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Estimate of Air Carrier and Air Taxi Crash Frequencies From
High Altitude En Route Flight Operations

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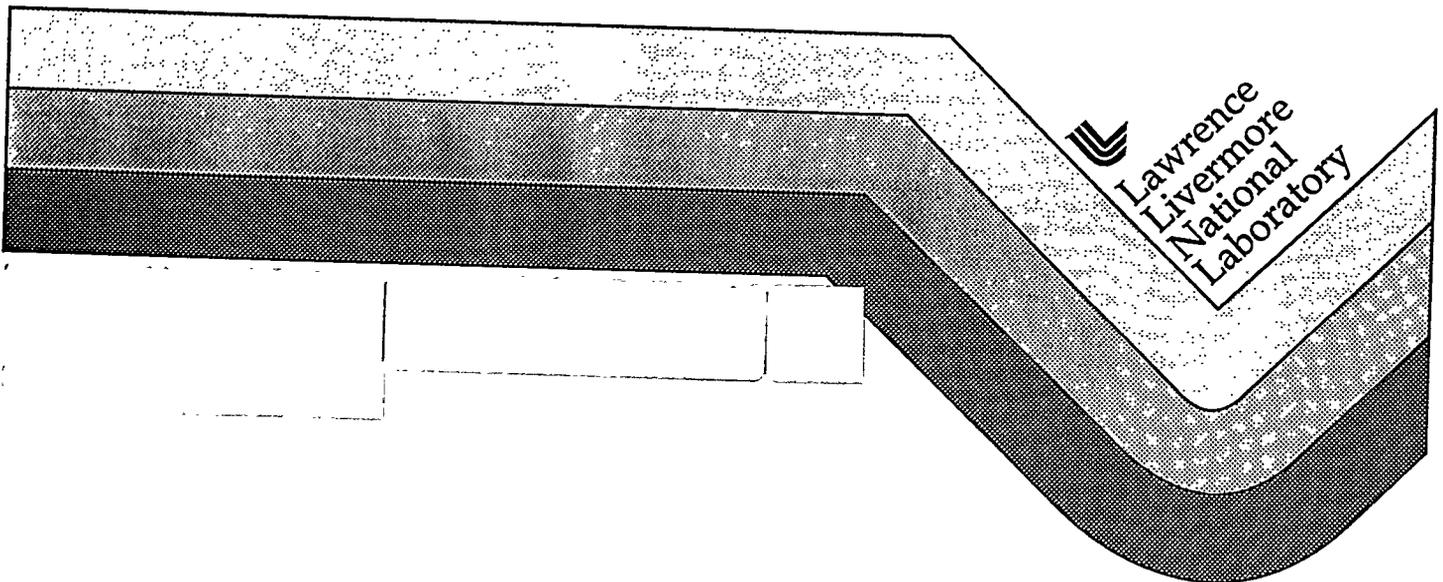
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ESTIMATE OF AIR CARRIER AND AIR TAXI CRASH FREQUENCIES FROM HIGH ALTITUDE EN ROUTE FLIGHT OPERATIONS

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ABSTRACT

In estimating the frequency of an aircraft crashing into a facility, it has been found convenient to break the problem down into two broad categories. One category estimates the aircraft crash frequency due to air traffic from nearby airports, the so-called near-airport environment. The other category estimates the aircraft crash frequency onto facilities due to air traffic from airways, jet routes, and other traffic flying outside the near-airport environment. The total aircraft crash frequency is the summation of the crash frequencies from each airport near the facility under evaluation and from all airways, jet routes, and other traffic near the facility of interest. Other papers [Refs. 1-2] have discussed the problems associated with estimating the aircraft crash frequencies onto facilities in the near-airport environment. This paper will examine the problems associated with the determining the aircraft crash frequencies onto facilities outside the near-airport environment. This paper will further concentrate on the estimating the risk of aircraft crashes to ground facilities due to high altitude air carrier and air taxi traffic. High altitude air carrier and air taxi traffic will be defined as all air carrier and air taxi flights above 18,000 feet Mean Sea Level (MSL). Another paper [Ref. 3] being presented at this conference will examine the risk of general aviation air traffic to ground facilities outside the near-airport environment.

