Analysis of National Delays and Throughput Impacts of a New Denver Airport

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Documented in this paper is an analysis of some of the impacts of a new airport at Denver, Colorado, that will be constructed to replace Stapleton International Airport. The model was developed by the MITRE Corporation for the Federal Aviation Administration's Operations Research Service. The simulation was carried out for three different daily weather scenarios, and considered the impacts in 1995 of the new airport on delay, both at Denver and at other major airports. It also assessed growth in traffic throughput in Denver airspace. The primary conclusion of the analysis is that the new Denver airport would significantly reduce delays at Denver, and would also produce large reductions in delays at many other major airports in the United States.

Airport planners in the Denver, Colorado, metropolitan area have been concerned that facilities at the Stapleton International Airport may not be adequate to handle the forecasted aviation activity. They have determined that a major new airport is needed for the region (*1*). The plan is for the new airport to become operational in 1993 and to accommodate anticipated traffic growth through 2010. On completion of the new facility, Stapleton airport will be closed and the property used for nonaviation activities.

Described in this paper is the analysis of impacts of the proposed new airport using a simulation model of the National Airspace System (NAS). The model was developed by the MITRE Corporation for the Operations Research Service of the Federal Aviation Administration (FAA). It is being used to assist in the evaluation of airport and airspace improvements. The model is one of the tools that has been produced as part of the National Airspace System Performance Analysis Capability (NASPAC) project. The NASPAC simulation model is one of the first models to represent how delays ripple through the system, and how the entire system will react to projected demand or capacity changes.

At the request of the FAA, this analysis of the impacts of the new Denver airport was performed to evaluate its benefits to the NAS. It examines delays at the Denver airport and at other major airports in the United States and traffic volumes in the sectors and arrival fixes in en route Denver airspace. The analysis supplements other studies of the new Denver airport that have focused exclusively on local Denver impacts. The audience is assumed to have a basic knowledge of air traffic control.

The simulation was performed for the 1995 time period, 2 years after the new airport is to begin operation. This time frame was chosen for the analysis because it is likely that new demand patterns will have developed at the new airport by then. The analysis takes into account the predicted capacity improvements at all other airports that are expected by 1995.

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BACKGROUND ON NEW DENVER AIRPORT

The current major airport in the Denver area is Stapleton International Airport, the airport code for which is DEN. A layout of the runways at Stapleton is shown in Figure 1. The airport has six runways, all of which can be used in visual meteorological conditions (VMC). However, they cannot all handle traffic streams independently because of close spacing. In instrument meteorological conditions (IMC), fewer runways are used. A common configuration in IMC is to use one runway for arrivals and two for departures.

Information about the new airport was obtained from staff at the New Denver Airport Planning Office. The new airport will be located about 8 mi northeast of Stapleton and will have much higher capacities. Its temporary airport code for planning is DVX. It is planned to open in November 1993 with five runways and one additional runway added by September 1995. A layout of the available runways at the new airport in 1995 (the analysis year of this study) is shown in Figure 1. (The scales of the runways for both the current and the new airport are identical in the figure.) The new airport is expected to be expanded to 12 runways by 2010. In the first few years of operation, all six runways will be used in both VMC and IMC.

The new airport will serve all types of aircraft, as does Stapleton. However, much of the general aviation activity at DEN is projected to move to the nearby Front Range airport. It is expected that DVX will continue to serve as a hub for Continental and United Airlines. The local planners and the FAA are assuming, in estimating future airport demand, that an additional carrier will also hub at Denver. Stapleton will be closed after the new airport becomes operational.

Stapleton is operated with four arrival fixes:

Byson: southwest
Drako: northwest
Keann: northeast
Kiowa: southeast

Each of the fixes is in a different en route sector. Over an entire day, the loads over the four fixes are fairly balanced

