this was the first such maneuver for the pilot, he was able to make use of the predictive trend vector time dashes ahead of his aircraft symbol and the rescheduled time box with the time dots ahead of it, to judge the start of his inbound turn and the maneuver to reacquire the time box. Other aids to the pilot for time control are the flight acceleration command bar (figure 9) for use of throttles, and a readout of time error and time error per minute, separation or closure, on the NCDU display shown in figure 8. Figure 33 shows that the pilot was able to close on the inbound track only 5 seconds behind the time box. He continued closing until he again coupled with the automatic mode 1.5 seconds behind the time box. The aircraft arrival at touchdown (rescheduled) was within 5 seconds of that planned.

Consideration is being given to revising the predictive vector dashes to represent 1 and 2 minute intervals, which may be more convenient for use in performing standard rate turns (2 minutes per 180 degrees). Indeed, the predictive information could well have several alternative representations and scalings, such as distance or time for a metering and spacing environment.

An important conclusion is that the displays and CWS modes give the pilot an alternative method of accurate navigation and control, which permits him quick reaction time for an occasion such as the change in arrival time requested, or avoiding a threat. The track angle hold mode gave him time on the outbound leg to reprogram the computer to the readjusted time for further automatic flight. Without the displays he would not have been able to execute this type of re-positioning pattern with any degree of expediency or precision on his own. It is felt that this control/display capability is very necessary for the widespread success of RNAV/4-D navigation in the future environment.

LOCAL FLOW MANAGEMENT/PROFILE DESCENT (LFM/PD) FLIGHT TESTS

Local flow management (LFM) is a term used to describe a system of matching the demand on an airport to that airport's capacity by using time control at the metering fixes. A separate but closely related technique used with the LFM is profile descent (PD), an uninterrupted descent from cruising altitude/level to interception of a glide slope
or minimum altitude specified for the initial approach segment. Figure 34 illustrates a typical LFM/PD. FAA circulars A. C. No. 90-71 and No. 90-73 describe the procedures for the PD and LFM, respectively. The LFM is a time based metering scheme to systematically control traffic prior to delivery to the Approach Control and the profile descent allows a clean descent at or near flight idle from enroute cruise altitude to the final approach.

The combined LFM/PD concept provides fuel savings by matching the airplane arrival flow to the airport acceptance rate through time control computations and by allowing the pilot to descend at his discretion from cruise altitude to the metering fix in an idle thrust, clean configuration. Substantial fuel savings have resulted from LFM/PD but air traffic control workload is high since the radar controller maintains time management for each airplane through either speed control or path stretching with radar vectors. Pilot workload is also high since the pilot must plan for an idle thrust descent to the metering fix using various rules-of-thumb. The TCV program has developed new airborne guidance and control algorithms that can deliver an airplane to the assigned terminal area metering fix in a fuel and time efficient manner. These algorithms have been flight tested in the LFM/PD environments of the Denver and Dallas-Fort Worth terminal areas.

Denver Profile Descent Flight Tests.- The NASA has implemented and flight tested (ref. 19) in its TCV B-737 airplane a flight management descent algorithm designed to increase fuel savings by improving the accuracy of delivering the airplane to the metering fix at an ATC designated time and by transferring the responsibility of time navigation from the radar controller to the flight crew. The algorithm computes a profile descent to the metering fix based on airplane performance at idle thrust and in a clean configuration. Time and path guidance is provided to the pilot for a constant Mach, constant airspeed descent to arrive at the metering fix at the ATC specified time, altitude, and airspeed.

Flight tests using the flight management descent algorithm were conducted in the Denver, Colorado, LFM/PD ATC environment. The purpose of these flight tests was to quantify the accuracy of the airplane's descent algorithm and to investigate the compatibility and pilot acceptability of an airplane equipped with a 4-D area navigation system in an actual ATC environment. The velocity vector control wheel steering (VCWS) mode (ref. 7, 14, and 15) was utilized during these flight tests.

Two options of the EADI display symbologies (fig. 35) used for lateral and vertical path navigation on these flight tests were the vertical and lateral course deviation indicators and the star and flight path angle wedges (ref. 19). The flight path angle wedges used with the star display represent the inertially referenced flight path of the airplane. If the airplane flight path angle and track angle are adjusted so that the flight path angle wedges center directly on the star, the airplane will be flying directly to the waypoint.
Figure 36 shows a drawing of the EHSI display operated in a track-up mode. This display is a plan view of the desired route and optionally displayed figures such as radio fixes, navigation aids, airports, and terrain features drawn relative to a triangular airplane symbol. The range/altitude arc was used on the descent profile during these tests by setting the reference altitude to the programmed altitude of the next waypoint. Then the pilot would adjust the flight path angle of the airplane so that the arc would lie on top of the next waypoint displayed on the EHSI. This would result in the airplane crossing the next waypoint at the programmed altitude.