I INTRODUCTION

In estimating the frequency of an aircraft crashing into a facility, it has been found convenient to break the problem down into two broad categories. One category estimates the aircraft crash frequency due to air traffic from nearby airports, the so-called near-airport environment. The other category estimates the aircraft crash frequency onto facilities due to air traffic from airways, jet routes, and other traffic flying outside the near-airport environment. The total aircraft crash frequency is the summation of the crash frequencies from each airport near the facility under evaluation and from all airways, jet routes, and other traffic near the facility of interest. Other papers [Refs. 1-2] have discussed the problems associated with estimating the aircraft crash frequencies onto facilities in the near-airport environment. This paper will examine the problems associated with the determining the aircraft crash frequencies onto facilities outside

the near-airport environment. This paper will further concentrate on the estimating the risk of aircraft crashes to ground facilities due to high altitude air carrier and air taxi traffic. High altitude air carrier and air taxi traffic will be defined as all air carrier and air taxi flights above 18,000 feet Mean Sea Level (MSL). Another paper [Ref. 3] being presented at this conference will examine the risk of general aviation air traffic to ground facilities outside the near-airport environment.

The motivation for performing this calculation was to determine the order of magnitude that high altitude air carrier and air taxi traffic pose to ground facilities and to determine if further data development or model development was necessary to refine the calculation.

II THE U.S. AIR TRAFFIC CONTROL SYSTEM

During the late 1950s and early 1960s, several serious high altitude midair accidents in the United States spurred the development of an air traffic control system which would control all high altitude air traffic and ensure a minimum separation distance between aircraft. The facilities established to provide air traffic control service to aircraft operating on Instrument Flight Rules (IFR) flight plans within controlled airspace, principally during the en route phase of flight are the Air Route Traffic Control Centers (ARTCCs). ARTCCs are the central authority for issuing IFR clearances, and provide nationwide monitoring of each IFR flight. Within the Continental United States, there are 20 ARTCCs, each responsible for handling en route traffic passing through a specific geographic area. Because of the size of the area covered by each ARTCC, each ARTCC's area is further divided into smaller blocks of airspace called Sectors. Each sector is monitored by one or more controllers who maintain lateral and/or vertical separation of aircraft within its airspace boundaries. Figure 1 presents the ARTCCs and their associated airspace boundaries within the Continental United States. [Refs. 4-7].

All airspace over the Continental United States from 18,000 feet Mean Sea Level (MSL) to 60,000 feet MSL has been established as Class A Airspace (formerly called Positive Control Area or PCA) by 14 CFR 71.31 [Ref. 8]. To assist aircraft in their navigation in the United States, a system of air routes have been established based on radio navigation

facilities called VORTACs (Very high frequency Omnidirectional Radio range and Tactical Navigation). Air routes established in Class A Airspace from 18,000 feet MSL to 45,000 feet MSL are called Jet Routes. Jet Routes are actually available to any aircraft capable of operating at 18,000 feet or above, not just jet traffic [Ref. 6]. All civil aviation operations conducted in Class A Airspace must be conducted under IFR as established by 14 CFR 91.135 [Ref. 9]. Therefore, it can be concluded that all air traffic in Class A Airspace including traffic in Jet Routes are under the direction and control of the ARTCCs. However, in discussions with the Federal Aviation Administration (FAA), the recent trend for routing of air traffic in Class A Airspace is toward increased point-to-point routing rather than the assignment along specific Jet Routes. Beginning in 1995, all flights above 41,000 feet MSL in Class A Airspace were allowed to be routed point-to-point, if so desired. At approximately two month intervals, the lower limit for point-to-point routing in Class A Airspace was decreased. It is currently at 31,000 feet MSL as of January 1996 and can be expected to be decreased even further in the near future. As a point of explanation, point-to-point routing is not equivalent to the concept of free flight. All separation margins between aircraft in Class A Airspace are maintained by the ARTCCs in point-to-point flights. What has been changed is that the point-to-point flights are not restricted to within a 4 mile air corridor on each side of the Jet Route centerline. This allows more direct flights between points (hence the name point-to-point). In contrast, the free flight concept, in its fullest application, would not be under the control of the ARTCCs and separation margins between aircraft in Class A Airspace would be maintained by onboard aircraft systems, perhaps an advanced version of the Traffic Collision Avoidance System (TCAS).