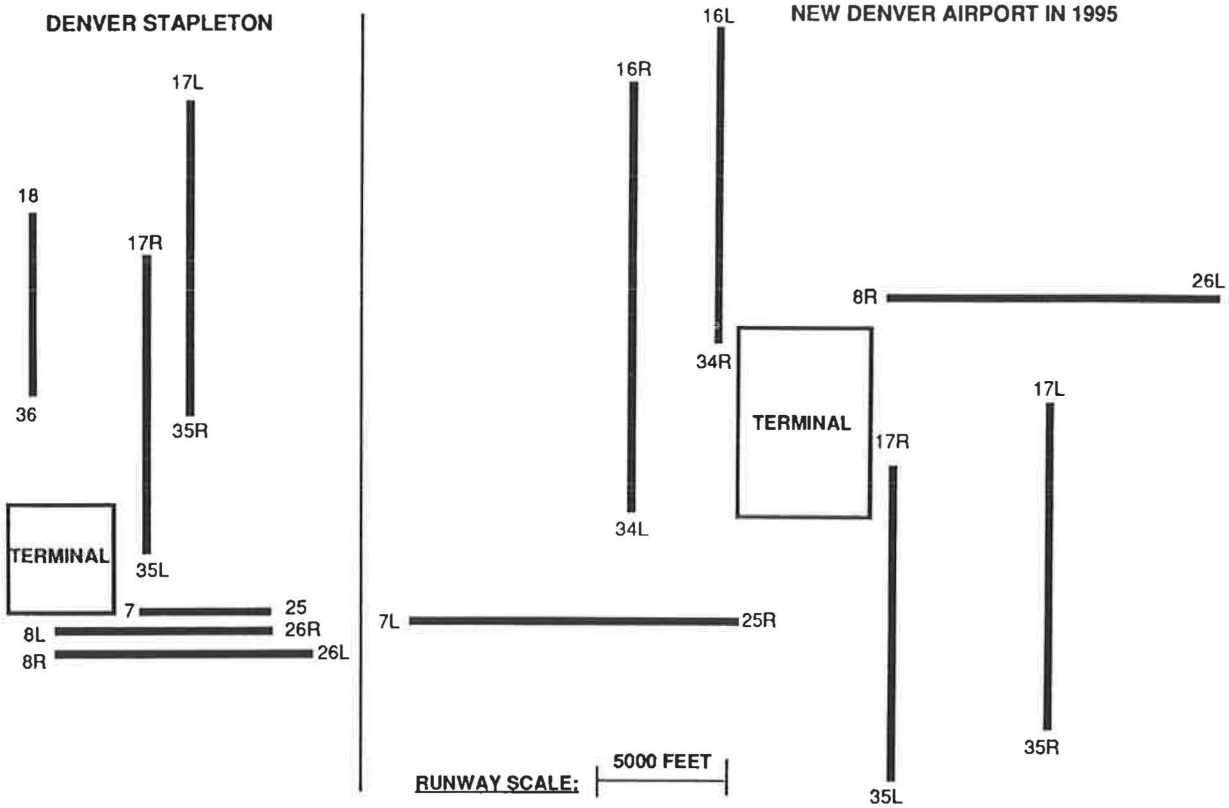

FIGURE 1 Airport layouts for current and new Denver airports.

because of the allocation of demand among the fixes by the Denver Air Route Traffic Control Center, the en route center.

The arrival fixes for the new airport will be oriented in the same directions as the current ones. However, each fix will accommodate up to four independent arrival streams. These streams will be separated by about 10 nautical mi at the fix, and directed at three or four new very high frequency omnidirectional ranges to be installed around the new airport.

Sector structure in the Denver en route air traffic center is planned to be changed only marginally when the new airport becomes operational. The sector boundaries will be moved to accommodate the 8-mi movement of the airport. In general, only those sectors surrounding the airport will be altered. Minimal operational changes are planned for the time period immediately following the new airport implementation. This conservative approach will be taken to minimize the new training required by controllers in a time period when new display consoles (that require extensive controller training) will be placed in the centers.

ANALYSIS OBJECTIVES

The overall objective of this analysis was to quantify several local and national impacts of the new Denver airport in the time period soon after it becomes operational. Three specific objectives were addressed. The first was to estimate for three weather scenarios the reduction in daily 1995 delays at Denver as a result of replacing Stapleton with the new airport. The second was to estimate the effect of this replacement on delays at other major U.S. airports. The third was to estimate the growth in throughput from 1989 to 1995 for the Denver airport arrival fixes and Denver en route sectors. This growth will result from increases in demand nationally, as well as additional operations that the new airport is expected to generate over and above those that would occur with Stapleton in 1995.

ANALYSIS APPROACH

Overview of the NASPAC Simulation Model

The NASPAC model is a discrete-event simulation of the NAS that has been described in several recent articles (*2–5*). It traces the progress of each aircraft through each event in its flight, from push-back at the departure gate, through takeoff, crossing fixes, and en route sectors, to landing and arrival at the destination gate. Currently, 58 airports, several fixes, and all sectors are modeled. These include the 50 airports with the most air carrier operations, plus others that compete for terminal airspace in major metropolitan areas. The 58 airports are listed in Table 1. (Other information in this table is discussed in the following paragraphs.) The airports, fixes, and sectors are called modeled resources. Principal model inputs include resource capacities, airspace geometry, scheduled and unscheduled demand, and applicable flow control actions (e.g., ground delay programs and en route flow restrictions). Principal model outputs include throughput and delay at each modeled airport, fix, sector, or restriction, plus NAS-wide totals of throughput and delay.