The flight management descent algorithm computes a five-segment descent profile (figure 37) between an arbitrarily located entry fix to an ATC defined metering fix. A sixth segment from the metering fix to the next fix (specified by ATC and called the aim point) is also generated. Time and path guidance descent information based on these six segments is provided to the pilot.

Between the top-of-descent and the metering fix waypoints, the airplane was flown at idle thrust and the use of speed brakes was not permitted. The captain used path guidance on the EHSI display and the lateral path deviation indicator on the EADI for lateral path guidance. For vertical guidance, he used the star and flight path angle wedges on the EADI and the range altitude arc on the EHSI display. It was the responsibility of the first officer to select the desired altitude for the range/altitude arc option so that the captain could devote his full attention to flying the airplane. The captain would anticipate leveling the airplane for the programmed altitude at the bottom-of-descent waypoint with reference to a conventional barometric altimeter and then would proceed to the metering fix.

The research flights demonstrated that time guidance and control in the cockpit was acceptable to the pilots and air traffic controllers. The flight data indicates that airspeed error of the airplane over the metering fix had a mean value of 0.27 knots and a standard deviation of 6.5 knots. Time error over the metering fix had a mean value of 2.5 seconds and a standard deviation of 6.9 seconds.

Fuel savings at the Denver airport as a result of LFM/PD operations have been estimated to be as high as three and a quarter million dollars per year (ref. 20). Additional fuel savings as a result of the airborne algorithms were quantified through an analytical comparison of a descent calculated by the flight management descent algorithm and a conventional descent typical of those airplanes observed on the ARTCC radar display (figure 38). Fuel usage for each descent was based on fuel flow for a B-737 airplane. Identical initial and final boundary conditions (location, altitude, speeds, and time) were used for both descents so that a valid comparison of fuel usage could be made. Both descents begin at the entry fix, 76 nautical miles from the metering fix, at an altitude of 10,668 m (35,000 ft), and at a cruise Mach of 0.78. The descents end at the metering fix at an altitude of 5,944 m (19,500 ft) and at a calibrated airspeed of 250 knots. Flying time for both descents is 11.7 minutes.
The conventional descent is based on idle thrust at a Mach of 0.78 with a transition to 340 knots airspeed. The descent from cruise altitude is started at a point 60 nautical miles from the metering fix which is consistent with various pilot rules-of-thumb for descent planning. At the bottom of descent, the airplane is slowed until reaching an airspeed of 250 knots. Thrust is then added as required to maintain the 250 knots airspeed. The descent calculated by the flight management descent algorithm is based upon an 11.7 minute time constraint. The calculated Mach/airspeed descent schedule for this profile is 0.62/250 knots. Thrust is set to flight idle approximately 7 miles prior to the descent point. A constant 0.62 Mach descent segment is started 40.6 nautical miles from the metering fix with a transition to a constant 250 KCAS airspeed descent segment to the metering fix.

Both descents, by definition of the comparison, require the same length of time to fly between the entry fix and the metering fix. This time objective is achieved with similar ground speeds on both descents. Even though the calculated descent is flown at a slower indicated Mach/airspeed descent schedule, similar ground speeds result since the airplane stays at higher altitudes for a greater time than on the conventional descent.

Fuel usage on these two descents is substantially different. The descent calculated by the flight management descent algorithm required approximately one-third less fuel to fly between the entry fix and the metering fix (653 pounds on the conventional descent and 447 pounds on the calculated descent). Approximately one-half of this fuel savings was attributed to the lower indicated airspeeds and one-half to flight at higher altitudes.

Fuel savings may be obtained on a fleet wide basis through a reduction of the time error dispersions at the metering fix and on a single airplane basis by presenting the pilot guidance for a fuel efficient descent. Pilot workload was reduced by automating those processes that required use of rule-of-thumb and/or extensive experience to achieve a solution to a complex 4-D navigation problem and through steering guidance for 4-D path following. ATC workload was reduced through a reduction of required ground-to-air communications and through the transfer of time navigation responsibilities to the cockpit.