III. HIGH ALTITUDE AIRCRAFT ACCIDENTS

Aircraft accidents where the initiating event occurred during the high altitude portion of a flight are rare events. We define the high altitude portion of a flight as that part of a flight which encompasses the climb to cruise phase, the cruise or en route phase, and the initial descent or descent from cruise phase. For further information on the definition of the various flight phases, see Ref. 10. From the review of aircraft accident data for air carriers operating under 14 CFR 121 [Ref. 11] drawn from the National Transportation Safety Board (NTSB) accident database for the 1975 to 1994 time period, it was determined in Ref. 10 that only seven accidents have occurred during the high altitude portion of the flight which resulted in the destruction of the airframe or caused such severe damage that the aircraft was considered a total loss. These seven accidents are listed below:

April 4, 1977 DC-9-32	Southern Airways Flight 242 New Hope, GA
Nov. 18, 1979 L.188CF Electra	Transamerica Salt Lake City, UT
May 30, 1984 L.188AF Electra	Zantop Intn'l Flight 931 Chalkhill, PA
Dec. 7, 1987 BAe.146-200A	Pacific SW Flight 1771 Paso Robles, CA
Dec. 21, 1988	Pan Am Flight 103

B.747-121	Lockerbie, Scotland, U.K.
Jan. 20, 1989 Convair 580	United Express Buena Vista, CO
July 14, 1990 L.188CF Electra	TPI Intn'l Airways Aruba, Netherlands Antilles

For air carriers operating under 14 CFR 135 [Ref. 12], the number of accidents (as defined for the previous definition for 14 CFR 121 air carriers) which occurred during the high altitude portion of flight for the 1979 to 1992 timer period as determined in Ref. 10 was 97.

IV. HIGH ALTITUDE AIRCRAFT OPERATIONS

High altitude aircraft flights over the Continental United States (CONUS) are presently regulated by 20 ARTCCs. This situation has remained unchanged since 1976 when the Great Falls, Montana ARTCC was merged with the Salt Lake City, Utah ARTCC. For the near future, this situation is expected to remain unchanged according to discussions with the Federal Aviation Administration (FAA). However, the institution of free flight on ARTCC operations is uncertain at the present time.

Data on the number of IFR aircraft handled by each ARTCC is available from the FAA Office of Aviation Policy, Plans, and Management Analysis document FAA Air Traffic Activity published annually by Fiscal Year. The FAA defines IFR aircraft handled by an ARTCC as including IFR Departures, and IFR Overs where IFR Departures are defined as IFR flights originating in the ARTCC's area, accepted by the ARTCC under Sole En route clearance procedures, and extended by the ARTCC. IFR Overs are defined as IFR flights that originates outside the ARTCC area and passes through the area without landing. IFR Aircraft Handled are then the number of IFR departures multiplied by two plus the number of IFR overs. This definition assumes that the number of departures (acceptances, extensions, and originations of IFR flight plans) is equal to the number of landings (IFR flight plans closed).

Data on the number of IFR aircraft handled for the 20 CONUS ARTCCs has been tabulated in Ref. 10, and is summarized for the 1975-1994 time period in Table 1.

V. MODEL/CALCULATION OF HIGH ALTITUDE AIRCRAFT CRASH FREQUENCY

Several models have been developed and used for the analysis of high altitude aircraft crash frequency. These include models developed by the USNRC [Refs. 13-14], Solomon [Refs. 15-16], Smith of the Sandia National Laboratory [Ref. 17], and Hornyik [Refs. 18-19]. The following equation is used to estimate the frequency of crashes into a target on the ground

$$F = Npf(x,y)A \quad (1)$$

where

F = The frequency of crashes on the ground at the target (per year)
N = Number of applicable flights (per year)

p = Probability of a high altitude crash for a single flight
 $f(x,y)$ = Crash location probability density function (pdf) value at target point x,y , given a crash ($1/\text{mi}^2$)
 A = Target area (mi^2)

x is the orthogonal distance from the flight path (mile), and y is the distance along the flight path (mile). If it is assumed that crash location pdf is independent in x and y , i.e., $f(x,y) = r(x)g(y)$, that $g(y)$ is uniform over the flight length L , and that $p = lL$, then (1) can be written as

$$F = Nlr(x)A \quad (2)$$

where

$r(x)$ = Crash location probability density function (pdf) value at x ($1/\text{mi}$)
 l = Inflight crash rate ($1/\text{mi}$)