TABLE 1 MODELED AIRPORTS WITH CAPACITY-RELATED IMPROVEMENTS

MODELED AIRPORT	AIRPORT CODE	ASSUMED CAPACITY-RELATED IMPROVEMENTS BY 1995*
Albuquerque	ABQ	
Atlanta Hartsfield	ATL	New parallel commuter runway
Baltimore	BWI	New parallel rwy; runway extension
Boston Logan	BOS	
Burbank	BUR	
Charlotte	CLT	New independent parallel runway
Chicago Midway	MDW	
Chicago O'Hare	ORD	
Cincinnati	CVG	New independent parallel runway
Cleveland Hopkins	CLE	
Dallas Love	DAL	
Dallas-Fort Worth	DFW	New parallel runway
Dayton	DAY	
Denver	DEN	New airport
Detroit Metro	DTW	New parallel and crosswind runways
Fort Lauderdale	FLL	Runway extensions
Houston Hobby	HOU	
Houston Intercontinental	IAH	New parallel runway
Indianapolis	IND	New parallel runway
Islip	ISP	
Kansas City	MCI	Two new runways: one independent
Las Vegas	LAS	New parallel runway
Long Beach	LGB	
Los Angeles	LAX	
Louisville	SDF	Two new independent parallels
Memphis	MEM	New parallel runway
Miami	MIA	
Milwaukee Mitchell	MKE	
Minneapolis-St. Paul	MSP	
Nashville	BNA	New parallel runway
New Orleans	MSY	Two new independent parallels
New York Kennedy	JFK	
New York La Guardia	LGA	
Newark	EWR	
Oakland	OAK	
Ontario	ONT	
Orlando	MCO	Two new dependent parallel runways
Philadelphia	PHL	New independent parallel runway
Phoenix	PHX	New close parallel runway
Pittsburgh	PIT	
Portland (OR)	PDX	
Raleigh Durham	RDU	New independent parallel runway
St. Louis	STL	
Salt Lake City	SLC	New independent parallel runway
San Antonio	SAT	
San Diego	SAN	
San Francisco	SFO	
San Jose	SJC	
Santa Ana	SNA	
Seattle Tacoma	SEA	
Syracuse	SYR	New independent GA runway
Tampa	TPA	New close parallel runway
Teterboro	TEB	
Washington Dulles	IAD	New parallel and crosswind runways
Washington National	DCA	
West Palm Beach	PBI	
White Plains	HPN	
Windsor Locks Bradley	BDL	

* These are improvements listed in the Airport Capacity Enhancement Plan (FAA 1989a) that were estimated to provide capacity increases on the modeled scenario days.

The capacity of each modeled resource is an input to the modeling process. The model uses the resource capacities to compute the required interarrival spacing at each resource; that is, the time at which the next aircraft may be served by that resource. In the real world, the capacities of these resources may vary with time, so the model inputs may be presented as capacity-time profiles. The nature of the capacity information is specific to the type of resource. Airport capacity is expressed as a range of arrival and departure capacity values. An algorithm performs a trade-off between arrival and departure capacity for a given scenario situation, reflecting actual practice. The appropriate service times for arrivals and departures are then computed based on the capacity values. The airport capacity estimates are based on airport surface weather observations of ceiling and visibility provided by the National Climatic Data Center. Fix capacity is expressed as a rate of aircraft crossing the fix. In the analysis described in this paper, en route flow control restrictions and sector capacities have not been used.

Airports and fixes are described by their names and locations. The name is the alphanumeric identifier of the facility, and the location is its latitude-longitude. Sectors are input as geometrical shapes by specifying the latitudes and longitudes of their vertices, and the altitudes of their ceilings and floors.

The modeled demand consists of scheduled and unscheduled flights departing from and arriving at airports represented by the model. Demand data contain the airline code, flight identification, departure airport and time, and arrival airport and time. This information may come from actual scheduled flights as listed in the *Official Airline Guide* (*6*), or it may be the result of analysis and hypothetical scenario generation. In the case of adverse weather at the destination airport, the FAA's Central Flow Control Facility, which is located in Washington, D.C., and provides national-level flow control, may require aircraft to take delay on the ground rather than risk airborne holding. If the scenario being analyzed includes a ground delay program, the estimated departure clearance times (EDCTs), which are the sums of the originally scheduled departure times and the ground delays, are computed and appended to the schedule for each affected flight. Unscheduled demand is described by daily and hourly distributions taken from real-world data, and the model probabilistically selects arrival and departure times within these distributions for each hour of the day. Flight times between modeled city pairs are included in the model, and are based on actual NAS performance data. The model stochastically varies the time to reflect typical variations in en route flight times. Individual flight legs are organized into itineraries (i.e., the daily sequence of airports visited by each aircraft during the simulation day).

The model tabulates the delay encountered by an aircraft at each stage of its simulated flight. Two types of delay are tabulated, reflecting definitions of delay used by the FAA and the airlines, respectively. These delays are tabulated by resource by hour, by resource for the entire simulated day, and for the entire NAS for the entire day. The first type of delay, called technical delay, is delay absorbed by aircraft while waiting for ATC resources, or while satisfying traffic management flow restrictions. Thus, for example, an aircraft that must wait its turn to use a departure runway accumulates technical delay. In the model, technical delay may be encountered at airports, fixes, sectors, and in the presence of traffic management flow restrictions.

The second type of delay, called effective arrival delay, measures the difference between scheduled and actual arrival times regardless of cause. Effective arrival delay is the type that directly affects passengers, as late arrivals (relative to schedule) cause missed connections or appointments.

Tabulation of effective arrival delay allows the model to track "delay ripple," that is, the propagation of delays throughout the system. When an aircraft arrives late, that delay may result in a late departure on the next flight that the aircraft makes and a subsequent late arrival at the next destination; in this way, delays can propagate throughout the system. Because one of the main purposes of the model is to isolate the source of problems in the NAS, it is important to track such delay propagation.

One of the challenges in tracking such delay propagation is accounting for the itinerary of each aircraft. In the normal course of a flying day, a commercial air carrier will fly a number of flight legs between city pairs (an average of five or six). These legs may all have the same flight number, but most often they are spread over two or more flight numbers. The model synthesizes an itinerary for each scheduled aircraft in the simulation, assigning flights to specific modeled aircraft so that delay ripple can be tracked and analyzed.