Dallas-Forth Worth Profile Descent Tests.- Flight tests having similar results were conducted in the LFM/PD environment of the Dallas-Fort Worth terminal area, using the Lockheed-California Company L-1011 test airplane, to evaluate the performance potential of a Flight Management System which was modified by Lockheed (under NASA Contract) to incorporate a 4-D capability to control terminal area metering fix arrival time during fuel-efficient descents from cruise altitude. The results of these flight tests were similar to those of the Denver flights and will be reported in a near-future NASA contractor report.
The two local flow management/profile descent flight tests provided a unique opportunity to improve the communications between pilots and air traffic controllers. They demonstrated that precision management of speed and altitude, with thrust and time constraints added, may be accomplished in the cockpit and is compatible with a time based metering air traffic control environment.

Cockpit Display of Traffic Information (CDTI) Research Results.- Potential benefits of the CDTI fall into the general areas of improved capacity, efficiency, and safety. Proponents of the CDTI believe its application in the ATC process can improve terminal area capacity by allowing for reduced aircraft separation, efficient merging, and general improvement in aircraft traffic control and crew execution. Simulation studies addressing these issues are reported in reference 21. By providing sufficient information, collisions may be avoided through advance indications of traffic conflicts wherein the air traffic controller and aircrew can make course changes to resolve the conflict. The display may also serve as backup for certain ATC system failures.

Concerns for the use of the CDTI are that it may result in less efficient operations, with the aircrew challenging the air controller, increasing workload and possibly unilateral action resulting in less control and safety. The effect of CDTI usage on the air traffic controller and aircrew operational procedures and workload must be determined to judge its utility in the ATC system.

One of the major issues is the role of the CDTI in the overall ATC process. Should its use be passive as in a monitor role, where its application is to provide the aircrew with independent information on traffic for providing assurance and an error detection capability? Or, alternatively, can the CDTI be applied in an active role, utilizing the traffic display to control in-trail spacing and lateral separation and to resolve traffic conflicts, etc.? Ultimately, if the CDTI is a useful approach for improving the ATC operations, its application may be a compromise between the two roles described above. The aircrew will be able to utilize the CDTI to execute certain functions that are best controlled from the air, with knowledge of the controller, who has the overall ATC responsibility.

In an attempt to answer the above and related questions, the NASA - Langley Research Center is participating in a joint program with the FAA and NASA - Ames Research Center to evaluate the capabilities, benefits, and liabilities of the CDTI in the future ATC environment. Items to be addressed are the means for providing data of sufficient accuracy and frequency, the role of aircrew and controllers in the ATC process, evaluation of performance and accuracies to determine effects on capacity, controller and aircrew workload, and effects on safety. Excellent previous work has been done in this area, as reflected in a number of reports (ref. 21 and 22).
The NASA - Langley Research Center will particularly address the operational aspects of the CDTI in the terminal area. CDTI will be evaluated in a total system concept, considering CTOL aircraft of varying capability, using the advanced systems described earlier in this paper. Both simulation and flight research on the addition of traffic to the present electronic horizontal situation (EHSI) map display are being pursued, with the full range of display and control capability available on the TCV aircraft.

One possible application of the traffic to the EHSI map is illustrated in figure 34. Ownship aircraft (B-737) is shown in the middle of the screen with the display of other pertinent traffic within 10 nautical miles of ownship. This figure includes waypoints, terrain symbology, flight plan, aircraft identification, speed, altitude and other symbols. Several options, including predictive vectors for all aircraft, are being pursued to enhance display symbology and format. In this scenario ownship is landing after a DC-9 and is being followed in order by a B-737 and B-727S. The position of ownship relative to the time box indicates that ownship is proceeding on schedule. Initial simulation and flight experiments using CDTI have been conducted by the TCV program. These experiments addressed symbology, merge and spacing tasks, pilot scan patterns (with and without traffic), separation variation, and effects of CDTI in actual flight.

CDTI Simulation Study.- The TCV program fixed base simulator was used to conduct an experiment involving the evaluation of cockpit display of traffic information. The experiment was conducted using taped time-dependent, non-interactive traffic in an approach to landing situation with two levels of pilot control: 3-D automatic and computer augmented control (VCWS). Speed control via manual speed selection and autothrottle was used in all tests (path stretching was not allowed for maintaining separation between aircraft). The results (ref. 23) indicate that reasonable approach task performance can be maintained when traffic information is displayed on a RNAV type map for both merge and follow type situations. A trend toward reducing separation where large gaps existed was observed. This gives some evidence of "electronic VFR" operation. Overall, the results are favorable toward presentation of traffic information during fixed path, descending, decelerating approaches. A sample photograph of the EHSI for the case of merging traffic is shown in figure 40.

