New Approach to Air Safety Statistics

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Differences in usage among aircraft types severely distort conventional accident rates. A scheme is therefore presented for separate (intrinsic) accident rates in takeoff, cruise, and landing. This is applied to U.S. air carrier accidents for 1961–1964. Comparisons are made among jets, pistons, turboprops, and helicopters. Intrinsic rates show that for the winged aircraft: all have the same cruise risk when expressed per cruise-mile; for jets, cruise risk is negligible compared with landing risk; jets are twice as dangerous in takeoff and landing as pistons or turboprops. Strong statistical correlation exists between landing accident rates and landing speeds, and this relationship is cubic. Jets' cruise risk decreased 40% during 1961–1964, but jets' dominant risks of landing and takeoff have been increasing since 1962. It is recommended that future airsafety trends be analyzed by the method of intrinsic rates.

Introduction

THERE are in common usage various alternative ways of computing safety rates, e.g., fatalities or accidents expressed per passenger mile, per flight hour, per flight mile, etc., but each of these methods attempts to describe the risk statistics by only one rate. We will show that any single number, no matter upon what basis computed, is logically insufficient for an adequate analysis of air safety; a meaningful and revealing evaluation requires a set of at least three independent rates.

As the basis for this analysis, we have taken all aircraft accidents involving U.S. air carriers in domestic and international flights during the 4-yr period, 1961–1964, inclusive. This constitutes 318 accidents, a large enough number so that sufficient reliability can be expected from a statistical analysis. Not included are aircraft "incidents," that is, accidents that are not "severe" in nature. The precise definition for this rests with the Civil Aeronautics Board (CAB) and is based upon the minimum requirement of major repair or major replacement in the aircraft for an "accident" classification. The 318 accidents used here thus range from "serious personal injury or substantial damage to the aircraft" up to "accidents with 100% fatalities." We have chosen this 4-yr period 1961–1964 because 1) this time interval is sufficiently long for investigation of trends within the period; and 2) since we seek also a comparison among different aircraft types, extension of the interval to years before 1961 would have included jet accidents connected with the introduction of jets before any stabilization of their safety characteristics could occur. Our 318 accidents include all those listed by CAB plus some other accidents. The full category covered here is termed by the Federal Aviation Agency (FAA) the "Air Carrier Operators," and includes scheduled passenger and cargo flights, plus "supplemental air carriers," plus the "commercial operators" and other unscheduled services.

All of the basic data used have been supplied to us by the Control Systems Div., Flight Standards Service, of FAA. We have chosen to analyze on the basis of aircraft accidents rather than on the basis of fatalities because a safety comparison among the various aircraft types is desired. A safety-level measurement of a specific aircraft type should be independent of its seating capacity and should refer only to the inherent risk of an accident regardless of size, or passenger capacity, or fraction of seats occupied.

Received November 8, 1966; revision received February 20, 1967. Abridgement of a paper presented at 19th International Air Safety Seminar (Flight Safety Foundation), Madrid, Spain, November 1966. [10.03]

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All rates given in Figs. 1–9 are based upon the entire 4-yr interval, 1961–1964, inclusive. Figures 10–16 show rates for shorter periods within this 1961–1964 interval.

Inadequacy of the Conventional Utilization Rates

Figures 1 and 2 illustrate some of the inadequate methods which attempt to evaluate and compare safety by means of some single rate.

Figure 1 shows the comparison when the single rate chosen is aircraft accidents per flight hour. Basic data are taken from Tables 1 and 2. On this basis, helicopters are eight times more "dangerous" than jets. However, this rate takes no account of the relative frequency of flight segments in the total air traffic considered.

Figure 2 shows the comparison when the single rate is chosen as aircraft accidents per flight segment. The basic data are again from Tables 1 and 2. This rate, on the other hand, takes no account of the total length or duration of flight. Now a completely different ordering results for the safety levels of the four aircraft types. On this basis the jets would be the most dangerous, and the turbos and pistons the "safest."

This reversal of the relative ordering in Figs. 1 and 2 illustrates the fact that objective safety levels cannot be de-

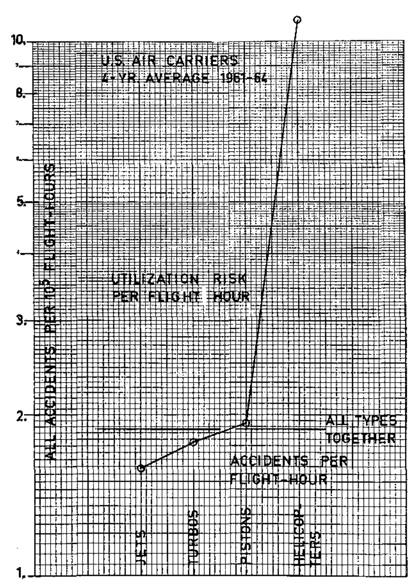

Fig. 1 Accidents per flight hour.

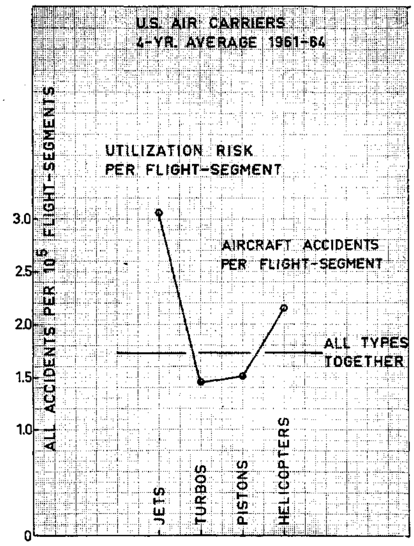

Fig. 2 Accidents per flight segment.

scribed by any single rate. We see from Fig. 2 how the number of takeoffs or landings is a factor of at least equal importance with the duration of flight. Although this obvious fact is well known qualitatively, it is the intention of our study to exhibit this dependence in a precise quantitative manner.