Analysis Measures Used

The measures selected to evaluate the effect of the new airport are as follows:

- Throughput at the Denver airports (Stapleton and the new airport),
- Technical and effective arrival delays at the Denver airports,
- Effective arrival delay at major airports affected,
- NAS-wide effective delay,
- Growth in throughput at fixes, and
- Growth in sector throughput.

Throughput refers to the number of arrival and departure operations at an airport, or the number of aircraft transiting a fix or sector in a given period of time. Technical delay and effective arrival delay are as previously defined.

Scenario Definitions

Three daily weather scenarios have been selected to represent a range of weather conditions at Denver and nationally. The weather at each of the modeled airports determines its arrival and departure capacities during the day. The three scenarios have been named VMC day, IMC1 day, and IMC2 day. The first scenario, VMC day, has VMC weather at all airports all day. It was selected to provide a case in which national delays would be low, and to set a lower limit on the delay reduction that could be expected from the new airport.

The second scenario, IMC1 day, has weather similar to that on February 14, 1989. For the NASPAC simulation, it was estimated that Denver had light snow and fog, with ceilings from 800 to 1,400 ft for 13 hr. Twenty-nine other airports out of the 58 modeled airports had IMC weather from 0.5 to 24 hr. There were EDCT programs at Denver plus 7 other airports.

The third scenario, IMC2 day, has weather similar to that on March 2, 1989. For 10 hr, Denver had IMC weather with fog, ceilings less than 300 ft, and visibility of less than half a nautical mile. It had fog, ceilings less than 400 ft, and visibility of up to three mi for 7 hr, and fog, ceilings to 25,000 ft and visibility less than 3 mi for 7 hr. In other words, Denver had IMC weather for the entire day. Twenty-nine other airports nationwide had IMC weather from 1.5 to 17 hr. Stapleton and 6 other airports had EDCT programs. This scenario day has extremely poor weather at Denver, and provides a useful contrast to the IMC1 day, where the Denver weather is not so severe.

Nine simulation model runs were performed for this analysis for each of the 3 scenario days, one for Stapleton in 1989, and one for each of the 2 Denver airports in 1995. The runs can be represented as the elements in the following matrix:

	DEN, 1989	*DEN, 1995*	*DVX, 1995*
VMC	X	X	X
IMC1	X	X	X
IMC2	X	X	X

Many of the numerical results of the analysis will be presented in tables like this one, with the results appearing at the X locations.

Methodology

Capacity Forecasts

The 1995 runway configurations and capacities for Stapleton were assumed to remain unchanged from the current levels, because information obtained from local planners indicated that environmental constraints could limit airport expansion. The current configurations were obtained from staff at the Denver Stapleton Tower. The 1995 configurations and capacities for the new airport were based on information obtained from staff at the New Denver Airport Planning Office. The configurations and capacities used for the analysis are listed in Table 2, in which the capacities are those that best satisfy 50-50 arrival and departure demand for a given runway configuration. In the table, marginal IMC conditions correspond to ceiling and visibility less than those required for visual approaches, but greater than those required for circling approaches. Category II conditions correspond to visibility of less than half a mile.

The overall effect on delays over a 24-hr period during each of the three weather scenarios is a function of when reduced capacities occur. The arrival and departure capacities used for each scenario, and the times—in Universal Coordinated Time (UTC)—during which the capacities are in effect are shown in Table 3. The UTC (the acronym is for the French term) is the commonly used international time at the zero meridian. Mountain Standard Time is 7 hr earlier.

Capacities in 1995 at other modeled airports were based on predicted airport improvements listed in FAA's Airport Capacity Enhancement Plan (*7*). In that plan, Denver, plus 23 out of the 58 modeled airports, were predicted to have increases. The future capacities were estimated using the FAA Airfield Capacity model and knowledge of current airport operations. These capacities were used to estimate the future airport arrival rates that are entered in the EDCT portion of the simulation model. The airport improvements that translated into modeled capacity increases are identified in Table 1.

Demand Forecasts

The number of operations at the modeled airports in 1995 is based on the FAA's Terminal Area Forecasts FY 1989–2000 (*8*). Additional steps, beyond the FAA forecasts, are required to estimate both future flights between airports and aircraft itineraries. The demand component of the NASPAC model estimates these additional flights, based on the assumption that the current flights remain unchanged [G.F. Roberts and S. B. Fraser. "The Air Traffic Demand Forecasting Model." Presented at the Joint National Meeting of ORSA/TIMS (Operations Research Society of America/The Institute for Management Sciences), The MITRE Corporation, McLean, Va., May 1989]. (This approach does not consider adjustments to airline schedules.) The current air carrier flights are those in the March 22, 1989, OAG. Future air carrier flights are forecast using growth factors from the Terminal Area Forecasts. Current unscheduled IMC flights are based on the actual traffic generated from the ATC Host computer messages. Future