Pilot Scan and Dwell Time Study.- A companion oculometer experiment was conducted during the CDTI simulation experiment to determine pilot visual scan patterns with and without traffic information on the EHSI. Long straight-in and close-in, curved, descending instrument approaches were made in NASA's fixed base TCV simulator. The pilot either manually controlled the simulator or monitored the automatic system control of the simulated aircraft during the approach. Tests were performed with and without the display of traffic. The results (ref. 24) indicate that the pilots' use of the EHSI increased for the manually controlled close-in, curved, descending approach compared to the conventional straight-in
When operating as a monitor of the automatic system, the pilot scanned around more with less attention devoted to the EADI. The pilots preferred the manual mode because it kept them in the control loop. The addition of displayed traffic to the EHSI increased the pilots' use of the EHSI with a corresponding reduction in his use of the EADI. A summary of dwell time percentages for the EADI and EHSI with and without traffic for the manual and automatic controlled straight-in and curved approach tasks is given in the following table.

### EFFECTS OF TRAFFIC SYMBOLOGY ON DWELL TIME PERCENTAGE

<table>
<thead>
<tr>
<th>Traffic</th>
<th>Straight Approach (VCWS)</th>
<th>Curved Approach (VCWS)</th>
<th>Curved Automatic Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFF</td>
<td>79</td>
<td>47</td>
<td>38</td>
</tr>
<tr>
<td>ON</td>
<td>68</td>
<td>35</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EHSI</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OFF</td>
<td>3</td>
<td>42</td>
<td>39</td>
</tr>
<tr>
<td>ON</td>
<td>16</td>
<td>53</td>
<td>56</td>
</tr>
</tbody>
</table>

This addition of traffic information to the EHSI increases the pilots' attention to this display by 11 to 17 percent with the greatest shift in attention occurring for the automatic control cases. A secondary result of this experiment shows that the pilot uses the EHSI considerably more for the curved approach case than for the straight-in approach case with or without the display of traffic symbology. It was also noted that the pilot's pupil diameter increased during the landing flare indicating a higher stress level even though the tests were conducted in fixed base simulator. This experiment has been repeated in flight to obtain data for simulation validation and to determine the effects of actual flight operations. Preliminary review of the flight data indicates a high degree of correlation between simulation and flight results. Final results of these flight tests will be reported in a near-future NASA report.

**CDTI Flight Experiments.** The CDTI simulation experiment, using the symbology of figure 40, has been repeated in a TCV B-373 flight experiment. Preliminary results indicate good agreement with results of the simulation experiment. Flight experiment results are being prepared for an NASA report.
An additional TCV B-737 flight experiment has been conducted to evaluate coded traffic symbology (fig. 41) for CDTI based on results of earlier human factors studies. The primary objective was to subject the coded traffic symbology to a realistic environment and to assess its value by means of a direct comparison with simple, uncoded traffic symbology. The tests consisted of curved, descending, decelerating approaches, flown by research pilot flight crews. The traffic scenarios involved both conflict-free and blunder situations.

Subjective pilot commentary was obtained through the use of a questionnaire and extensive pilot debriefing sessions. The results (ref. 25) of these debriefing sessions group conveniently under either of two categories: display factors or task performance. A major item under the display factor category was the problem of display clutter. The primary contributors to clutter were the use of large map scale factors, the use of traffic data blocks, and the presentation of more than a few aircraft.

In terms of task performance, the coded traffic symbology was found to provide excellent overall situation awareness. Additionally, the pilots expressed a willingness to utilize lesser spacing than the 2.5 mile separation prescribed during these tests. This result agrees well with the similar observations, using the traffic symbology (fig. 40), of the earlier CDTI simulation and flight experiments. Results of pilot scan and dwell time measurements obtained during these flight experiments will be reported later. The demonstrated use of CDTI offers potential to improve safety in crowded terminal areas.

NASA and FAA are developing additional test scenarios to address the various roles and application of CDTI in projected ATC environments with TCV aircraft flight tests planned for the NASA - Wallops Flight Center (WFC) and FAA-NAFEC.

