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# Simulation Study of the Operational Effects of Fuel-Conservative Approaches

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**Fuel-conservative procedures have been investigated using real-time air traffic control simulations linked to two piloted simulators. The fuel-conservative procedures studied were profile descents and two types of landing approaches, delayed flap and IATA. The investigation determined the effect of these procedures on the ATC system operation. It examined the mixing of aircraft executing fuel-conservative approaches with those executing conventional approaches. The most difficult approach type mix of traffic was found to be 50% conventional and 50% delayed flap. However, for the test scenario chosen, arrival rates of at least 30 aircraft per hour were feasible and resulted in a net average fuel saving, even for the most difficult mix. Also, there is a fuel savings and reduced controller workload for the profile descent procedures.**

## Introduction

THE current energy situation (fuel shortage and rising costs) has mandated the development of inflight aircraft operational procedures that provide greater fuel economy than those presently used. Various fuel-conservative procedures have been proposed. Those to be considered here are profile descents and two types of landing approach procedures, the delayed flap approach and the International Air Transport Association (IATA) low power noise abatement approach technique (hereafter referred to as IATA approach). In terms of an individual aircraft, each procedure, if executed as planned, saves fuel for that individual aircraft. However, the impact of these procedures on the Air Traffic Control (ATC) environment is uncertain. For a procedure to be worthwhile, it must not only save fuel for the individual aircraft, but also must result in a reasonable workload for the controller and the pilot. Further, it should not significantly delay other aircraft, nor shift the delay to another part of the ATC system such that the overall system fuel usage is increased.

The purpose of this study is to evaluate the effect of the fuel-conservative approaches on ATC procedures and terminal area capacity. Since these procedures involve both the pilot and controller, they must be studied by means of real-time simulations of airborne and ground systems. During the past 4 years, NASA's Ames Research Center and FAA's National Aviation Facilities Experimental Center (NAFEC), operating under a joint research program, have interconnected ATC and piloted simulation facilities at both centers to create a unique national facility for the study of pilot-controller interactions.

First, the simulation facilities are described. Then the aircraft operational procedures evaluated in the experiments are outlined. Next, two experiment studies are discussed. The first, conducted in February 1977, concerned two types of landing approaches; the second investigated profile descents in July-August 1977. Both experiments are discussed briefly. Individual, detailed reports on each of the simulations are in preparation and should be available later this year.

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## Simulation Facilities

ATC simulation facilities at both FAA NAFEC and NASA Ames were used in the real-time simulation studies. For the profile descent experiment, the Air Traffic Control Simulation Facility (ATCSF) at NAFEC was used. The facility consists of a computer complex and a number of air traffic controller and keyboard pilot stations. Up to 64 keyboard pilot positions are available to control the computer-simulated aircraft. Each position can handle up to 10 aircraft simultaneously. The aircraft are controlled by keyboard entry, and the clearance vocabulary permits these aircraft to respond to the same set of clearances that are issued in today's ATC system.

Piloted aircraft simulators at Ames can "fly" in this ATC environment, which has been created by the ATCSF via transcontinental voice and data links that were developed jointly by Ames and NAFEC. Aircraft identification, position, velocity, and heading were transmitted to NAFEC via a data link. In addition, the number of the voice channel currently in use by the pilot was transmitted via data link. The voice link was then connected at NAFEC to permit the pilot to establish contact with the appropriate control sector. Details of this communications link can be found in a separate NASA publication.[1]

Two flight simulators at Ames participated in the ATC simulation. One simulator, the moving base transport cab, simulates a wide range of aircraft during takeoff, approach, cruise, landing, and taxiing. The cab has out-the-window virtual-image TV displays; panel, center, and overhead instruments; programmable force-feel flight controls; and autothrottles. In the study, the cab was used as a fixed base, configured as a Convair (CV) 990. The CV-990 was simulated, rather than a more commonly used turbofan aircraft, because Ames has previously conducted flight and simulation tests of the delayed flap procedures with a CV-990 aircraft. The second simulator, a general purpose simulator called the flight management research simulator was also used. It can provide the controls, displays, and tasks of a large number of advanced avionics systems. The simulator is a two-seat cab equipped with the standard mechanical in-