It is models for the crash location pdf, $r(x)$, that have been developed by various authors. The models for $r(x)$ have apparently been developed without the aid of actual crash location data. Given the number of models that have been developed, and used, it is reasonable to conclude that whatever data are available, do not support any particular model. Most of the models that have been developed generally assume that given a crash, there is a very high probability that the crash is located relatively close to the aircraft's flight path, although at least one of the models allows for a much larger potential impact area. The estimated crash frequency F at a target that results from using different crash location pdfs can vary significantly, as shown in the jet route analysis below.

Essentially all of the models developed have assumed that high altitude aircraft follow specific, well-defined jet routes. This requires that the jet routes be identifiable and that appropriate values of N along the routes obtainable. While this has been true in the past, it is no longer true in general. The advent of point-to-point routes has in effect removed aircraft from jet routes and smeared them out over sectors and centers. A model to deal with this situation has been developed and is presented in the point-to-point analysis below.

Analysis Based on Jet Routes

Jet routes are assumed to be at a fixed distance from the target area, with all high altitude traffic being assigned to specific routes. The main point being that all traffic along a particular jet route is assumed to result in a specific value for $r(T)$ (T indicates a specific target point). The inclusion/exclusion of specific jet routes in the calculation depends upon the model chosen. Two cases for $r(x)$ illustrate the variability in results that can be obtained. The models developed by various researchers for $r(x)$ tend to fall between these examples. These cases assume that there is a single jet route of interest. Contributions to the crash frequency from multiple jet routes are summed.

For example, if in the extreme case an inflight crash is assumed to occur literally on the flight path ($r(x) = \text{delta function}$), Eq.(2) would become

$$F = NlL \quad (3)$$

where L is the target length along the flight path. Note that in this case the jet route must be *directly* over the target area to be counted as part of the crash frequency. Under the assumptions of this example, if the flight path is not directly over the target facility, then there is no inflight contribution to the crash frequency.

As another example, if the aircraft is assumed to be able to crash anywhere uniformly over its "glide" range, ($r(x) = 1/2gh$), Eq. (2) would become

$$F = NlA / 2gh \quad (4)$$

where g is the glide ratio for the aircraft and h is its altitude along the flight path. In this case a jet route within a distance gh of the target would be counted in the crash frequency. Under the assumptions of this example, if the flight path is more than a distance gh from the target, there is no inflight contribution to the crash frequency.

The practical value of these examples is the estimated contribution each provides to the overall crash frequency. By way of illustration, to provide order of magnitude estimates for each of these examples, suppose the target area is $0.5 \text{ mi} \times 0.5 \text{ mi}$, and plausible values of $l = 7E-10/\text{mi}$ (typical of large commercial aircraft), $g = 15$, and $h = 7 \text{ mi}$ are chosen. Then in the first example to reach a crash frequency, of say, $F = 1E-6/\text{yr}$, would require about $N = 2857$ overflights/yr. Recall that these overflights must be in a jet route *directly* over the facility to be counted. Similarly, for the second example the value is about $N = 1,200,000$ overflights/yr to reach a value of $F = 1E-6/\text{yr}$. In this example however the jet route could be within a 105 mile distance of the target.

It is apparent that there is a tradeoff in reaching a specific value of F . This is clear if other adjacent jet routes are visualized. In the first example, these nearby jet routes contribute nothing to the crash frequency, as they do not fly over the facility. In the second example all jet routes within 105 miles would contribute to the crash frequency, as a crash along any these could reach the target under the assumptions of the example. Thus, spreading out the pdf yields a larger N for a given value of F , but jet routes included in a larger range must be considered.

Analysis Based on Point-to-Point Routes

With the advent of point-to-point routes, air traffic is no longer restricted to specific jet routes. Intuitively, this means that air traffic which was restricted to a jet route is now able to "spread out". The effect of this spreading out on crash frequency F will manifest itself in the values of N and $f(x,y)$.

The values of N will change depending on how the air traffic is assumed to change over the targets of interest, as well as the model used. $f(x,y)$ determines the extent of the model and hence the appropriate value for N .