TABLE 2 AIRPORT CONFIGURATIONS AND CAPACITIES USED FOR ANALYSIS

Weather Condition	Configuration	Arrival/Departure Capacities
DEN		
VMC	Arrivals: 25, 26L/R; Departures: 35L/R, 36	78/88
Marginal IFR	Arrivals: 26L/R; Departures: 35L/R	45/66
Standard IFR	Arrivals: 26L; Departures: 35L/R	38/60
Category II IFR	Arrivals and Departures: 35R	22/22
DVX		
VMC	Arrivals: 35L/R; Departures: 8, 25, 34R	111/150
Marginal IFR	Arrivals: 35L/R; Departures: 8, 25, 34R	94/127
Standard IFR	Arrivals: 34L, 35L/R; Departures: 8, 25, 34R	90/80
Category II IFR	Arrivals: 34L, 35L/R; Departures: 8, 25, 34R	90/80

TABLE 3 TIMES THAT AIRPORT CAPACITIES ARE IN EFFECT FOR 3 SCENARIO DAYS

Scenario	Time Period (UTC)	DEN Capacities	DVX Capacities
VMC Day	1000-3400	78/88	111/150
IMC1 Day	1000-1020	78/88	111/150
	1020-2320	45/66	94/127
	2320-3400	78/88	111/150
IMC2 Day	1000-1040	38/60	90/80
	1040-1500	22/22	90/80
	1500-1830	38/60	90/88
	1830-2520	45/66	94/127
	2520-2830	38/60	90/88
	2830-3400	22/22	90/80

unscheduled IMC flights are estimated using the current flights as a baseline and growth factors from the Terminal Area Forecasts. Future VMC operations are based on the Terminal Area Forecasts and are not translated into flights between airport pairs.

The FAA forecast for 1995 at Denver assumes that the new airport will be operational and that there will be three hubbing airlines. The present analysis also considers a 1995 scenario in which Stapleton remains operational. The FAA had made forecasts for this situation but they were not available. Instead, the FAA forecasts for the years before the new airport opening (in 1993) were extrapolated to obtain a 1995 forecast.

The estimates of the total number of daily operations (scheduled plus unscheduled) at Denver for 1989 and 1995 are as follows:

DEN, 1989: 1,345
DEN, 1995: 1,480
DVX, 1995: 1,870

The first and third numbers are from the FAA, whereas the second has been estimated in this analysis. The growth from 1989 to 1995 is estimated to be only about 10 percent if the new airport is not built. Alternatively, if the airport is built, traffic would grow by 39 percent. The new airport is estimated to have 26 percent more traffic than would Stapleton in 1995.

The demand estimates for Stapleton in 1995 are based on an increase of scheduled operations of 15 percent over 1989, and a decrease of 86 percent for unscheduled operations. The new airport is estimated to have 33 percent more scheduled operations in 1995 than Stapleton would in that year and the same number of unscheduled operations.

Modeling Airspace Changes

As already discussed, the Denver airspace will have some changes to sector boundaries and fix locations. For the NASPAC model, the capacities of the fixes were increased to represent the multiple streams using them. No other changes were made to the airspace structure. The new airport was modeled as if it were located at Stapleton, and the sectors were modeled as if their boundaries did not change. This approximation results in some of the Denver sectors that are located away from the airport having somewhat lower or higher traffic counts than would actually occur.

ANALYSIS RESULTS

The following analysis results have been rounded to two significant figures. It should be noted that the percentages that are shown were calculated from the original figures and then rounded.

Local Airport Delays

Technical delays for the three scenario days were estimated for Stapleton in 1989 and 1995, and for the new airport in 1995. The total minutes of delay, including both arrivals and departures, are shown in the following table:

	DEN, 1989	*DEN, 1995*	*DVX, 1995*
VMC	2,800	3,600	1,800
IMC1	6,300	16,000	2,600
IMC2	18,000	66,000	6,800

Delays increase significantly at Stapleton between 1989 and 1995 for the two IMC day scenarios—by more than a factor of two. The percentage increases for the three scenario days are as follows:

VMC 27
IMC1 150
IMC2 260

Even more significant is the decrease in delays in 1995 with the new airport. The percentage decreases of the total technical delay caused by DVX are as follows:

VMC 50
IMC1 84
IMC2 90

For all three scenario days, the total technical delays at the new airport in 1995 are estimated to be less than the delays at Stapleton in 1989. These results indicate that the six-runway configuration at the new airport will be sufficient for some time beyond 1995 (in the sense that the delays will remain below the 1989 levels). It should be pointed out that the large reductions in technical delays occur even with the increase in airport operations at the new airport already mentioned.

It is also interesting to see the changes in the average minutes of technical delay per operation (arrival or departure). These are as follows:

	DEN, 1989	*DEN, 1995*	*DVX, 1995*
VMC	2	2	1
IMC1	5	11	1
IMC2	14	45	4

It can be seen that for the IMC2 day, a day with IFR capacities in effect at Denver for 24 hr, the average operation would have a long delay in 1995 at Stapleton: 45 min. With the new airport, this average delay would be reduced to only 4 min.