It must be emphasized that all of our subsequent safety comparisons (except Fig. 6a) among jets, pistons, etc. refer only to their safety characteristics as exhibited in the use of these aircraft by the U.S. Air Carrier Operators during 1961–1964. It is not necessarily implied that the same relative safety performance must prevail when the same aircraft types are used in general aviation, or by the military, or by foreign operators.

Definition of Intrinsic Safety Rates

The rates in Fig. 1 are affected in a hidden way by the average frequency of takeoff-landing operations made by the different aircraft types. This frequency is relatively greatest for the helicopters and piston aircraft and least for the jets, as seen from the last column of Table 1. This puts a very favorable bias on the jet rate in Fig. 1. Conversely, the rates in Fig. 2 are affected in a hidden manner by the cruising duration of the flights, thus making the helicopter rate appear too favorable and the jet rate too unfavorable. Since all such single-number rates are inherently dependent upon the particular way in which an aircraft is utilized, we call here all such quantities "utilization" rates to distinguish them from more objective measures of safety. The latter should depend only upon the safe operating procedures and the engineering design of an aircraft type and should be independent of the relatively safe or dangerous services which that aircraft type may be selected to perform. This more objective type of rate we will term an "intrinsic" rate.

Table 1 U.S. air carriers[a]

Type	Passenger miles in thousands[b]	Flight hours[c]	Flight operations[d]	Average operations/hour
Jets	144,632,952	4,793,917	2,486,100	0.52
Turboprops	20,156,742	2,517,411	3,100,200	1.23
Pistons	42,852,952	9,612,178	12,266,100	1.28
Helicopters	45,645	97,142	510,500	5.26

[a] Four years combined (1961 through 1964).
[b] Taken from T-4 schedules submitted to the CAB.
[c] Total A/C flight-hours reported to FAA.
[d] For total A/C operators. These totals have been obtained from the exact plus the extrapolated data for operations/hour given in Table 6, and rounded off to the nearest hundred.

To define intrinsic safety rates, we divide every flight operation into three mutually exclusive parts: the takeoff phase, the cruise phase, and the landing phase. In the definition adopted here, the takeoff phase continues until final leveling off from climb to begin cruise, and the cruise phase terminates when the first descent is made preparatory to landing and/or initiation of holding pattern. Estimates indicate that the cruise phase so defined for the winged aircraft comprises, on the average, about 85% (helicopters, 95%) of flight hours. These percentages enable us to calculate from total flight hours the number of cruise hours for each type of aircraft. It should be emphasized, however, that the values of these percentages are in no sense critical. Other estimates would change the calculated cruise rates only slightly, and would make no significant quantitative change in our results.

A study of the file for each of the 318 accidents has been made, and each accident has been classified by the FAA staff as occurring in exactly one of the three flight phases. One could, of course, divide a flight into more than three phases, but then one soon runs into the difficulty of creating sparse data by too fine a subdivision. We have, therefore, pre-

Table 2 Numbers of aircraft accidents[a]

Type	1961	Severity wt.	1962	Severity wt.	1963	Severity wt.	1964	Severity wt.	Total	Total severity wt.
Cruise										
Jets	6	24	6	30	8	35	3	12	23	101
Turboprops	1	4	1	10	4	22	2	11	8	47
Pistons	7	31	7	28	5	32	5	20	24	111
Helicopters	1	10	0	0	0	0	0	0	1	10
Totals	15	69	14	68	17	89	10	43	56	269
Takeoff										
Jets	3	3	3	12	6	21	6	27	18	63
Turboprops	1	10	2	5	2	2	2	5	7	22
Pistons	18	57	9	21	11	38	15	42	53	158
Helicopters	1	1	0	0	2	11	0	0	3	12
Totals	23	71	14	38	21	72	23	74	81	255
Landing										
Jets	12	18	6	6	6	18	11	23	35	65
Turboprops	6	6	8	8	5	17	11	32	30	63
Pistons	33	54	28	67	25	49	23	62	109	232
Helicopters	4	4	0	0	1	1	2	2	7	7
Totals	55	82	42	81	37	85	47	119	181	367
								Totals	318	891

[a] Total U.S. Air Carrier Operators, domestic and international flights, FS-FAA accident data 1961–1964.

ferred to use the minimal number three as our basic structure. This, then, gives us separate accident counts for each of the three phases of flight, and we proceed to calculate separate accident rates for each of these three categories independently. The numbers of accidents occurring in each of these flight phases are shown in Table 2. One sees that less than 18% of all the accidents occurred during cruise.

Intrinsic Rates for the Four-Year Period 1961–1964

Figure 3 shows the separate accident rate (intrinsic rate) for cruise expressed as cruise accidents per cruise hour. This rate, when calculated for helicopters, is the only one of our twelve intrinsic rates to be derived for which the basic data are too sparse to furnish reasonable reliability; there was only one helicopter accident during cruise in the entire 4-yr period. The rate based upon this very rare occurrence has only minimal significance, and is therefore shown by dashed lines in Fig. 3. The other three rates for winged aircraft are statistically reliable. A precise discussion of confidence limits will be given later. Figure 3 shows, when based upon cruise hours, that the jet is the most dangerous winged craft in the cruise phase, and the piston is the safest, by a ratio of two to one.