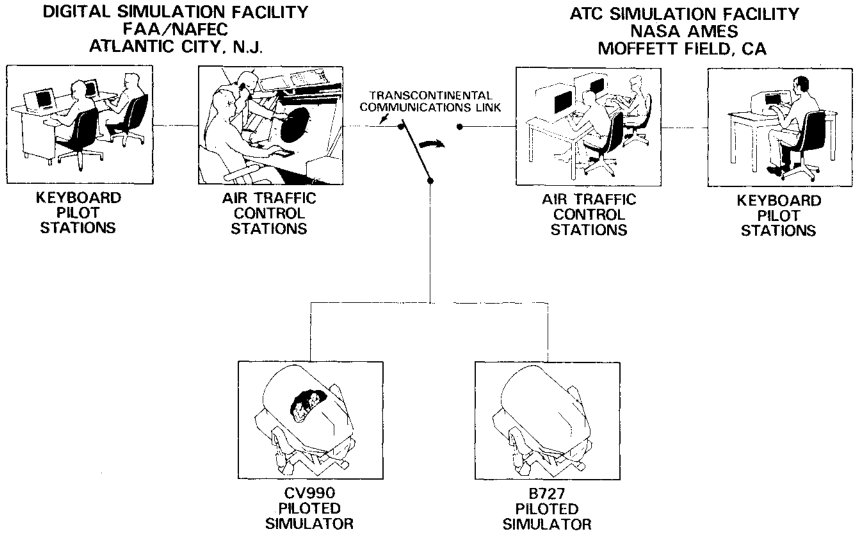


**Fig. 1 Joint FAA-NAFEC/NASA Ames Simulation Facility.**

strumentation, as well as an autopilot and an electronically generated area navigation (RNAV) map display. For these simulations, the RNAV system was not used and a standard horizontal situation indicator (HSI) was drawn on the map display. This simulation was configured as a Boeing (B) 727. For the remainder of the paper, the piloted simulators are referred to as B-727 and CV-990.

As previously noted, an investigation was also conducted involving the interactions of the ATC system with delayed flap and IATA approaches. In this case, a less elaborate ATC simulation facility at Ames was used. This facility was developed with the assistance of FAA to provide a versatile ATC research simulator for investigating the interaction between the ATC system and the advanced aircraft guidance systems. The facility consists of 2 alphanumeric displays (for up to 4 controller positions) and 3 keyboard pilot stations. Additional details on the Ames ATC simulator can be found in a NASA technical note.[2] A block diagram of the facilities described above is given in Fig. 1.

## Flight Path Descriptions

### Delayed Flap and IATA Approaches

The delayed flap approach was developed as a low-noise, fuel-conservative alternative to the conventional jet transport instrument landing approach procedure.[3] In contrast to a conventional approach, which is flown at a constant airspeed of 140 to 160 knots, depending on aircraft type and weight and high landing flap settings throughout, the delayed flap approach begins in the clean configuration at a high initial speed (210 to 240 knots). The pilot intercepts the Instrument Landing System (ILS) glidepath at about 10 n. mi. from touchdown and at an altitude of 3000 ft (all altitudes are above ground level). At the glide-slope intercept, he then retards the throttle to idle, and the aircraft begins to slowly decelerate on an approximate 3 deg glidepath. At about 6 n. mi. from touchdown, the pilot is given a cue from an onboard computer to lower the landing gear. At about 5 n. mi., another cue is given to lower the approach flaps, after which the flaps are commanded to the landing position at about 4 n. mi. The aircraft decelerates to final approach speed at an altitude of 500 ft, 1.5 n. mi. from touchdown. At this point, the pilot advances the throttles to approach power, and the last portion of the approach is flown at a stabilized airspeed similar to a conventional approach.

The IATA approach[4] requires no onboard computer. The approach speeds are higher than a conventional approach, but less than the speeds used in the delayed flap approach. The IATA arrival procedure is such that at a distance of 12 to 15 n. mi., the aircraft flies level at 3000 ft at a speed of 210 knots and in a position to intercept the ILS. Prior to glide-slope

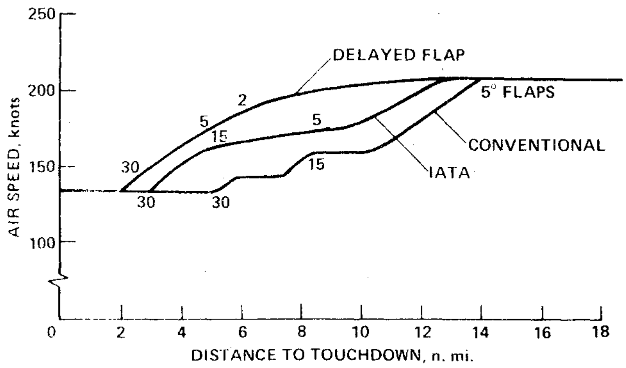


**Fig. 2 Speed profile for conventional, IATA and delayed flap approaches.**

intercept, the aircraft decelerates to reach 185 knots at glide-slope capture. On the glide slope, the aircraft decelerates to its final approach speed plus 20 knots by the time it reaches an altitude of 1500 ft. Final approach speed should be achieved by 1000 ft. Figure 2 shows speed profiles vs distance to touchdown for delayed flap, IATA and conventional approaches. Note that the difference in speeds in these approaches occurs between 12 and 2 n. mi. from touchdown. The touchdown speeds are the same for a given aircraft type.

### Profile Descents

Recent FAA studies have indicated the possibility of reducing fuel consumption by improving descent profiles. Procedures were implemented to minimize the amount of time high-performance aircraft operate at low altitudes in the terminal area. Besides saving fuel, other benefits of profile descents are 1) increased safety by reducing exposure time between controlled and uncontrolled aircraft at lower altitudes in the vicinity of airports, 2) reduced aircraft noise in the vicinity of airports, and 3) standardized high-performance aircraft arrival procedures.