In conjunction with the modeling, attention must be paid to the available data. Based on conversations with FAA personnel, the most comprehensive data for use in a high altitude in-flight model kept by the FAA is at the ARTCC level. This data provides the number of aircraft handled by each center.

The model assumes that there is a constant value of p (the probability that a high altitude flight crashes) across the Continental United States (CONUS). Furthermore, based on the assumption that point-to-point routes tend to spread air traffic out uniformly across centers, $f(x,y)$ is assumed uniform over individual centers. Thus, in Eq.(1), F is assumed to vary from center to center based on center specific values of N and $f(x,y)$. If we let center values of $f(x,y)$ and N be denoted by f_c and N_c , and corresponding values for CONUS denoted by f_u and N_u . The estimated frequency of crashes for any target within a specific center is then given by

$$F_c = N_c f_c p A \quad (5)$$

which can be rewritten as

$$F_c = (N_c f_c / N_u f_u) N_u f_u p A \quad (6)$$

The term in parenthesis represents the variation in air traffic density between centers relative to the CONUS value, while $N_u f_u p$ represents the average number of crashes per year per square mile across CONUS. By assumption, f_c is given by $1/A_c$ where A_c is area of a center. Assuming that crashes across the CONUS are distributed uniformly, f_u is given by $1/A_u$, where A_u is the area of CONUS. Substituting for f_c and f_u into eq. (6) yields

$$F_c = (N_c A_u / N_u A_c) N_u p A / A_u \quad (7)$$

where the term $(N_c A_u / N_u A_c)$ is the adjustment factor to account for ARTCC specific air traffic densities.

To perform calculations, values for the terms in Eq. (7) are needed. Table 1 shows the relevant information for each of the 20 CONUS ARTCCs. Data from the 20 year period 1975-1994 were used in the analysis. In this table, p is based on the amount of aircraft handled. Note that the $N_u f_u p$ base rate is given for both Air Carriers and Air Taxis. This base rate is multiplied by the appropriate adjustment factor for each center (the parenthetical term in Eq. (7)) to obtain an estimate for $N_c f_c p$. This value, along with a target area A , allows an estimate for F_c to be made.

As an example, an $A = 0.25$ (0.5×0.5) mi^2 target in the Albuquerque center, has an estimated Air Carrier crash frequency of $F_c = 0.476 \times 1.18\text{E-}7 \times 0.25 = 1.4\text{E-}8$ crashes/yr.

CONCLUSION

Air traffic patterns in high altitude (Class A) airspace in the United States are undergoing significant changes presently. Previous risk assessment models for high altitude aircraft traffic were based on jet routes. As the use of jet routes by high altitude air traffic is phased out, then risk assessment models based on jet routes should also be phased out. This paper presents a first attempt at modeling the risk of crashes onto ground facilities from point-to-point high altitude air carrier and air taxi traffic which seems to be the practice to which future U.S. high altitude air traffic control is headed.

Based on 20 (1975-94) years of aircraft handled data from the 20 ARTCCs which control the high altitude airspace over the Continental United States, the average (base) rate for high altitude en route air carrier crashes is $1.18\text{E-}7/\text{yr}/\text{mi}^2$. The average (base) rate for high altitude en route air taxi crashes is $2.34\text{E-}6/\text{yr}/\text{mi}^2$ for 14 (1979-1992) year time period. To determine the ARTCC-specific high altitude en route crash frequency, the adjustment factor based on ARTCC-specific traffic handled and area is used.

Finally, it was concluded that while high altitude air carrier traffic poses only a minor risk to ground facilities, high altitude air taxi traffic could present a risk that is unacceptable to some agencies. Further refinement of the high altitude air taxi accident data should be performed for future analysis.