Figure 4 shows in the top curve the intrinsic accident rate for the combined takeoff and landing phases. This is expressed as the number of accidents occurring during either takeoff or landing divided by the number of flight operations. All these rates have very good statistical reliability. They show that the jet in takeoff-landing is the most dangerous of all four types, even exceeding the helicopter rate, with turboprops and pistons being the safest by a factor of almost two to one. We will show this takeoff-landing risk to be the dominant risk. If one compares this risk with the utilization rates in Figs. 1 and 2, it is therefore seen that the rate in Fig. 1 is the more misleading, and the rate per flight segment (Fig. 2) the less misleading of these single utilization rates.

Although we do not use passenger miles in our study, it is not intended to imply that the passenger-mile unit should never be used. When it is used, however, (except for a blanket comparison with other media of transportation) one should introduce with it the concept of intrinsic rates, e.g., landing fatalities per passenger landing, etc.

The bottom and middle curves in Fig. 4 are the separate contributions for takeoff and for landing. The landing risk of the jet is the highest of all these eight rates shown. The helicopter is safer than the jet in respect to both landing and takeoff. The safest rates are for the pistons in landing and the turboprops in takeoff. One sees that, for each type separately, the intrinsic landing risk is greater than the intrinsic takeoff risk by roughly two to one.

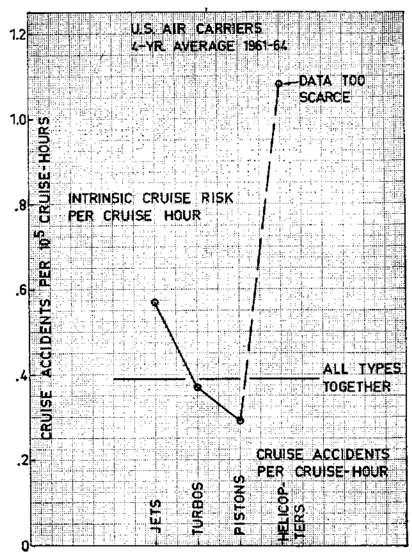

Fig. 3 Intrinsic accident rate for cruise.

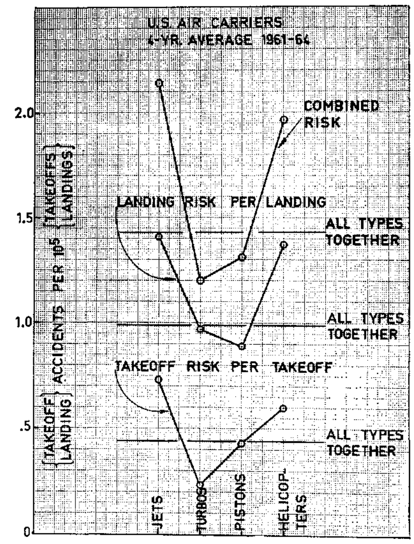

Fig. 4 Intrinsic rates for takeoff and landing.

Since jets are being flown with relatively very few operations per flight hour (Table 1) and pistons with relatively very many, this means that the jet rate of Fig. 1 consists of a large contribution from the rate of Fig. 3 and only a relatively small contribution from the rates of Fig. 4. Conversely, the piston utilization rate consists of a large contribution from the Fig. 4 rates and a small contribution from the Fig. 3 rate.

It is easy to calculate how risk is distributed between cruise and takeoff-landing. For all types together in the fleet, the average shows that 3.67 cruise hours contain the same amount of accident risk as one takeoff-landing operation contains. For the jet, the value is 3.7 hr when based upon our total period 1961–1964. However, to anticipate a later section, when we take the rates for the most recent single year, 1964, due to the trends within our 4-yr period, the jets require nine cruise hours for risk equal to one takeoff and landing. This means that cruise risk is negligible relative to takeoff and landing risks for jets.

The total probability for an accident on a specific flight with a given number of intermediate stops and for a specific aircraft type can be calculated by

$$\text{Total risk} = h_c e_c + n_o e_o$$

for a flight with h_c total cruise hours, involving n_o total flight operations, where the e's are the corresponding intrinsic rates; this total risk is a dimensionless number measuring the probability of an accident on the flight.

In Fig. 5, from the data of Table 3 for flight hours and aircraft miles, the weighted average flight velocities have been calculated. Results for winged aircraft are 203, 267, and 469 mph for pistons, turbos, and jets, respectively. We take these values in the central two years to be representative of the 1961–1964 averages. Figure 5 graphs the intrinsic cruise risks expressed per cruise hour (Fig. 3) against these average flight velocities. A least-squares straight line has then been fitted to these points as shown. The strict linearity is rather surprising.

Since the points graphed in Fig. 5 fall on the straight line, it follows that the accident rates, if based upon cruise miles, would then be approximately equal. A statistical test shows that the small differences in these new rates among the three types do not have statistical significance. We can, therefore, conclude that all three winged aircraft types have the *same* accident rate in *cruise* when expressed in cruise miles.

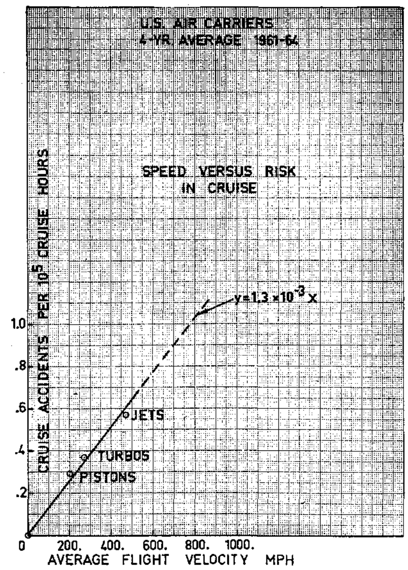

Fig. 5 Speed vs risk in cruise.