ADDITIONAL TCV PROGRAM RESEARCH

Additional research activities, presently being focused or planned as future efforts, are required to accomplish the TCV objectives and to address the many aspects of terminal area operations as previously illustrated in figure 4. These areas of research are: metering and spacing, curved path guidance and control for both automatic and manual flight, wind shear hazard alleviation, landing displays, and landing and turnoff operations. The extent of research accomplished or planned in each of these areas varies from feasibility studies or benefit analyses, to simulations, and to flight tests for verification and demonstration.

Metering and Spacing. - Metering and spacing (M&S) is an initial time based control concept for controlling aircraft from the metering fix to the runway. A fixed path speed control concept of M&S currently under study is one in which the ATC aids an aircraft to achieve a
scheduled landing time by issuing airspeed commands to the pilot at pre-selected locations in the airspace. A joint NASA/FAA study has been implemented to evaluate application of the MLS to an automated terminal area metering and spacing concept. Present efforts include considering more fully the interactions between multiple aircraft in the terminal area. In addition, it is necessary to determine if theoretical results will be confirmed with human pilots in the control loop. Also, it is necessary to determine if the maneuvers for path stretching and speed control are acceptable to the pilots.

Wind Shear Sensing, Display, and Control.- A recent series of aircraft crashes attributable to severe wind shear have focused attention on the shear hazard and have led to the establishment of a large program for research on means to alleviate the hazard. It is felt that no matter how well one estimates shear from a comparison of groundspeed and airspeed, or from sensors near ground level, the pilot needs immediate information of shear encounters on his primary displays with which he can instinctively take the proper course and degree of action. It was decided to explore wind shear instrumentation using the EADI in the TCV B-737 since this is the primary approach instrument. The EADI of the TCV B-737, in its normal format, presents instantaneous flight path aiming point, derived from the inertial system, with a pair of separated wedges (figure 9), which move up and down with respect to the horizon for climb or dive, and left and right from the airplane symbol to indicate lateral drift. They remain parallel to the horizon at all times. To the left of the wedges is a bar representing acceleration along the flight path, or potential flight path angle. When this bar is alined with the wedges the airplane is in stabilized flight with respect to groundspeed.

To adapt the EADI to shear detection the potential flight path angle bar was mechanized to separate from alinement with the flight path wedges in response to airspeed error, related to a selected "bug" speed, and airspeed error rate. The bar moved above the wedges if speed were high and below if speed were low. The bar thus became a thrust command when misalined with the wedges. The flight path wedges retained their normal function. The pilot, when encountering shear, would correct changes in the flight path angle, as indicated by the wedges, with elevator input and would correct airspeed changes, indicated by the thrust command bar, with throttle use in the same sense as for speed control. The pilots found this display very effective in coping with shear of the normal varieties. The display will be investigated for effectiveness in severe thunderstorm shears, definition of which have recently been obtained for implementation in the simulation. These studies will be reported when the evaluation of the display effectiveness with the severe shears is completed.
New automatic control laws for the final approach are being developed to anticipate wind shear and provide lead information for improved control. The wind shear is anticipated from groundspeed and airspeed differences along the approach path compared with anticipated groundspeed at touchdown derived from known ground winds. Ground speed in flight can be determined from sources such as a MLS guidance system, ILS co-located DME, inertial or doppler navigation system, etc. It remains to be seen if such anticipatory automatic systems can cope successfully with the severe storm shears.

In addition to display and control concepts, a new total energy probe (ref. 26) is being evaluated for application as a wind shear sensor on the TCV B-737. It senses a pressure change of $\Delta q$, a combination of static and dynamic pressures, throughout the required speed range. This measurement is insensitive to sideslip and angle of attack through large ranges. The output of the sensor should read a constant value with constant thrust and configuration under constant air mass conditions regardless of flight path angle variations. An analysis of how to use this sensor for wind shear detection and for control and display application is underway.

Landing Displays.- Schedule reliability and safety during landing approach and landing in low visibility must be improved for future operations. An obvious step toward this capability is required for future systems in order to:

1. Improve schedule reliability with regard to weather (ref. 27), not for "airline economics" solely, but for the benefit of industry, military, and the traveling public.

2. Reduce accident potential present in "See-to-Land" concepts in all reduced visibilities, CAT I and II included.

3. Reduce landing aborts to the minimum possible because of the impact on an already congested traffic situation and wasted fuel.