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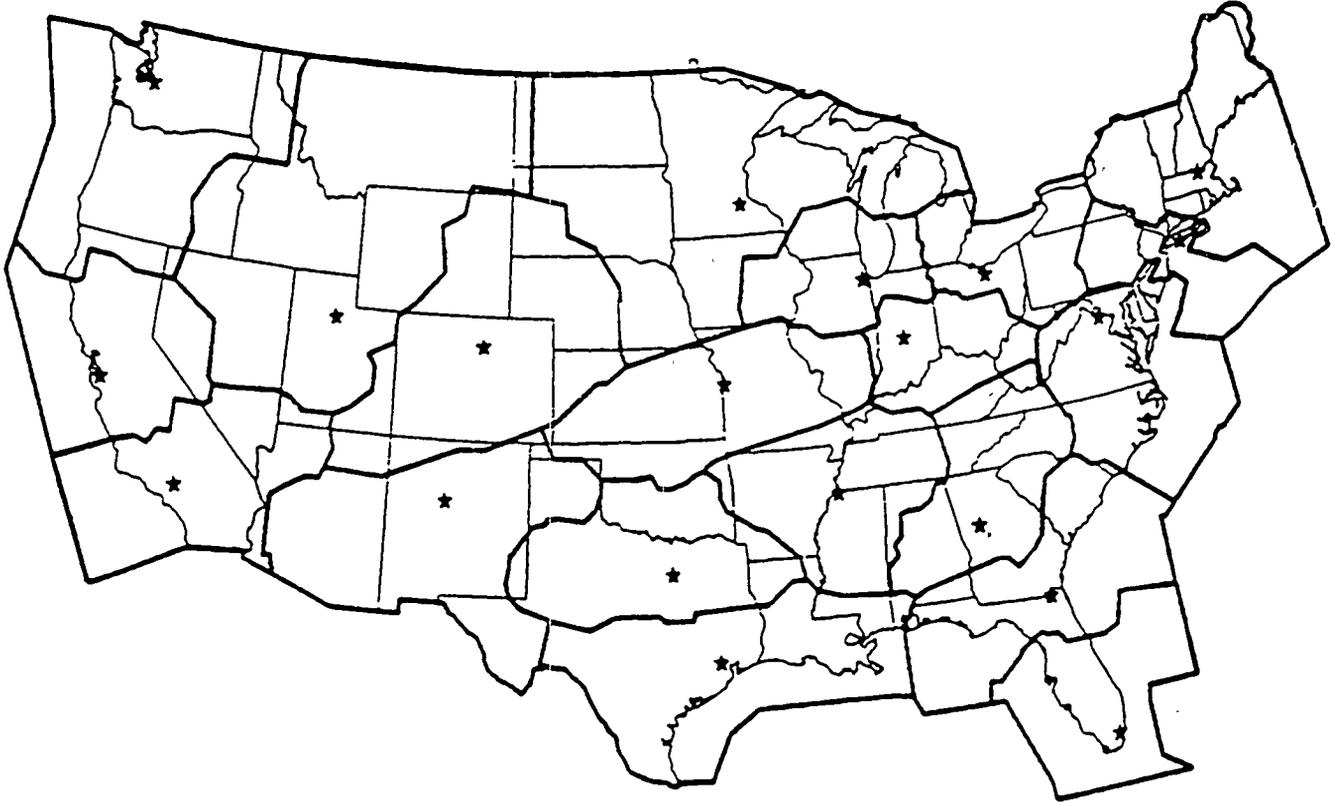