Effective arrival delays at Denver are a function of the weather and capacities at other airports, as well as the situation at Denver. This is because an aircraft destined for Denver that departs late from another airport may arrive late at Denver, even though the aircraft has no technical arrival delays at Denver. The total minutes of effective arrival delays at Denver are as follows:

	DEN, 1989	*DEN, 1995*	*DVX, 1995*
VMC	2,800	3,100	2,600
IMC1	8,800	20,000	3,600
IMC2	35,000	83,000	5,200

This table appears to be generally similar to the one for total technical delays. Effective delays increase at Stapleton between 1989 and 1995 less than do the technical delays for the three scenario days. The percentage increases of total effective arrival delay at DEN during that period are as follows:

VMC 11
IMC1 120
IMC2 140

The percentage decreases in total effective arrival delay in 1995 resulting from the construction of the new airport are as follows:

VMC 14
IMC1 81
IMC2 94

For the VMC scenario, the percentage savings of effective arrival delays are smaller than those for technical delays. This is because when the weather is good nationwide, some of the small technical delays that occur at Denver and elsewhere can be made up in the airline schedules.

For the two IMC day scenarios, the relative sizes of technical and effective delay savings at Denver resulting from construction of the new airport depend on how bad the weather is at Denver compared with that in the rest of the country. Hence on IMC1 day, the percent savings in effective delays is somewhat lower than that for technical delays, whereas for IMC2 day the reverse is true.

The average effective delays per arrival show the same relative difference as do the total effective delays. However, the averages provide a useful indication of the impact of the new airport on an average aircraft. The average minutes of effective delay per arrival at Denver are as follows:

	DEN, 1989	*DEN, 1995*	*DVX, 1995*
VMC	4	4	3
IMC1	13	26	4
IMC2	52	110	6

Systemwide Delays

The effect of the new Denver airport on other airports is best indicated by the change in effective arrival delays, because that measures the ripple effect of Denver delays. Technical delays (both arrivals and departures) at other airports may also change, but this will be caused by the changed distribution of arrivals that result from both the greater throughput and the smaller departure delays at Denver. The total minutes of systemwide effective arrival delay are as follows:

	DEN, 1989	*DEN, 1995*	*DVX, 1995*
VMC	240,000	260,000	260,000
IMC1	320,000	410,000	390,000
IMC2	500,000	650,000	530,000

Although there are significant reductions in total effective delay for the two IMC days with the new airport, there is no significant reduction for the VMC day. The percent savings of total systemwide effective arrival delay for the three scenario days caused by the construction of DVX is as follows:

VMC 0
IMC1 4
IMC2 18

The negligible savings of total delays for the VMC day are partly caused by the number of new operations generated by the new airport. (Using averages instead of totals changes the percent savings for the VMC day to 0.3 percent.) They also partly result from the ability of the schedule to absorb small technical delays, as already mentioned. However, the system-wide savings for the two IMC days are significant.

The amount of delay reduction at individual airports resulting from the use of the new Denver airport depends on a number of factors. These include the fraction of arrivals at the airport that come from Denver, times of arrivals, itineraries of aircraft after they leave Denver, and weather and capacities at the airports. The airports with the most savings a day differ for each scenario day.

The airports with the most minutes saved for the IMC1 day are shown in Table 4. The percent reduction in the total minutes of delay is also listed. The airports with the most minutes saved for the IMC2 day are shown in Table 5.

The two lists of 10 airports have 7 airports in common, but 3 that are different. Also, not surprisingly, the size of the savings on IMC2 day is much larger, ranging up to 2,400 min at Los Angeles International. Houston Intercontinental Airport and Salt Lake City Airport have the largest percentage of savings on both days.

The replacement of Stapleton with the new airport has a complex effect on the distribution of arrival and departure times. This effect may occur for all aircraft in general because of the random nature of the model. It may also occur for

TABLE 4 AIRPORTS WITH MOST MINUTES SAVED FOR IMC1 DAY

AIRPORT	CODE	MINUTES SAVED	PERCENT REDUCTION
Albuquerque	ABQ	530	9
Los Angeles International	LAX	480	11
Dallas-Ft. Worth	DFW	420	4
Phoenix	PHX	420	7
Dallas Love	DAL	360	9
Houston Intercontinental	IAH	360	24
Salt Lake City	SLC	300	12
St. Louis	STL	280	2
San Francisco	SFO	220	10
Atlanta	ATL	200	8

TABLE 5 AIRPORTS WITH MOST MINUTES SAVED FOR IMC2 DAY

AIRPORT	CODE	MINUTES SAVED	PERCENT REDUCTION
Los Angeles International	LAX	2400	4
Phoenix	PHX	1800	17
Chicago O'Hare	ORD	1400	3
Salt Lake City	SLC	1200	34
Houston Intercontinental	IAH	1200	36
Albuquerque	ABQ	1200	16
San Francisco	SFO	1100	9
Dallas-Ft. Worth	DFW	1100	12
Chicago Midway	MDW	1000	12
Ontario	ONT	840	27

particular aircraft after leaving Denver because some may experience larger effective arrival delays if their actual arrival times are moved to a more peaked period. The other operations in the peak could also experience longer delays. For the IMC1 day, three airports, Newark, Pittsburgh, and Seattle, had significant delay increases. For the IMC2 day, Newark and Santa Ana had significant increases. These airports all had large average technical arrival delays (13 to 26 min) on the relevant days, and are sensitive to changes in the temporal distribution of arrivals.