It is interesting to speculate on this somewhat surprising result. Since the equal cruise risk for all winged aircraft types is dependent only upon cruise distance, and not upon the cruise time, this suggests a model in which potential cruise accidents are distributed geometrically at fixed random locations throughout the airspace; then an airplane simply "hits" one as it flies through, regardless of its velocity. When one realizes that some causes of cruise accidents are actually describable in this manner, e.g., turbulence patches, potential lightning strikes, bird strikes, midair collisions, etc., then this model may not appear farfetched. We shall see later, however, that the situation is totally different with respect to takeoff and landing accidents, which comprise the large majority of all accidents.

Figure 6: The landing accident rates for the winged aircraft from Fig. 4 have been plotted in Fig. 6 against weighted averages of landing speeds. The landing speeds used are in no sense arbitrary estimates, but were calculated by the Flight Standards Service of FAA as weighted averages of the individual speeds at touchdown for each model of aircraft in the air carrier fleet. Weighting is in terms of the relative fraction of the total activity for each model. The calculations are indicated in Table 4 for the central 1962–1963 period

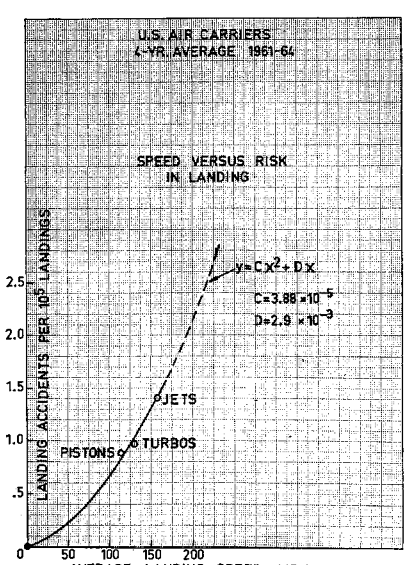

Fig. 6 Speed vs risk in landing (U. S. air carriers 1961–1964).

Table 3 Certified route air carriers[a]

Type	Aircraft miles	Aircraft hours	Average flight velocities, mph
Jet	1,084,076,031	2,309,250	469
Turboprops	297,716,169	1,116,570	267
Pistons	780,280,404	3,847,854	203
Helicopters	3,109,702	35,679	87

[a] Source: FS-FAA, revenue data, two years combined (1962 and 1963).

(for which data were readily available), which we take to be representative of the full 1961–1964 period. The velocities are 157, 129, and 114 mph for jets, turboprops, and pistons, respectively. Including the point at the origin, we have fitted a least-squares quadratic curve to these four points since the variation shown is clearly more rapid than linear.

We are, of course, using these touchdown velocities as single numbers to describe the entire landing phase for comparisons of aircraft types. Although this cannot be precise for any portion except the touchdown, types which are faster in touchdown will normally also be faster in descent, holding pattern, etc., so that these single touchdown velocities should therefore give us relative numerical ratings for the entire landing phase, and are used here only in that context.

To determine precisely the degree of the best fitting polynomial would require narrower confidence limits (more landing accidents) for the turboprops and jets. Because of this, the conclusion here can only be that the behavior is more rapid than linear.

Since there is a nonlinear behavior of accident rate with speed, this therefore suggests a model where accident potential

Table 4 Average landing speeds for aircraft types operated by certificated route air carrier operators in revenue service during 1962 and 1963[a]

Aircraft type	Average landing speed, mph[b]	Percent of total revenue operations	Weight contribution to weighted average
B-707	153	24.12	36.9
B-720	151	30.34	45.8
CV-880	161	12.23	19.7
CV-990	184	2.58	4.7
DC-8	163	25.09	40.9
SE-210	160	5.64	9.0
All jets combined			Average 157 mph
CL-44	144	0.71	1.0
F-27	104	26.86	27.9
L-188	141	46.34	65.3
PC-6A	52	0.10	0.1
V-745	131	19.56	25.6
V-810/812	135	6.42	8.7
All turboprops combined			Average 129 mph
CV-240	126	5.99	7.5
CV-340/440	123	20.17	24.8
CW-46	99	0.48	0.5
DC-3	95	28.29	26.9
DC-4	112	0.30	0.3
DC-6	121	18.30	22.1
DC-7	131	9.54	12.5
L-749	108	2.44	2.6
L-1049	129	3.53	4.6
L-1649	131	0.44	0.6
M-202	116	2.39	2.8
M-404	112	7.90	8.8
PC-6	52	0.23	0.1
All pistons combined			Average 114 mph

[a] Source: FS-FAA.
[b] This figure is 1.3 times the stalling speed actually measured by phototheodolites in the landing configuration at the maximum landing weight of the aircraft. This estimates the actual touchdown speeds. The 1.3 factor is the result of repeated measurements by FAA and NASA of typical approaches.

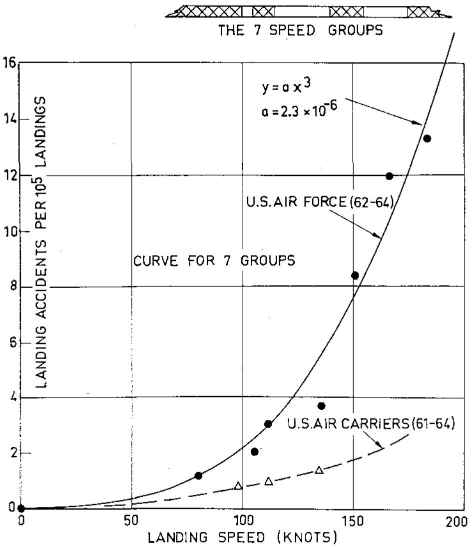

Fig. 6a Speed vs risk in landing (U. S. Air Force 1962–1964).

is coupled with the specific kinetic energy of the aircraft in the landing phase. This is altogether different from our suggested model for cruise accidents where accident rate is independent of speed.