FIGURE 1
ARTCCs AND AIRSPACE BOUNDARIES WITHIN
CONTINENTAL UNITED STATES

ARTCC	AIR CARRIER (FY1975-1994)				AIR TAXI (FY1975-1994)				Estimated Land Area (mi. ²)	Air Carrier N/Area (AC/yr/mi ²)	Air Taxi N/Area (AC/yr/mi ²)	Air Carrier Adjustment Factor	Air Taxi Adjustment Factor
	Departures	Domestic Overs	Oceanic Overs	Aircraft Handled, N	Departures	Domestic Overs	Oceanic Overs	Aircraft Handled, N					
Los Angeles, CA (ZLA)	7,858,048	992,277	0	16,708,373	1,963,445	14,166	0	3,941,056	123,983	6.738	1.589	1.331	1.189
Oakland, CA (ZOA)	5,127,604	1,025,938	2,081,913	13,363,057	1,594,727	48,972	7,450	3,245,876	100,478	6.650	1.615	1.314	1.209
Denver, CO (ZDV)	3,621,334	5,412,678	0	12,655,346	1,245,146	202,206	0	2,692,498	268,185	2.359	0.502	0.466	0.376
Washington, DC (ZDC)	6,840,796	6,976,105	0	20,857,697	1,283,358	130,894	0	2,697,610	N.A.	N.A.	N.A.	N.A.	N.A.
Jacksonville, FL (ZJX)	3,025,610	7,296,490	0	13,347,710	1,073,462	166,070	0	2,312,994	N.A.	N.A.	N.A.	N.A.	N.A.
Miami, FL (ZMA)	6,254,663	679,999	3,424,969	16,614,294	1,597,487	9,498	378,807	3,583,279	N.A.	N.A.	N.A.	N.A.	N.A.
Atlanta, GA (ZTL)	7,948,944	4,474,694	0	20,372,582	2,223,949	379,449	0	4,827,347	127,928	7.963	1.887	1.573	1.412
Chicago, IL (ZAU)	8,874,905	4,135,960	0	21,885,770	3,444,033	365,600	0	7,253,666	102,383	10.688	3.542	2.111	2.651
Indianapolis, IN (ZID)	3,946,741	7,421,296	0	15,114,778	2,085,483	465,121	0	4,638,087	87,881	8.600	2.638	1.699	1.974
Boston, MA (ZBW)	4,434,852	2,672,635	0	11,542,339	2,450,086	349,737	0	5,243,909	N.A.	N.A.	N.A.	N.A.	N.A.
Minneapolis, MN (ZMP)	3,872,395	4,570,104	0	12,314,894	2,329,855	71,358	0	4,731,068	N.A.	N.A.	N.A.	N.A.	N.A.
Kansas City, MO (ZKC)	4,384,267	4,948,665	0	13,717,199	1,840,425	232,046	0	3,912,896	N.A.	N.A.	N.A.	N.A.	N.A.
Albuquerque, NM (ZAB)	3,720,105	3,971,870	0	11,412,080	504,107	89,366	0	1,097,580	236,753	2.410	0.232	0.476	0.173
New York, NY (ZNY)	7,751,607	3,529,945	1,920,001	20,953,160	1,931,493	528,253	42,848	4,434,087	31,839	32.905	6.863	6.500	5.211
Cleveland, OH (ZOB)	6,914,338	8,323,884	0	22,152,560	2,723,348	652,530	0	6,099,226	N.A.	N.A.	N.A.	N.A.	N.A.
Memphis, TN (ZME)	3,225,974	6,574,140	0	13,028,088	1,603,228	421,723	0	3,628,179	139,465	4.870	1.301	0.922	0.973
Fort Worth, TX (ZFW)	6,294,549	2,848,087	0	15,437,185	2,075,630	133,722	0	4,284,982	N.A.	N.A.	N.A.	N.A.	N.A.
Houston, TX (ZHU)	5,283,331	1,033,000	399,205	11,958,867	1,259,310	44,151	11,697	2,574,468	N.A.	N.A.	N.A.	N.A.	N.A.
Salt Lake City, UT (ZLC)	2,012,757	4,513,820	0	8,539,394	1,316,200	222,321	0	2,854,721	415,008	1.029	0.344	0.203	0.257
Seattle, WA (ZSE)	3,625,362	424,851	0	7,875,575	2,517,467	7,017	0	5,041,951	186,624	2.056	1.351	0.406	1.011
Continental US Total	104,899,182	81,826,436	7,826,088	299,648,888	37,062,239	4,528,200	440,802	79,093,480	2,959,545	5.062	1.336	1.000	1.000

CONUS Area
Air Carriers
7 In-Flight Crashes in 20 years
Np(x,y) base rate = 7/20/2,959,545
1.18E-07 acc./yr/mi²
N(x,y) base rate = 269,648,888/20/2,959,545
5.062 AC handled/yr/mi²

Air Taxi
97 In-Flight Crashes in 14 years
Np(x,y) base rate = 97/14/2,959,545
2.34E-06 acc./yr/mi²
N(x,y) base rate = 79,063,480/20/2,959,545
1.336 AC handled/yr/mi²

N.A. = information not available at time of table preparation.

TABLE 1
CONTINENTAL UNITED STATES ARTCC AIR CARRIER AND AIR TAXI AIRCRAFT
HANDLED FOR FY1975-1994, ARTCC LAND AREA, TRAFFIC DENSITY, AND ADJUSTMENT FACTOR