A profile descent is defined in Ref. 5 as "an uninterrupted descent (except where level flight is required for speed adjustment; e.g., 250 knots 10,000 ft MSL) from cruising altitude/level to interception of a glide slope or a minimum altitude specified for the initial or intermediate approach segment of a nonprecision instrument approach." As implemented in this study, arrival flights cruising at or above FL240 used a profile procedure. For a given cruise speed and altitude, descent began at a distance that allowed for a descent rate of 300 ft/mi. A typical descent profile, as flown by the B-727 simulator, is shown in Fig. 3. By contrast, a typical conventional descent might begin descent further from

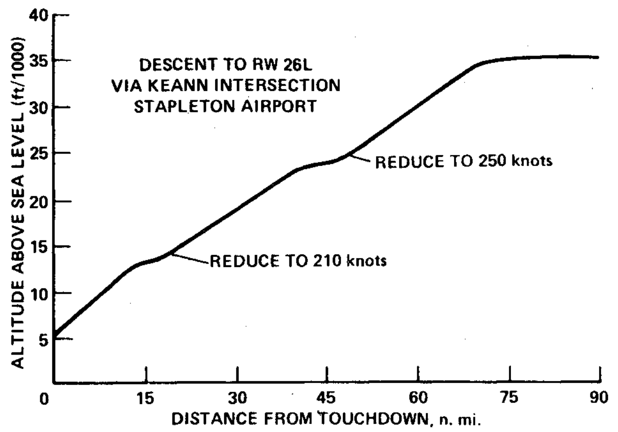


Fig. 3 Profile descent flown by the B-727 simulator.

touchdown, descend more rapidly and in general spend a greater percentage of its time flying level at lower altitudes.

## Delayed Flap and IATA Approaches Experiment

### Description of Experiment

The delayed flap and IATA experiment consisted of 32 runs of 70 min duration each (4 runs per day). This simulation took place entirely at Ames using the Ames ATC simulator, computer-generated aircraft, and two piloted simulators. The route structure was based on two routes at the John F. Kennedy International Airport (JFK). The route structure is shown in Fig. 4. The controller subjects were FAA research controllers from NAFEC; the pilot subjects were airline pilots affiliated with major airlines operating out of San Francisco and Oakland.

### Experiment Variables

One variable was arrival rate in the terminal area. The delayed flap flight experience shows that; in light traffic, controllers had no difficulties accommodating the delayed flap approaches. However, analyses and fast-time simulation studies indicated that difficulties might be encountered in handling a mix of approach types at, or near, ATC system capacity. Therefore, it was important to pinpoint the arrival rates that could be accommodated without excessive workload and without introducing additional aircraft delays. An arrival rate of 25 aircraft/h was expected to be a moderate rate, while 35 aircraft/h was expected to be near saturation. Additional data were taken at 30 aircraft/h. It should be emphasized here that the variable is arrival rate in the terminal area, not runway operations rate. For the 70-min duration of each experiment run, these can be considerably different. Just how the terminal area arrival rate effects the number of missed approaches and the delays will be discussed shortly. Note, however, that increased missed approaches and delays will decrease runway operations rate.

The second variable was the mix of the approach types. The following approach mixes were examined: 50% conventional, 50% IATA; 50% conventional; 50% delayed flap; and 33% conventional, 33% IATA, 33% delayed flap. Random arrival sequences were generated for each of the mixes. (Randomness was introduced into order of arrival types as well as times of arrival at the feeder fixes.) Data were also taken for single approach types: 100% conventional, 100% IATA, and 100% delayed flap. These were used as baseline runs.

### Controller Instructions

In the first simulation at Ames, two air traffic control positions were established. The approach controller handled all incoming traffic. Handoff to the final controller from Cassville (South approach route) occurred about halfway down the route; the Deerpark (North approach route) hand-

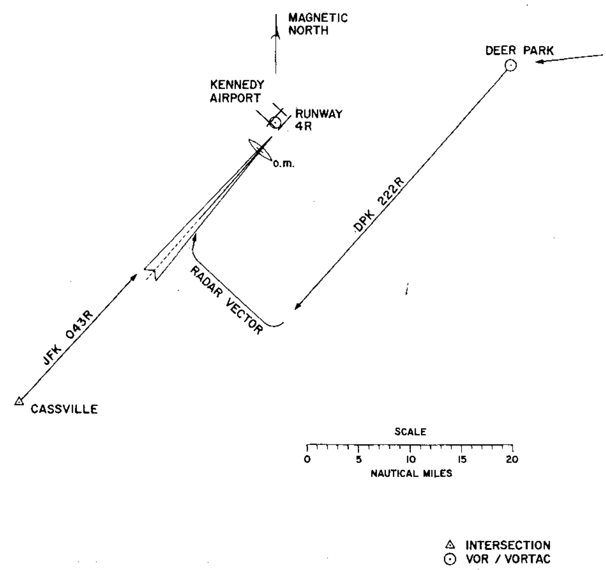


Fig. 4 Route structure for delayed flap and IATA approaches experiment.

off was at the turn to the base leg.§ The final controller used the base leg to provide the required spacing between aircraft.

Prior to taking data, the controllers were given the following instructions:

1) All aircraft must have an in-trail separation of at least 3 n. mi.

2) Aircraft on a missed approach were directed to proceed over the runway and then to the Deerpark route and merge with incoming traffic as soon as adequate spacing was available.

3) The delayed flap and IATA approaches should generally be flown without altering the speed profile. (Data next to the aircraft tag on the controller screen indicated the type of approach the aircraft wanted to fly). On occasion, speeds could be reduced to establish spacing. Also, the approach controller was told to accept only as many aircraft as he could handle without requiring large path-stretching maneuvers. All other aircraft were to hold at the start points; additional spacing could be obtained by this method, though at the expense of delays outside the terminal area.