Figure 6a: The curve of landing risk vs landing speed in Fig. 6 was deduced from only 174 landing accidents. Furthermore, these were grouped into only 3 average-speed classes, and each class consisted of only one type of aircraft, i.e., piston, turboprop, or jet. Also, the range of landing speeds occurring in the present air carrier fleet is relatively narrow. For these reasons, the tentative conclusion reached from Fig. 6 was liable to some uncertainty. It would be futile to subdivide the same aggregate of accidents into more speed groups; the sparser data resulting would have too great a sampling error to produce any conclusion with more reliability. Therefore, we have subsequently sought some independent method to confirm (or deny) our tentative conclusion, but at a very much higher confidence level. For this purpose the Directorate of Aerospace Safety, Norton Air Force Base, has most kindly furnished us with the full data for all winged aircraft for the 3-yr period 1962–1964 on U.S. Air Force landing accidents. Although the basic data are classified, an abridged unclassified report of the derived rates has been approved for release. For fuller details, the reader is referred to the paper by Dressler.[1] For present purposes, it will suffice to consider just one figure taken from Ref. 1, which appears as Fig. 6a in this report. This curve is based upon a very large number of landing accidents, many times greater than our air carrier record, and upon a very much wider range of landing speeds, and with different aircraft types represented in each speed range in most cases. For an overall grouping into seven landing-speed classes, the intrinsic landing-accident rates are shown in Fig. 6a. Careful tests indicate that this accident-vs-speed behavior follows a third-degree curve with very high correlation. This result has the desired statistical reliability and not only confirms our tentative conclusion for air carriers, but intensifies it from a second-degree to a third-degree relationship. The three air carrier rates from Fig. 6 are also reproduced in Fig. 6a and denoted by triangles. The air carrier rates are seen to be lower than their U.S. Air Force counterparts; this is to be expected in view of the different requirements and different environments of the two services.

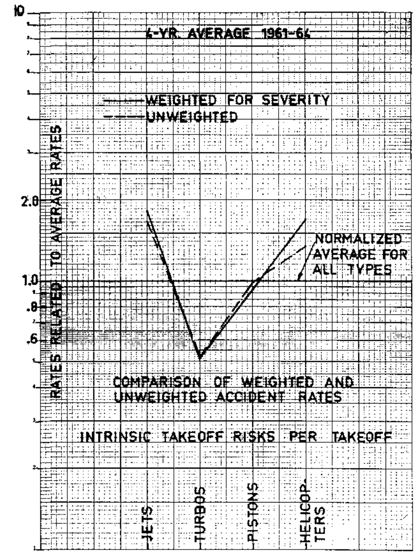

Fig. 8 Weighted rates for takeoff.

Intrinsic Rates Weighted for Accident Severity

Figures 7–9: All previous figures have shown rates based upon merely a count of the number of accidents, without regard to the severity of the accidents. One might naturally wonder if the relative rankings for safety among the four aircraft types would significantly alter when the severity

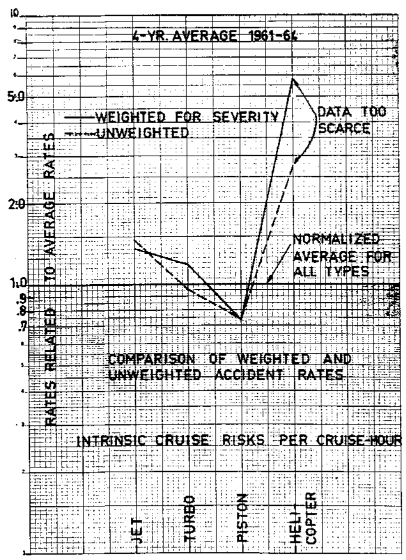

Fig. 7 Weighted rates for cruise.

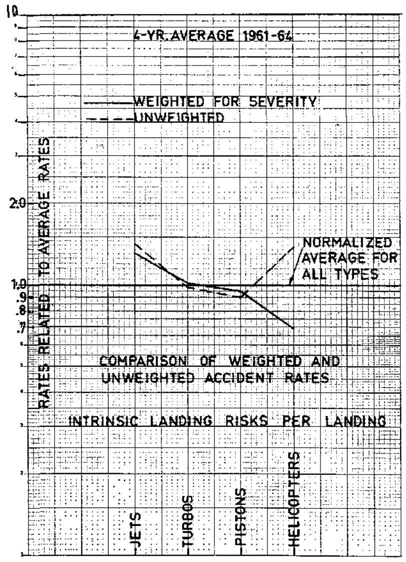

Fig. 9 Weighted rates for landing.

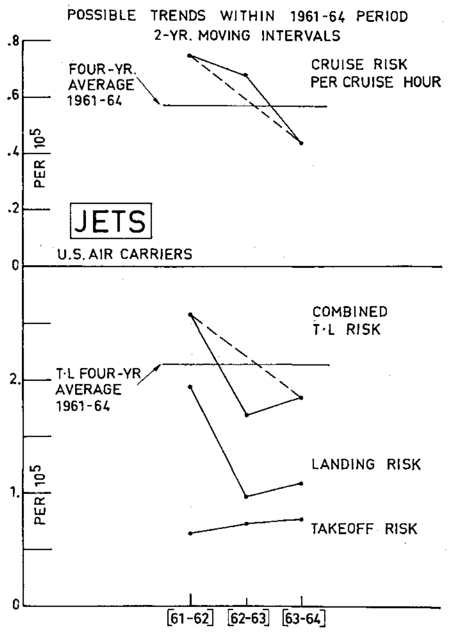

Fig. 10 Possible trends for jets.