CAT III conditions (in an "effective" sense) also occur in conditions other than fog with light winds, such as in strong crosswinds with blowing and drifting snow, for example. Thus, CAT III systems must be designed with wider operational envelopes (headwinds, turbulence, shear, crosswinds, tailwinds) than they are today. To add pilot confidence and acceptance to a truly operational CAT III system, it is felt that situation information approaching an "absorb-at-a-glance" format must be available to the pilot. The display must be informative, accurate and compelling enough that the pilot does not feel the need to look elsewhere for flight control information. It must be adequate for the pilot to do something about his situation if it is not to his liking - not simply to execute an abort to cause more problems, unless necessary. In CAT III - like conditions it is considered unlikely that a pilot can concentrate on transient, distorted and inadequate outside references for judgment of the critical landing maneuver and make use
of skeletonized HUD information at the same time, except to tell him where to look. Considering these factors it is, therefore, reasoned that head-down-display (HDD) development is necessary in achieving safe and reliable operations in all visibility conditions. Recent European developments tend to substantiate this reasoning (ref. 28).

It is felt that if the display is good enough to give the pilot the information and confidence for monitoring an automatic approach, regardless of outside visibility, it may very well be adequate for manual landing, assuming some form of augmented control system. If this were true, pilots would be able to retain currency by executing landings with it in normal as well as low visibility operations.

This is not to say that the head-up display (HUD) should not be used. It is thought that the pilot monitoring the approach should stay on a basic HDD throughout approach and landing. The overall approach and landing manager should, perhaps, have a HUD for whatever information he can obtain with it and outside visual references. Also, the HUD may be a useful backup against failure of the HDD in the eventual system.

It is felt that an operational CAT III "landing" display should be pursued on a long range basis. Today, such a display does not exist in an operational sense. However, Langley Research Center is sponsoring research and development of landing display technology. Computer generated images of terrain and airport features and runway texture and marking are being evaluated with respect to contributions to approach, and particularly, landing performance. A modest range of color, shading and a spread of magnification ratio are being investigated, all in a head-up position as though looking through the windshield in this case. An oculometer is being used also to obtain look points for different pilots with the differing display formats. The data are being analyzed to see if an understanding can be obtained of what information the pilot is seeking and using. The pilots being evaluated include research, airline, instructor, and executive types. No conclusions have been drawn as yet as the program is ongoing.

Landing and Turnoff Operations.- Increased efficiency and capacity of operations in the terminal area are considered important TCV research objectives. As enroute, descent, and approach operations improve, the landing and runway occupancy time will become the major constraint in achieving overall capacity increases.

As illustrated in figure 42, (ref. 29), the potential increase in capacity resulting from a reduction in spacing is significant. In the study of reference 29 a traffic mix of only two types of aircraft was used, a large aircraft with a final approach speed of 127 knots, and a heavy aircraft with a final approach speed of 137 knots. When compared to current vortex separation standards the gain in capacity with a 3 nautical mile separation goes up appreciably with the increase in percentage of heavy aircraft (due to speed) as shown in the figure. This is a significant factor as more heavy aircraft go into service. Also noteworthy, is the significant capacity gain due to increased delivery accuracy at the runway in terms of time. There is thus an urgent requirement for better performance of the future traffic control
systems in terms of time. The curves for 2 nautical mile separation illustrate what may be achieved with further alleviation of the vortex hazard and a reduction of runway occupancy times.

Efficiency operation resulting in high capacity cannot be achieved unless aircrafts can land and consistently exit the runway in minimum time. This must be accomplished even in very low visibility conditions. To achieve this objective, better aircraft control is required to consistently land at a more precise point on the runway. After touch-down, the aircraft must quickly exit, so as to allow for the safe approach and landing of trailing aircraft. Runway exits which will allow much higher exit speeds must be designed for efficient operations, considering safety, tire wear, and passenger comfort.

The TCV program is performing research in a number of areas in an attempt to solve these problems. New autoland control laws which include the flare and improved autothrottle action, with and without direct lift control, are being developed to cope with shear and the effects of ground winds in improving the precision of touchdown. New flare laws have been developed and flight tested with promising results. One of these flare laws uses ground speed as a parameter in the time constant of the flare law. Another is based on a fixed path in space from flare initiation to touchdown. Touchdown dispersion data obtained from flight tests of these two laws agree very well with the predicted results based on simulator experience. The variable time constant law produced a standard deviation in touchdown dispersion data of approximately 36 m (126 ft) while the fixed path law produced a standard deviation in touchdown dispersion data of approximately 30 m (100 ft). These results represent an improvement of at least a factor of three over the touchdown dispersion data of the more conventional flare laws. Coupled with this activity is the necessity for pilot display development to allow monitoring or control of landing rollout deceleration and turnoff.