## Results: Delayed Flap and IATA

First, qualitative results including observations and controller evaluations are discussed, followed by data on missed approaches, air space, and fuel usage.

### Observations and Controller Evaluations

Qualitative data were obtained both from controller-written evaluations and by observing the controller activity during the course of the experiment.

Controllers had no trouble with the baseline runs. They felt that 100% of any type of approach is easy to handle, even at the high arrival rate. If anything, the 100% delayed flap case seemed easier, possibly because each aircraft was in the system for the least time (approximately 1 min less than a conventional approach). Next in ease of handling was the 50% conventional, 50% IATA mix; with only a 20-knot speed difference between these two types, the controllers learned that they could essentially handle all aircraft as a single type. The most difficult mix was 50% conventional, 50% delayed flap. As a consequence, the mix of three types was essentially

§Only 20% of the traffic was from Cassville. If there was a more even mix of traffic from Deerpark and Cassville, a second approach control position would have been required. Since the Ames ATC simulation facility was limited to one final and one approach control position, it was necessary to restrict traffic from Cassville.

**Table 1 Average number of missed approaches (% of total approaches)**

| | | | |
|---|---|---|---|
| Baseline | 0.0 | ... | 1.2 |
| 50% Conventional<br>50% IATA | 0.0 | ... | 1.5 |
| 50% Conventional<br>50% Delayed flap | 1.3 | 3.7 | 4.1 |
| 33% Conventional<br>33% IATA<br>33% Delayed flap | 1.2 | 1.7 | 1.5 |

a mix of two types: 67% conventional-IATA, 33% delayed flap.

Controllers felt that the arrival rate of 25 aircraft/h caused little difficulty with any mix. In fact, aircraft arriving at a rate of 30 aircraft/h could be handled without increased delay or excessive controller workload, even at 50% conventional, 50% delayed flap approach. Major difficulties were experienced with the heavy arrival rate of 35 aircraft/h. Controllers felt that more concentration was required at 35 aircraft/h and that it was more difficult to accommodate a diversion (i.e., the system was unforgiving of any error). At lower arrival rates, controllers might have to path-stretch an aircraft or two, but the delays would eventually die out. However, no catchup time existed at the higher arrival rate. Thus, the number of delays increased, as a result of either holding at the feeder fix or increasing path-stretching, and these delays persisted for the duration of the run.

Based on the above, it is no surprise that the combination of the most difficult mix (50% conventional, 50% delayed flap) and the high arrival rate (35 aircraft/h) was the test condition that provided the highest workload for the controllers.

**Missed Approaches**

In addition to experimenter-generated missed approaches, the controllers called for a missed approach when they felt there would be less than minimum separation on final. Generally, these occurred when the controller misjudged how much in-trail separation between aircraft types was needed to achieve the desired final separation. These additional missed approaches are shown in Table 1. The following is noted: First, there was generally a larger percentage of controller-initiated missed approaches as the traffic levels increased. This increase probably resulted from trying to keep minimum separation distances as traffic levels increased. Second, the largest percentage of missed approaches occurred in the 50% conventional, 50% delayed flap mix, for each arrival rate. Again, this is reasonable since a large initial separation was required to assure the minimum separation at touchdown. The largest *initial* separation along a common path was required when a conventional approach landed first and was followed directly by a delayed flap. The controller had to judge this initial separation accurately, since by the time the conventional approach aircraft was ready to land, the spacing was shortened considerably. Any initial error in separation might result in less than desired spacing near touchdown. Since no path-stretching was possible in this region, a missed approach was the only option available to achieve the desired spacing. This finding can be considered to reflect the increased difficulty the controllers experienced in managing the traffic flow and maintaining a high landing rate for this traffic mix.

**Airspace Used**

It is of interest to compare the envelope of airspace used by all the flights in a given run with the airspace used under difference mix conditions. An airspace plot for a run was obtained by plotting the *x-y* position of each aircraft in the system every 2 s. From this tape, an *x-y* plot was obtained for each flight. From the outline of all the *x-y* plots in the run, the maximum excursion boundary was found. The plots do not contain information on Cassville arrivals (only 20% of the simulated traffic started from Cassville), nor on missed approaches. From these plots, the airspace used in a single run was computed. Table 2 summarizes the total airspace used under six different run conditions.

In addition to the arrival rate and mix, the plots gave the airspace used (n. mi.)$^2$, the normalized airspace (normalized airspace used in the 25 aircraft/h baseline case described below), and the average hold time per aircraft in minutes. The average hold time is the time spent in holding prior to feeder fix departure. When and how long to hold aircraft were matters of controller judgment. It should be noted that the airspace required is at most 252 (n. mi.)$^2$, and that essentially no start point holding is required for the following: baseline— a) 25 aircraft/h or b) 35 aircraft/h; and 50% conventional, 50% delayed flap— c) 25 aircraft/h or d) 30 aircraft/h. These figures should be compared with the airspace used at 35 aircraft/h (lines e and f). The airspace used for the last run at 50% conventional, 50% delayed flap at 35 aircraft/h (line e) is 240 (n. mi.)$^2$. However, in this case the average hold time is 4.0 min. Thus, to minimize airspace usage, it was necessary to hold traffic at the start points (i.e., slow the traffic). In the earlier runs in the experiment, the controllers were reluctant to slow traffic; rather, they would take all traffic into the system and path-stretch when delays were necessary. Line f shows an earlier run (in fact, the first run of 50% conventional, 50% delayed flap at 35 aircraft/h). The average hold time was zero, but the airspace required was 445 (n. mi.)$^2$, almost double that required in any of the previous cases. Thus, operation at 35 aircraft/h for the 50% conventional, 50% delayed flap results either in additional