Table 5 Definitions of weighting factors[a]

Severity weight	Category
10	Fatal injury to all occupants
7	Fatal injury (less than all) or serious injury to one-half or more
4	Serious injury (less than one-half) or destruction of aircraft
1	Minor or no injuries but substantial damage to aircraft

[a] These are definitions of the four categories used by the Control Systems Division of the FAA with a 10 to 1 linear scaling.

of accidents for each type is considered. Figures 7–9 answer this question; every intrinsic risk rate has been recalculated on a new basis wherein each accident has first been weighted by a severity factor. The choice of numerical values for weighting factors is necessarily somewhat arbitrary, but we have adopted the definitions of the four categories used by the Control Systems Division of FAA with a 10 to 1 linear scaling, as shown in Table 5.

In Table 2, the numbers in the columns headed "Severity weight" are the sums of the severity weights for each accident counted in the adjacent columns. When these sums are used as numerators for new rate calculations, the resulting weighted risk rates (in normalized form) are shown in Figs. 7–9 by the solid lines. The severity-weighted rate for all four aircraft types combined is first normalized as unity, and the normalized individual weighted rates for each type are then shown as percentages above or below the normalized average. For comparison, the previous unweighted rates are shown by dotted lines, also on a normalized basis. One sees that for all of the eleven reliable intrinsic rates which we have developed, there is no appreciable difference between weighted and unweighted rates, with the single exception of the landing risk for helicopters. In this exception, the weighted rate shows a marked safety improvement over the unweighted rate; on the average, helicopter landing accidents were not severe. One can therefore state that on the basis of the weighted rate, the helicopter is the safest of all four types of aircraft in the landing phase.

Possibility of Significant Trends

All of the preceding figures have exhibited risks computed as over-all rates for the total 4-yr period 1961–1964. By contrast, all subsequent figures will deal with the determination of the presence or absence of significant trends within this 4-yr period. Such examination in more detail is always somewhat less precise, since a splitting into shorter intervals makes the data become relatively more scarce. This leads to the usual complication of statistical variations due possibly to sampling errors rather than to genuine trends. For this reason, the next three figures, 10–12, are labeled only as possible trends within the 1961-1964 period. Here we first merely observe uncritically the fluctuating behavior for each intrinsic rate. (The remainder of this report deals with unweighted rates only.) Since accident rates for individual years always exhibit considerable random scatter, we have used the simple "smoothing" procedure by plotting rates as 2-yr moving averages in Figs. 10–12. To calculate the rates for these shorter periods, we use the basic data for each year shown in Table 6.

If these curves show no appreciable variation, then the available data can contain no indication of a significant trend. On the other hand, if these curves do exhibit an appreciable over-all variation between beginning point and end point, then we thus far can conclude only that the data indicate the

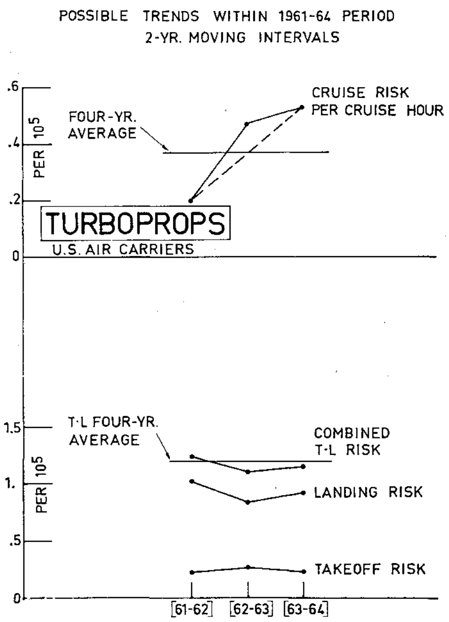

Fig. 11 Possible trends for turboprops.

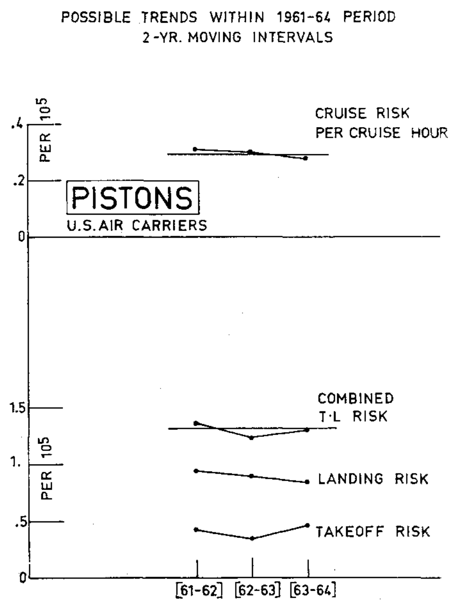

Fig. 12 Possible trends for pistons.

Table 6 Revenue flight operations per flight hour[a]

Type	1961	1962	1963	1964
U.S. air carriers: individual years 1961 to 1964				
Jets	0.485	0.507	0.529	0.551
Turboprops	1.111	1.191	1.271	1.351
Pistons	1.177	1.244	1.311	1.378
Helicopters	4.903	5.144	5.385	5.626
All air carrier flight hours reported[b]				
Jets	773,929	1,096,956	1,318,750	1,604,282
Turboprops	575,562	615,768	637,150	688,931
Pistons	2,927,556	2,447,000	2,194,959	2,042,663
Helicopters	35,899	20,461	17,213	23,569
All aircraft	4,312,946	4,180,185	4,168,072	4,359,445

[a] Source: FS-FAA. Values for 1962 and 1963 are based upon actual counts; the bordering values for 1961 and 1964 are extrapolated.
[b] Source: FS-FAA.

possibility of a significant trend. In this latter case, each rate must then be examined critically by statistical hypothesis-testing techniques to decide whether the apparent trend is statistically significant or merely the manifestation of sampling scatter of a random nature.