An angled exit concept is being studied which will provide information on exit speeds, turnoff design, distance and time from touchdown to exit, and other parameters. Control laws have been developed for automatic high speed turnoff considering a magnetic leader cable for guidance. Such a system is ready for ground test. A runway turnoff has been built at the NASA - Wallops Flight Center for flight evaluation of pertinent parameters and control and display concepts.

Potential operational benefits of the expected results of these additional areas of research are discussed in detail in references 8 and 30.
FUEL ECONOMY IMPLICATIONS OF TCV PROGRAM RESEARCH RESULTS

In many cases research results of the TCV program have been applied and demonstrated on the TCV B-737 in real world operational environments. Benefits have been estimated for operations using the concepts developed and demonstrated by the TCV program.

LFM/PD which the FAA now has operational in the field (at the Denver and Forth Worth Air Route Traffic Control Centers) uses a method of time based metering of arrivals. Relatively simple calculations are used to estimate the time each arrival should pass a metering fix so that it can fly directly to the runway and land without delay. As these calculations are made while the aircraft are still at cruise altitude, any necessary delay can be absorbed at higher altitudes where jets operate more efficiently. Although the system is initially manually implemented and uses vectoring to achieve the metering fix times, significant operational improvements have been reported. The terminal area peak traffic count and arrival controller workload are reduced and aircraft save fuel by avoiding excessive low altitude vectoring. An average fuel saving of 630 pounds per arrival has been estimated.

Flight manager computer systems are being designed for the next generation airplanes and for retrofit into existing airplanes. This equipment can accommodate 4-D navigation and guidance. The benefits of this equipment include reduced pilot workload and fuel savings enough to provide a cost benefit payoff. A study performed for NASA (ref. 31) shows a potential 10.2 percent (397 pounds) fuel saving (short range flight) and a 5.0 percent (538 pounds) fuel saving (medium range flight) for an energy managed airplane over a conventional present day profile. These savings are total fuel for all phases of flight and so could be applied theoretically to all airline operations. It should be noted that these savings do not take into account the potential benefits of reducing the schedule build-in-delays discussed in this paper.

The two programs discussed above can be combined into a time based ATC system using 4-D navigation and guidance. This concept has been called strategic control. Strategic control is a high density terminal area ATC concept. It can achieve increased airport capacity by precisely spacing aircraft at the runway. Precise spacing depends on aircraft being equipped with 4-D navigation systems so that they can arrive at a destination within 5 seconds of a planned time. The ground system provides an automatic separation and flow management planning function. This gives 4-D route profiles for each aircraft. These profiles are fuel efficient, assure separation and maximize flow. They extend about 150 nautical miles, so that, once cleared to fly, the pilot would not normally be disturbed by ATC for a reasonably long time. An additional 350 pounds of fuel saved per arrival is estimated for a 4-D equipped airplane over an unequipped airplane in a strategic ATC system. This savings has been at least partially verified by the TCV Program LFM/PD flight tests at Denver.
The benefits of area navigation in general have led to its current use in many general aviation airplanes and in some air carriers. Studies performed for the FAA (ref. 32) estimated savings to air carrier airplanes of the following:

<table>
<thead>
<tr>
<th>FUEL (1,000 POUNDS)</th>
<th>TIME (1,000 Min.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-D</td>
<td>995,975</td>
</tr>
<tr>
<td>3-D</td>
<td>476,800</td>
</tr>
<tr>
<td>4-D</td>
<td>980,370</td>
</tr>
<tr>
<td></td>
<td>2,453,145</td>
</tr>
</tbody>
</table>

These savings are an annual estimate based on 1984 forecast traffic levels and airplane mixes. The study assumes some accommodation by ATC to area navigation equipped airplanes (RNAV routes, SIDs and STARs, parallel routes for better altitude selection, etc.); however, the strategic control type ATC scenario was not assumed in the benefits of the paper. Therefore, the benefits calculated are proportional to the number of equipped airplanes and on an average will accrue to only those equipped. Further benefits have been estimated to the ATC system as follows (ref. 33):

- 3.2% Increase in Arrival Rate
- 6% Reduction in Arrival Time In System
- 34% Reduction in Arrival Delay
- 42% Reduction in Control Radio Transmission Time
- 39% Reduction in Control Radio Transmissions
- 54% Reduction in Number of Control Instructions
- 93% Reduction in Radar Vectors
- 71% Reduction in Altitude Instructions
- 74% Reduction in Combined Instructions

Area navigation using the MLS will allow more direct flight to the runway and can save up to 2.36 percent of block fuel using a 1 nautical mile final approach.