**Table 2 Terminal area airspace usage**[a]

| Arrival rate | Mix | Airspace used (n. mi.)$^2$ | Normalized airspace | Average hold time per aircraft (min) |
|---|---|---|---|---|
| 25 | Baseline (100 % IATA) | 242 | 1.00 | 0.0 |
| 35 | Baseline (100% IATA) | 252 | 1.04 | 0.3 |
| 25 | 50% Conventional<br>50% Delayed flap | 189 | 0.78 | 0.0 |
| 30 | 50% Conventional<br>50% Delayed flap | 240 | 0.99 | 0.0 |
| 35 | 50% Conventional<br>50% Delayed flap | 240 | 0.99 | 4.0 |
| 35 | 50% Conventional[b]<br>50% Delayed flap | 445 | 1.85 | 0.0 |

[a] Data shown are for last data run under this arrival rate and mix. [b] Data shown in this row only are for first data run under this arrival rate and mix.

Table 3 Comparison of fuel used

| | Extra delay per A/C (min:s) over 100% conventional | | | Net fuel savings per aircraft over 100% conventional (lb of fuel) | | |
|---|---|---|---|---|---|---|
| | 25 aircraft/h | 30 aircraft/h | 35 aircraft/h | 25 aircraft/h | 30 aircraft/h | 35 aircraft/h |
| 50% Conventional 50% IATA | 00:00 | no data | 01:30 | 100[a]/150[b] | ... | −109/−59 |
| 50% Conventional 50% Delayed flap | 00:00 | 00:09 | 01:58 | 150/275 | 123/248 | −204/−79 |
| 33% Conventional 33% IATA 33% Delayed flap | 00:34 | 00:00 | 00:58 | 77/190 | 167/280 | 13/126 |

[a] Low estimate: IATA, 200 lb; delayed flap, 300 lb. [b] High estimate: IATA, 300 lb; delayed flap, 550 lb.

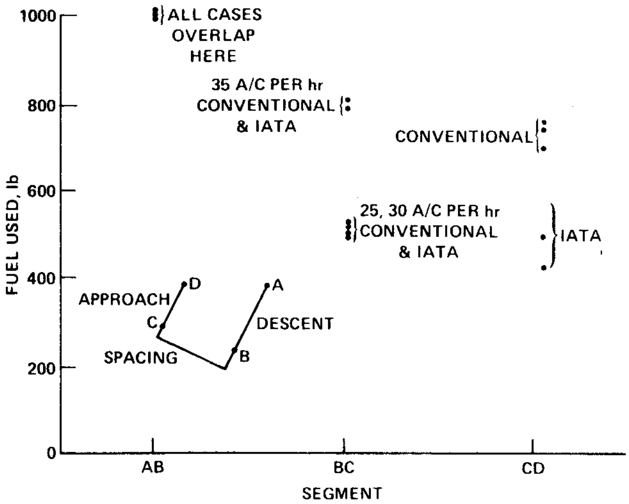


Fig. 5 B-727 simulator: fuel used in each segment.

holding time per aircraft at the start point or additional airspace to provide delays through path-stretching. This increases the controller workload, the systems fuel used, or both.

### Comparison of Fuel Used

The IATA approach saves fuel over the conventional approach. A low estimate of this savings is 200 lb/flight. A high estimate (based on the B-727 simulator flights) was 300 lb. Similarly, the delayed flap approach saves 300 to 500 lb more fuel than the conventional approach. However, for a mix of approaches, delays are introduced, as previously noted, resulting in the use of extra fuel. Table 3 examines the fuel used under different run conditions. The left-hand side shows the additional delay per aircraft compared to the baseline average. These additional delays were translated into pounds of fuel based on the assumption that, on the average, delays were accomplished at 5000-ft altitude and at a speed of 250 knots for each aircraft type. (The delay data presented include keyboard aircraft and both simulators.) The fuel used to execute these delays was then subtracted from the fuel saved as a result of the fuel-conservative approaches, giving the net fuel savings. The right-hand side shows the net fuel savings per aircraft over the baseline (100% conventional) case. The two numbers in each entry represent a minimum and maximum value of savings based on low and high estimates. Negative numbers represent fuel loss.

Based on the table, the following conclusions are drawn:

1) Net fuel savings are feasible for any mix for arrival rates of 25 and 30 aircraft/h.

2) At 35 aircraft/h, fuel was lost for the following mixes: 50% conventional, 50% IATA; and 50% conventional, 50% delayed flap. The data also indicate a small fuel savings for the mix of 33% conventional, 33% IATA, 33% delayed flap. Controller comments and observations made during the course of the experiment indicate considerable difficulty with this mix at the high arrival rate. Thus, even though a modest fuel gain is indicated, operations for this condition would not be expeditious from a controller workload standpoint.