In Fig. 10 the top curve indicates the possibility of a strong trend (dotted line) of increasing safety for jets in cruise. In the lower half of the page, the curve for takeoff-landing risk drops very steeply in the beginning of the period, but then climbs to the end of 1964. One sees there was no improvement in the takeoff phase during the entire period (bottom curve).

In Fig. 11 the top curve indicates the possibility of a trend of increasing accident rate for turboprops in cruise. This, however, can be ignored because the rates are based upon scarce data; there were only 8 accidents for turboprops in cruise during the entire 4-yr period. The three curves in the lower half of the page show no indication of trends in takeoff or landing phases, and therefore will not be examined further.

Figure 12 shows the behavior for piston aircraft. We see no indications of appreciable trends, either in cruise, takeoff, or landing. This is perhaps not unexpected, since piston aircraft have been operating for the longest time of all models considered. One would therefore expect their safety characteristics to have become well stabilized, through rectification of design faults and completion of the "learning curves" for safe operation.

We have omitted the figure for helicopters. In the takeoff-landing rate, there is an indication for a possible trend upwards; this will be tested for significance later.

A Statistical Test for Significance of Trend

Figures 13 and 14 show graphically some of the results of our first statistical-hypothesis test to determine significance or nonsignificance of the "apparent" trends indicated by the previous figures. The first test which we shall employ is based upon the following proposition: if there is no significant change in the "true" rate within the 4-yr interval, then, to avoid contradiction, this implies in a probabilistic sense that the wider confidence interval associated with the scarcer data for a shorter period should include the narrower confidence interval associated with the fuller data of the longer period. Conversely, when this is not the case, then the rates for the shorter interval exhibit a significant trend.

It is appropriate at this point to insert some remarks concerning confidence limits. Dimensional rates, such as accidents per cruise hour, measure the average density of an underlying Poisson distribution. This describes the random occurrence of accidents throughout a continuous independent variable, the denominator of the rate. A dimensionless rate,

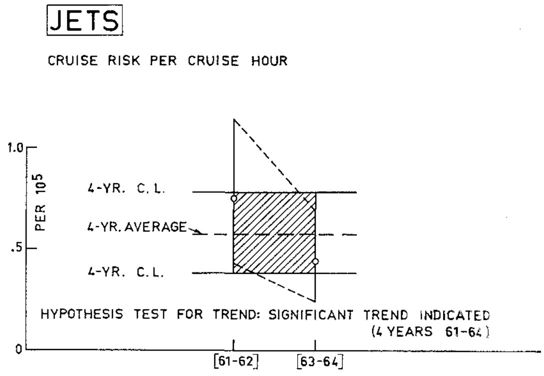

Fig. 13 **Significance test for jet trend.**

however, such as "takeoff accidents per takeoff," could be treated as a dichotomous proportion, governed by a binomial distribution, but this would be essentially equivalent to description by a Poisson distribution. To retain a unified procedure, we are therefore treating all rates in terms of the Poisson law. Whitworth[2] showed that for an average rate E, the random Poisson intervals between events are distributed as

$$f(t) = Ee^{-Et} \qquad (t > 0)$$

From this law, Maguire et al.[3] derived the result that the average length $\bar{t}$ of intervals, for n consecutive accident intervals, follows the Chi-square distribution with $d.f. = 2n$ when the variables are grouped as $(2nE\bar{t})$. If $\bar{E}$ denotes the observed sampling density, where $\bar{E} = 1/\bar{t}$, it follows that the confidence limits at a probability level of $1 - 2\alpha$ for the true rate E are given by

$$({}^{(2n)}\chi_\alpha{}^2/2n)\bar{E} < E < ({}^{(2n)}\chi_{1-\alpha}{}^2/2n)\bar{E}$$

where the α subscripts represent the lower and upper percentile points of the Chi-square distribution χ^2. We have used this inequality for our confidence limits, taking Chi-square values from the tables in Ref. 4.

Figure 13 diagrams the statistical test for a trend in the cruise rate for jets. It shows the over-all 4-yr rate as the horizontal dashed line. The 90% confidence limits associated with this 4-yr sampling rate are shown by the parallel horizontal solid lines. The individual sampling rate for the first half of the full period (the 2-yr interval 1961–1962) is shown by the encircled point on the left; the other rate for the 1963–1964 interval is shown by the encircled point to the right. The 90% confidence limits for the 2-yr periods are shown by the oblique dotted lines. One sees that on each side, these do not completely include the 4-yr confidence interval. Geometrically, the shaded rectangular area is not completely contained within the larger trapezoidal area. Hence, this test concludes that a statistically significant downward trend has occurred in risk.