Airspace Impacts

Discussed in this section is the throughput growth at Denver fixes and sectors between 1989 and 1995. It provides an indication of how much traffic loads will increase by 1995 when the new Denver airport is operational.

As already mentioned, Denver will keep the four fixes for arrival traffic, but will allow independent arrival streams to the new airport. This analysis assumes for comparison that the new arrival fixes will keep the names of the current fixes. The growth in traffic was assumed independently of the weather scenario. The estimated growth of daily and peak-hour traffic from 1989 to 1995 is shown in Table 6.

The growth in daily traffic is estimated to be fairly similar for all four arrival fixes, with Kiowa in the southeast having the largest. The growth during the peak hour is lower than the daily rate for three of the fixes, indicating some amount of traffic spreading over the day. At the fourth fix, Drako in the northwest, the peak is estimated to grow somewhat more than the daily level.

Daily traffic at the four arrival fixes is estimated to grow about 50 percent overall. This compares with 39 percent growth in traffic at the airport. The difference results from the fact that for this analysis the NASPAC model did not route unscheduled aircraft through arrival or departure fixes (and that unscheduled operations at Denver are forecast to decline between 1989 and 1995). Therefore, only scheduled aircraft, which had a higher growth rate than the unscheduled traffic, used the fixes. (This deficiency has subsequently been corrected.)

There are 38 sectors in the Denver center: 16 lows, 19 highs, and 3 ultrahighs. They are distributed into five areas of responsibility. The sector and area boundaries are shown in Figures 2 and 3 (*9*). Growth of the sectors has been examined at two levels: by sector, and by 10 groups that are combinations of highs (and ultras) and lows for each area.

The sectors that have the largest percentage increases in daily throughput have been identified. The counts for the ultrahighs have been combined with the highs that underlie them. This was done because all additional forecast flights have been assumed to be made by aircraft that cruise at the ultrahigh levels. The results are shown in Table 6. All six of the low sectors in this table are adjacent to the Denver airport. Four of the six contain the arrival fixes. Two of the three highs are in the southeast quadrant of the Denver center—the same quadrant in which the highest growth fix is located. The results, when the sectors are aggregated into the 10 groups already described, are shown in Table 7.

The group with the highest growth is 3H. This is the airspace segment that is defined by the combined highs and ultrahighs previously listed in the sector table; it is in the southeast portion of the center. The groups with the lowest growth are 5L and 5H. They are located north of the Denver airport. This result is consistent with the identification of the northeast arrival fix as having the lowest growth of daily throughput.

SUMMARY OF RESULTS

The NASPAC model has been subjected to a lengthy validation process for simulations of the current time period, and, as with other models, its accuracy depends on the quality of its input data (*10*). Forecasts add an additional burden to producing accurate results, because future input data are uncertain. In applying the results of this analysis, the reader should also bear in mind the following:

1. The model does not simulate terminal airspace. The airport capacity values used in the model are assumed to represent the combination of the airport and its terminal airspace.
2. The model contains random elements that can cause statistically significant differences in results between runs with identical input data, but different random seeds. However these differences generally correspond to small absolute differences in delays. For the present analysis these absolute differences were judged to be negligible, and the results shown in this paper were derived from single model runs.
3. The effective arrival delays include only those generated by late arrivals. When a flight arrives early, it could be considered to have "negative effective delay." Although the model

TABLE 6 PERCENT GROWTH OF DAILY AND PEAK-HOUR TRAFFIC AT ARRIVAL FIXES FROM 1989 TO 1995

ARRIVAL FIX	PERCENT GROWTH: 1989 (With DEN) to 1995 (With DVX)	
NAME--DIRECTION	DAILY	PEAK HOUR
Byson -- SW	49	23
Drako -- NW	49	55
Keann -- NE	42	20
Kiowa -- SE	56	10

FIGURE 2 Denver Center low-altitude sectors and areas (*9*).