### Simulator Aircraft Fuel Data

Fuel usage is first discussed for the B-727 simulator, where data were collected to relate fuel usage as a function of various flight segments. Next, fuel usage is discussed for both the B-727 and CV-990 simulators for the entire flight from feeder fix to touchdown.

The B-727 simulator flew conventional and IATA approaches, always starting from Deerpark. The flights were broken into three stages for evaluation: descent, spacing, and approach. The descent stage, shown as segment AB in Fig. 5, essentially covers the flight from feeder fix departure through the downwind leg. The spacing stage BC is the base leg region, while the approach stage CD covers the final approach.

Figure 5 shows the fuel used in each of the three stages as a function of the approach type. In the descent stage, all B-727 aircraft consumed approximately the same amount of fuel regardless of approach type. This seems reasonable, as neither experimental variable has come into play. The fuel efficiency of the descent stage is primarily a function of the airspeed and rate of descent. Fuel used in the spacing stage is highly sensitive to the traffic density, but still independent of approach type. At arrival rates of 25 and 30 aircraft/h, there is no significant difference in fuel consumption. At the rate of 35 aircraft/h, fuel consumption increases by 270 lb. A reasonable conclusion is that considerably more airspace is required by the controllers to provide the required spacing. Thus, more fuel is consumed under this condition. Fuel used in the final approach stage is very dependent on the type of approach flown. On the average, an IATA approach used 231 lb less fuel than a conventional approach. (Arrival rate is not very significant here.)

Fuel data for the entire flight from feeder fix to touchdown for both simulators are given in Table 4. For the CV-990 simulator, fuel data are compared for delayed flap and conventional approaches. The fuel data for the delayed flap approaches are averaged over all delayed flap approaches flown (i.e., averaged over all combinations of traffic mixes). In particular, delayed flap approaches were flown under the following two mix conditions: 50% conventional, 50% delayed flap; and 33% conventional, 33% IATA, 33% delayed flap. For the B-727 simulator, fuel data are compared for IATA and conventional approaches. In either case, more fuel is used in the conventional approach at both the moderate (25 aircraft/h) and heavy (35 aircraft/h) arrival rates. For both piloted simulators, the average fuel use is clearly higher at the 35 aircraft/h rate for each type of approach. In fact, an average of 300 lb more fuel is based at the 35 aircraft/h arrival rate than at the lower rate. This difference is consistent

**Table 4 Fuel used for simulators (in lb)**

| | CV-990 simulator | | | B-727 simulator | | |
|---|---|---|---|---|---|---|
| Arrival rate/approach type | Delayed flap | Conventional | Difference | IATA | Conventional | Difference |
| 25 aircraft/h | 2250 | 2600 | 350 | 1711 | 1866 | 155 |
| 35 aircraft/h | 2495 | 3070 | 575 | 2024 | 2274 | 250 |
| Difference | 245 | 470 | ... | 313 | 408 | ... |

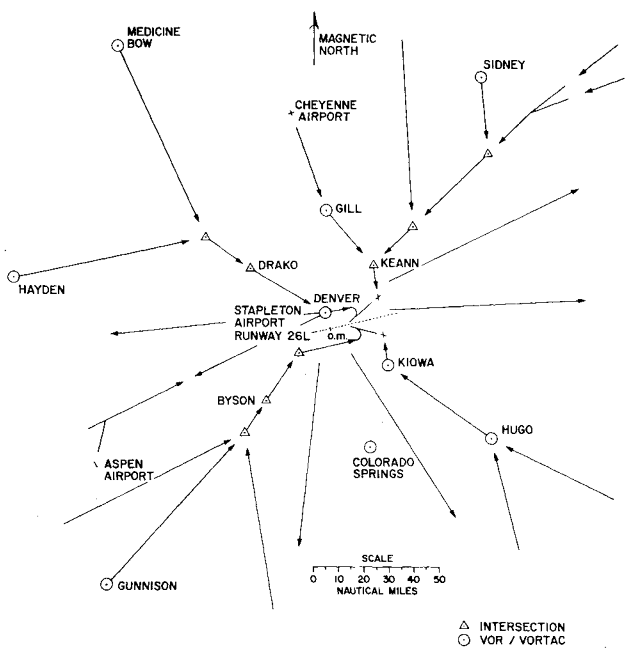


**Fig. 6 Route structure for the profile descents experiment.**

with the fuel data of Table 3. Thus, while the CV-990 simulator executing delayed flap approaches and the B-727 simulator executing IATA approaches at the 35 aircraft/h both save fuel with respect to conventional approaches (as shown in Table 4), the net systems effect shown in Table 3 is an overall fuel loss per aircraft in the heavy traffic mixed modes.

This completes the discussion of the data from the delayed flap and IATA experiment. The objectives of this experiment were to get a basic understanding of the required controller procedures to handle a mix of approach types and to determine the effect of arrival rate on system operation. In order to concentrate on these variables, given the limitations on the number of runs in a real time simulation involving traffic controllers and pilots, other potential variables were not considered. For example, winds were not considered, nor were the separation regulations regarding light, large and heavy aircraft. Also, as pointed out earlier, the traffic flow was primarily from Deerpark, rather than being evenly split from the two directions.