Improved touchdown dispersion will help reduce occupancy time and thus increase runway utilization rates. It will help optimize field length performance and locate high speed runway turnoff points. Improved touchdown dispersion will increase autoland utilization, especially under marginal weather conditions and thus result in better adherence to published schedules. This in turn will contribute significantly to passenger confidence and airline profitability.
The velocity CWS system with corresponding display can help minimize the transition problem from automatic to manual control, without significantly increasing pilot workload, loss of performance or compromise in flight safety. Optimal control responses and properly displayed information allow the pilot to execute the same complex maneuvers as can be executed by the fully automatic system. Without additional pilot control inputs after the airplane is on the desired path, the airplane will maintain the established earth referenced horizontal and vertical paths, regardless of turbulence, wind shear, speed or configuration changes. Complex maneuvers that normally require a high level of piloting skill and training, such as decrab and flare, are simplified to easily and reliably executable maneuvers. The integrated nature of this control/display concept provides a unique opportunity to further integrate the concept with a head-up display.

The integrated system design will force the consideration of time, cost and fuel for each flight condition. The integrated control law design will, from the start, establish the proper priorities as a function of flight condition and schedule the use of throttle and elevator for control accordingly. For example, during cruise, the system performance emphasis is on minimum throttle excursions (fuel economy), passenger comfort, and safe control in cases of large gust upset. During final approach, emphasis is on flight speed and path tracking, regardless of throttle and pitch activity.

The value of the TCV program to industry and to the nation has been demonstrated in the first years of this program. However, there is much advanced technology which is in the laboratory development stage and has shown significant potential for further operational benefits. Minimum fuel guidance algorithms for operation in the future ATC system, improved flight control laws, MLS guidance development, and the integration of new high capacity computing and color display technologies are but a few of the items we know need testing and validating.

CONCLUDING REMARKS

1. Accurate 4-D flights over long distance for control of arrival times are readily feasible. Accurate control of threshold arrival times can result in large increases in capacity, particularly if longitudinal spacing of aircraft can be reduced.

2. Instrumentation for 4-D fuel efficient descents is feasible.

3. The MLS provides very precise guidance that an automatic system can follow accurately for close-in curved paths, approaching VMC operational capability, through landing and rollout. Through use of advanced electronic displays the pilot, using CWS modes, can also fly equivalent curved paths manually with overshoots of 50 m or less during alinement with the runway as close as 1 mile, even with very little practice. The paths can save time and airspace on arrival.
as well as provide merge capability from several directions. Because of the reduced possibility of significant overshoot, more closely spaced runways for simultaneous approaches in IMC seem feasible.

4. Alleviation of noise impact on the ground through use of avoidance paths is feasible and has been well demonstrated.

5. In order to take advantage of improved displays the controls and displays must be considered together in design as a single system to assure quick and precise corrections and maneuvers.

6. Electronic displays in combination with appropriate sensors for providing advance information enable the crew to navigate and control the aircraft manually with precision and safety in 4-D flight in lieu of automatic control or in any combination of automatic and manual control. The displays also provide redundancy for the automatic modes, permit piloted contingency action, and permit instant response to ATC directives without reprogramming the flight computers.

7. Display of pertinent traffic on the navigation displays, particularly in the terminal area, would seem to be very important for crew assurance, at least, in closely spaced traffic, even in visual conditions. With additional display enhancement it may prove feasible for the crew to establish and maintain its own separation, or to take threat avoidance action when required.

8. Distributed control is a viable concept for the future, particularly with advanced displays for the pilot, and has been illustrated during MLS demonstrations in Buenos Aires, New York, and Montreal.

9. In retrospect, pilots found curved approach paths to runways both acceptable and comfortable as for visual flight, and passengers offered no adverse comments.

10. It cannot be over-emphasized that the TCV program, as well as some other NASA programs, must work hand-in-hand with FAA to accelerate the application, exploitation and integration of promising research results into the air traffic system toward needed major improvements. This applies to research ongoing in navigation, guidance, communications and airborne systems, as well as operating techniques and procedures.

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