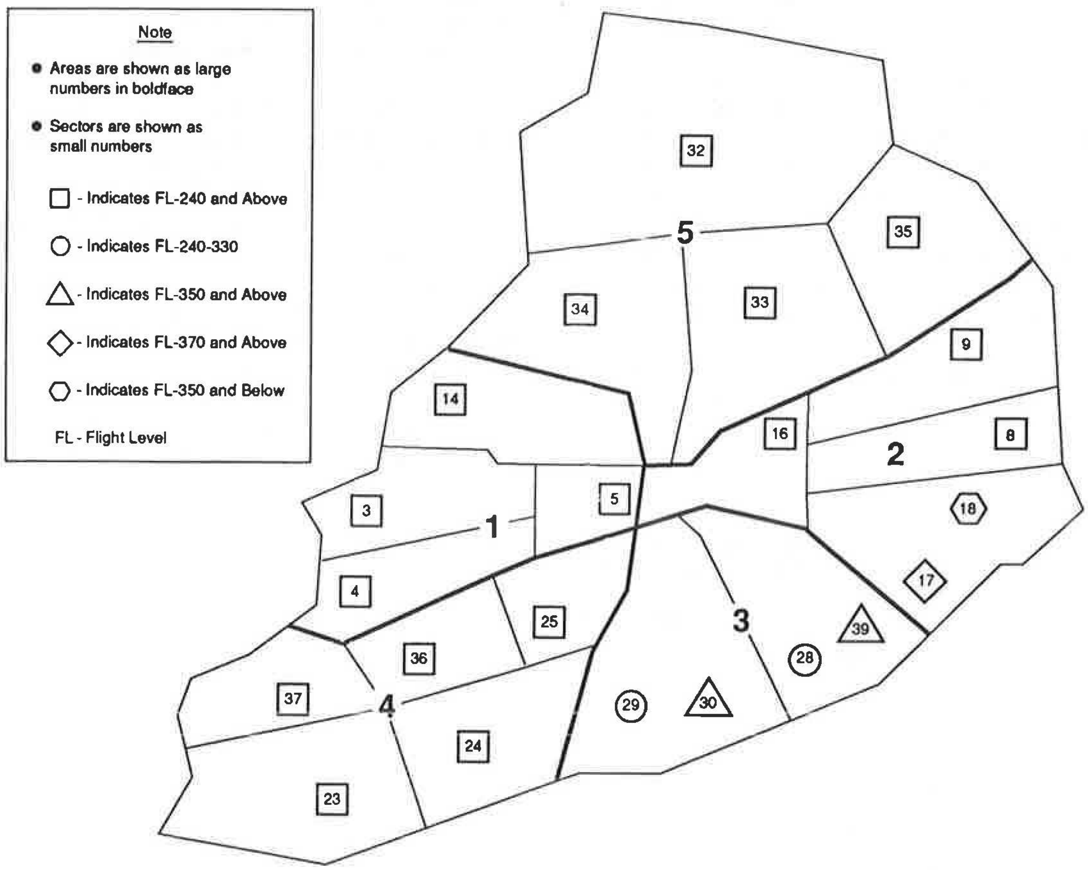

FIGURE 3 Denver Center high-altitude sectors and areas (*9*).

TABLE 7 DENVER SECTORS HAVING LARGEST PERCENTAGE INCREASES IN DAILY THROUGHPUT

SECTOR & ALTITUDE	PERCENT INCREASE
27L	42
28UH+39H	41
7L	39
26L	37
16H	36
6L	35
13L	34
15L	34
5H	33
29UH+30H	33

TABLE 8 DENVER EN ROUTE AREAS HAVING LARGEST PERCENTAGE INCREASES IN DAILY THROUGHPUT

AREA & ALTITUDE	PERCENT INCREASE
3H	41
4L	33
1H	31
2L	29
2H	29
3L	29
1L	27
4H	27
5H	17
5L	12

tracks both late and early arrivals, only data on late arrivals are usually tabulated.

4. At the time this analysis was conducted, the model did not include flight cancellations or swapping of arrival slots by airlines. These practices may be significant during IMC, and are planned to be added to the model.

5. In developing the scenarios involving IMC, it was necessary to simulate the issuance of ground delays, as already discussed. The starting and ending times of these simulated delay programs are only estimates, and may not be identical to those that would have been used by the FAA under the conditions analyzed.

The new Denver airport is planned to become operational in 1993. By 1995, it will handle 26 percent more traffic (scheduled plus unscheduled) than Stapleton would in that year, and 39 percent more than Stapleton does now. On a day that is IMC for 24 hr (the IMC2 scenario day), average technical delay per operation at Stapleton could grow from 14 min in 1989 to 45 min by 1995. The new airport would reduce this to only 4 min in 1995. Effective arrival delays at Stapleton could be even worse for the same scenario day. Average effective arrival delay would grow from nearly 1 hr to nearly 2 hr. The new airport would reduce this average delay to only 6 min.

The amount of delay savings from the new airport is very weather dependent. Summarized in the following table is the percentage savings of delay resulting from the construction of the new Denver Airport in 1995.

	Technical Delay at Denver	*Effective Arrival Delay at Denver*	*Effective Arrival Delay Systemwide*
VMC	50	14	0
IMC1	84	81	4
IMC2	90	94	18

On the IMC2 scenario day, systemwide effective arrival delays would be reduced by about 18 percent. About two thirds of the systemwide delay savings on that day occur at Denver. However, many other airports would also see delay reductions. Effective arrival delays at the 57 other airports in the NASPAC model would decrease about 6 percent overall. The two airports with the largest reductions in effective arrival delays are Houston Intercontinental and Salt Lake City. The savings on the IMC2 day in 1995 for each would be about 35 percent. Even on the IMC1 scenario day, when Denver has a shorter duration of IMC weather, these two airports would get a 12 to 24 percent reduction in effective arrival delays from the new Denver airport.

Traffic in the Denver airspace will increase between 1989 and 1995 (with the new Denver airport) because of the general growth of aviation traffic as well as the additional growth that the new airport will generate. Traffic at the four arrival fixes of the Denver airport is estimated to grow about 50 percent overall.

Traffic in Denver's en route sectors is estimated to grow about 28 percent between 1989 and 1995 (with the new airport). The low sectors grow an average of 26 percent, and the highs and ultrahighs 29 percent. This growth is lower than the 39 percent growth at the Denver airport, because of the lower growth of overflights in the center.

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