One might speculate that the effects of including the above would be in the direction of increased delay and workload; however, additional studies are required before definitive conclusions can be drawn.

## Profile Descents

### Description of Experiment

The second experiment consisted of 32 runs of 1¾ h duration (two runs per day). The NAFEC ATCSF laboratory provided the simulation environment; and two Ames Research Center piloted flight simulators, interfaced with the ATCSF, participated in the flight operations together with the computer flights generated at NAFEC. The Denver Terminal ATC Facility was simulated and the Denver En Route Facility was simulated only in part as necessary to support the tests. Six controller positions were established: Denver Center North, Denver Center South, North Arrival, South Arrival, Final, and Departure. The Center positions handled the aircraft from problem entry to one of the four corner posts, Keann, Bison, Drako or Kiowa. The locations of the corner posts are given in Fig. 6. Approach control handled aircraft from the corner posts to about 15 miles from the airport. The final controller picked up traffic from the approach controller, and merged them into a single stream for landing on a single runway.

The controller subjects were FAA research controllers from NAFEC; the pilot subjects were airline pilots affiliated with major airlines operating out of San Francisco and Oakland.

### Route Structure

The area simulated, as shown in Fig. 6, was approximately a 150-mile radius of the Denver, Colorado VORTAC. The route structure and profile descent procedures were patterned after the Denver four-corner post system and the Experimental Profile Descent Procedures published by the FAA for Denver Stapleton Airport in December 1976. These December 1976 procedures were modified slightly for simulation. The profile descent procedure was extended so that both horizontal and vertical guidance were provided to ILS capture. These modifications formed a procedure which enabled aircraft to make the profile descent and ILS approach without ATC vectors to final. Controllers issued clearances only as necessary for purposes of separation. All arrivals conformed with the Stapleton runway 26L ILS procedure, and it was assumed that weather conditions precluded the use of runway 26R. Independent departure operations were conducted on runway 35R.

### Traffic Sample

The traffic sample was developed from an analysis of Denver traffic on a busy day. The traffic was categorized by aircraft types, routes, and number of flights. The traffic sample defined by this analysis resulted in an average landing rate of 35 aircraft/h. About 25% of these flights were low-performance aircraft. Representative departure flights were programmed in accordance with the same parameters as the arrivals.

### Main Variables

The main variable was the descent procedure. Either a profile descent or a conventional descent was flown. For the conventional descent, all arrival flights navigated by present day methods using VOR route structures and radar vectors from ATC. Altitude change and speed control clearances were given by ATC in the usual manner. Profile descents were initiated at or above FL240. For the profile descent, altitude and speed profiles were specified as well as horizontal guidance information. Controllers monitored the progress of flights and gave alternate clearances only as necessary for ATC purposes. Profile descent charts were designed by NAFEC specifically for the Ames piloted simulators.

In addition to the two descent procedures, two landing approach procedures were tested. In one case, all aircraft flew conventional approaches; in the second, delayed flap and IATA approaches were flown. For the delayed flap and IATA

**Table 5 Fuel used from approximately 150 n. mi. to touchdown (in-lb)**

| Run condition | Fuel | % savings (with respect to baseline) |
|---|---|---|
| 1) Conventional descent, conventional approach (baseline) | 3325 | ... |
| 2) Profile descent, conventional approach | 2936 | 11.6 |
| 3) Conventional descent, mix of landing approaches | 3388 | −2.0 |
| 4) Profile descent, mix of landing approaches | 2891 | 13.1 |

runs, half the aircraft flew delayed flap, and the other half flew IATA. Note that as a ground rule for this simulation, no aircraft cruising below FL240 (approximately 25% of the sample) flew any fuel-conservative procedure. Thus, there was a mix of landing approach types as follows: 37.5% delayed flap, 37.5% IATA, 25% low performance. In this experiment the controllers were instructed to handle the delayed flap and IATA approaches as they saw fit, that is, to alter the approach speed at their option.

These variables resulted in the four test conditons below:
1) conventional descent, conventional approach (baseline);
2) profile descent, conventional approach;
3) conventional descent, mix of landing approaches; and
4) profile descent, mix of landing approaches.

These conditions (hereafter referred to as conditions 1-4) were replicated 8 times for a total of 32 runs.

## Results: Profile Descents

### Controller Workload

Controller workload is defined as the number of ATC control messages per run. These messages were of three types: radar vectors, speed changes, and altitude changes. As compared with the baseline (condition 1), controller workload reductions of 32.5, 17.8, and 37.4% were found for conditions 2, 3, and 4 respectively. Although all three of the workload messages were reduced, the differences were mainly found the in the number of radar vectors and speed control clearances. As expected, the greatest reductions were found when the profile descent procedures were used, because the profile descent procedures provided the pilot with both horizontal and altitude guidance information.

However, the controllers expressed some difficulty with handling the profiles. Since it is ideally a hands-off procedure from cruise to about 1500 ft above ground level, the controller's last decision on spacing the aircraft had to be made at cruise. Since this is not the way the present ATC system operates and since no computer assistance was provided to controller or pilot, many profile descents had to be terminated to achieve better aircraft spacing. Thus, the final controller's workload in the profile procedure was not reduced significantly as the center or arrival controllers.

A general criticism expressed by the controllers with regard to the four cornerpost procedure, as simulated, was that the procedure required the final controller to accept aircraft from four directions, merge them, and achieve efficient spacing. It was suggested that some of this final controller workload might be alleviated if the North Approach merged the two north routes and South Approach merged the two south routes. In that way, the final controller would only handle traffic from two directions.

### Fuel Used

Table 5 summarizes the average fuel saved for an aircraft flying from approximately 150 n. mi. out to touchdown for each of the four test conditions previously noted. Each number presented is the fuel averaged over approximately 250 flights in the experiment. The percent savings in fuel, for test conditions 2, 3, and 4 compared to the baseline conditions, are also shown. It can be seen that there was an 11.6% reduction in the amount of fuel consumed for the aircraft that flew the profile descent (condition 2). For aircraft flying conventional descents and a mix of landing approaches (condition 3), no fuel savings were evident. For aircraft flying profile descents and a mix of landing approaches (condition 4), the percentage of fuel reduction was about 13%. However, statistical tests showed no significant difference in the fuel used between conditions 1 and 3, nor between 2 and 4. In essence, any fuel saved was entirely attributable to the profile descents, not to the delayed flap or IATA procedures.

Several reasons account for the lack of significant systems fuel savings attributable to the delayed flap and IATA approaches. First, the interaction between aircraft flying delayed flap and IATA procedures and low-performance aircraft did not allow for the best efficiency of the delayed flap and IATA procedures. A 70-knot difference in approach speed existed at 10 n. mi. from touchdown between an aircraft executing a delayed flap approach and a low-performance aircraft. Thus, controllers found it necessary to path-stretch the delayed flap aircraft, and flight pattern distances were increased from 8 to 10 miles per aircraft. The additional fuel consumed because of the path-stretching offset the fuel saved by the delayed flap and IATA procedures. Second, fuel was not saved because landing rates were at or above 35 aircraft/h. From the study reported in the first part of this paper, under conditions of high arrival rates and a mix of aircraft approaches with large speed differences, the controller workload would be excessive and the en route delays large if the controllers chose to accommodate the delayed flap and IATA approaches. (Note, however, that controllers did not permit the IATA approach aircraft, which were slower than the delayed flap approach, to complete more approaches. Only 67% of the aircraft requesting delayed flap approaches were allowed to complete them, while 88% of the IATA approaches were completed.) Thus, the test conditions in this experiment, i.e., the difficult mix and high arrival rate, precluded effective use of the delayed flap and IATA approaches.

The data in Table 5 represent averages over three controller teams. The data from a fourth team was not included because the controller techniques adopted by this team were significantly different from the other three teams. The techniques used by the fourth team in essence cancelled the profile descent clearances. Alternate clearances were issued earlier and at higher altitudes than those issued by the other teams. The alternate clearance sometimes caused extended flight patterns, but always caused the aircraft to leave the profile descent and revert to the greater fuel-consuming configuration of conventional flight.

## Conclusions

Two simulation experiments were conducted to investigate fuel-conservative approaches in an ATC environment. The first experiment centered on delayed flap and IATA approaches and how they could be mixed with conventional approaches under various traffic levels. The second experiment investigated the fuel savings potential of profile descents.

For the test scenario chosen, in the first experiment, arrival rates of at least 30 aircraft/h (but less than 35 aircraft/h) can be accommodated without creating excessive controller workload, increasing delay, or increasing terminal airspace usage for any of the mixes run. Because of the cumulative nature of the delays, a point (between 30 and 35 aircraft/h) exists at which the system behavior changes from acceptable to unacceptable.

Of the approach mixes considered, the mix of 50% conventional, 50% delayed flap results in the greatest controller workload. The time difference between aircraft flying these two approaches is about 1 min, which makes for a more difficult spacing task for the controllers.

At 35 aircraft/h, a significant percentage of delayed flap and IATA approaches cannot be accommodated in the traffic mix without causing considerable delays, which in effect negate the fuel savings.

The IATA approach appears to offer a good compromise between fuel efficiency and capacity in a mixed environment. While it saves about one-half to two-thirds of the delayed flap approach fuel, it has less impact on capacity and controller workload in the 35 aircraft/h traffic situation.

The best situation would be for all aircraft to execute the same fuel-conservative approach, either all delayed flap or all IATA, since the controller operation for 100% of any one type was about the same.

The second experiment, which utilized the ATC simulation facility at NAFEC as well as piloted simulators at Ames, was primarily concerned with profile descents. It was found that the profile descent procedures would result in at least a 10% average fuel savings during descent. In addition, since fewer radar vectors were required for profiles, the profiles showed a significant reduction in controller workload with respect to conventional aircraft.

A major difficulty with profile descents was spacing. (Spacing was also a problem for delayed flap and IATA approaches, though for different reasons.) To make the profile descents a procedure that requires minimal controller clearances from the beginning of descent until final approach, requires that the final approach spacing between aircraft initially on different routes be established before the start of descent. This proved to be difficult. Computer assists offer the possibility of increasing the accuracy of the controller's judgment and making these decisions more exact. The use of airborne and ground computers in fuel conservative approaches is currently under investigation.

## References


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