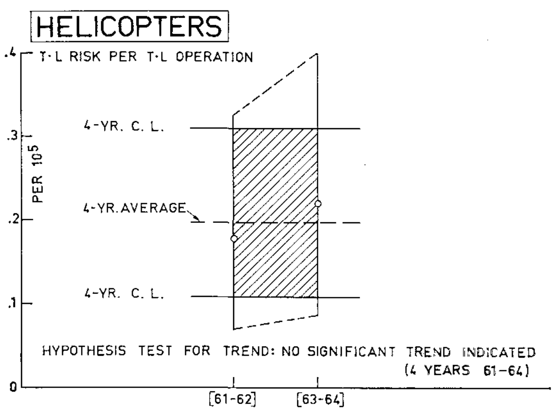

Fig. 14 **Significance test for helicopter trend.**

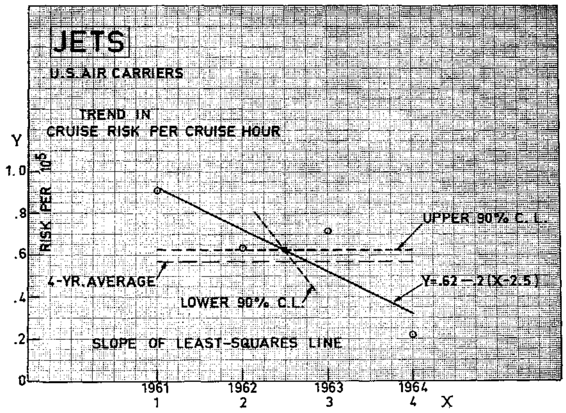

Fig. 15 Trend for jets in cruise.

Figure 14 shows the hypothesis-test result for the takeoff-landing rate for helicopters. The wide confidence limits indicate the relative scarcity of the basic data, but here the shaded rectangle is contained completely inside the trapezoid; thus, this test concludes that no significant trend is indicated.

When applied to the cruise risk for turboprops, the test indicates a significant upward trend. The total number of accidents involved, however, is only 8, so we will not discuss this trend further since it is relatively unimportant. The test indicates also a trend in jet takeoff-landing rate, which we will discuss in detail in Fig. 16.

When future safety goals, as targets for trends, are adopted, it would be consistent with the use of our various intrinsic rates to assign a separate, independent quota to each rate as its individual target. Such a suggestion is not original with our paper, however. It has been advocated in earlier publications, for example, in Lundberg,[5] where a procedure termed "allotment of probability shares" was proposed for many more risk categories than just the three flight phases analyzed in our present paper.

Most Probable Magnitudes of the Significant Trends

There remain from the preceding analysis only two important accident rates where significant trends have occurred. We next investigate the behavior of these rates in detail to determine the most probable magnitudes of these trends. This will be done by the usual procedure of fitting a least-squares (linear regression) straight line through the individual points. We now take as individual points the rates for each of the four years separately during 1961–1964. After determining the regression line and its slope in the usual manner, we will determine also the confidence limits for the slope of the least-squares line. As is well known,[6] the slope statistic in the combination

$$(b - B)\, s_x\, (N - 1)^{1/2}/s_{yx}$$

follows the t distribution with $d.f. = N - 2$. From the t distribution, upper and lower confidence limits for the true slope B can be determined. Here b is the calculated slope of the least-squares line, N the number of points, s_x^2 the x variance, and s_{yx} the standard error of estimate. Conformity to the t distribution is exact only if the observables are taken from a normal distribution. Since our accidents follow a Poisson distribution, this is not quite precise, but our numbers of accidents are all in the range where the Poisson distribution can be replaced with close approximation by the binomial curve, and this in turn by the normal curve.[7]

Figure 15 shows the individual annual rates for cruise risk of jets as encircled points. The least-squares straight line is the solid line sloping downwards. The dotted lines directed above and below this solid line indicate the 90% confidence limits for the least-squares slope. As the slope for the upper confidence limit is horizontal, one can state that the probability of a true downward trend in risk is associated with 95% confidence.

Figure 16: The least-squares straight line through the four annual rates (encircled points) for takeoff-landing jet risk is shown by the downward sloping solid line. The upper and lower 90% confidence limits on its slope, however, as shown by the dotted lines, diverge so widely that their ambiguity indicates the existence of two opposing trends within the period. It is clear that the significant downward trend occurred only between 1961 and 1962. It might prove valuable to investigate fully the reason for this sudden improvement between 1961 and 1962. From 1962 onward, however, there is an upward trend in risk which our trapezoid test indicates is significant.

Jets are the most important aircraft type in current air carrier use, and the takeoff-landing risk (especially the landing risk) is the dominant risk; furthermore, $\frac{3}{4}$ of the upward increment in this jet risk is due to an increase in the jets' landing rate (Fig. 10). The 3-yr upward trend, therefore, occurs for the most important intrinsic rate we have studied.†

This upward trend in the dominant jet risk during 1962–1964 might be contrasted with some conclusions obtained from the usual manner of presenting jet statistics for the same years. For example, Moss,[8] in a study of world-wide commercial jets, claims that the jet "safety record continues to improve steadily." This claim is based upon the sampling behavior of a rate defined as jet hours per fatal jet accident. This number changed over the three years, 1962–1964, from 220,000 to 700,000, an apparent safety improvement of more than 3 to 1. One must first note, however, that statistical interpretation of this rate is difficult because the yearly values are based upon scarce data: world-wide, only 5 and 4 fatal accidents in 1963 and 1964, respectively. Let us compare this rate for the 1962–1964 period with an analogous utilization rate obtained from our U.S. data (Table 2) but now counting all serious jet accidents, both fatal and nonfatal. This changes the basic data from scarce to relatively ample (20 and 20 accidents in 1963 and 1964, respectively), and now the statistical confidence in determining the presence or absence of a significant trend is much higher. Our results for 1962–1964 in jet hours per jet accident are 73,000, 66,000, and 80,000, respectively. This more reliable rate shows only a fluctuating behavior without appreciable improvement, in contrast with the 3 to 1 improvement inferred from the fatal accidents. Also important is the fact that both quantities are only single utilization rates. Inferences made from either rate would be contradicted by the upward trend for the takeoff and landing rates of jets during 1962–1964.

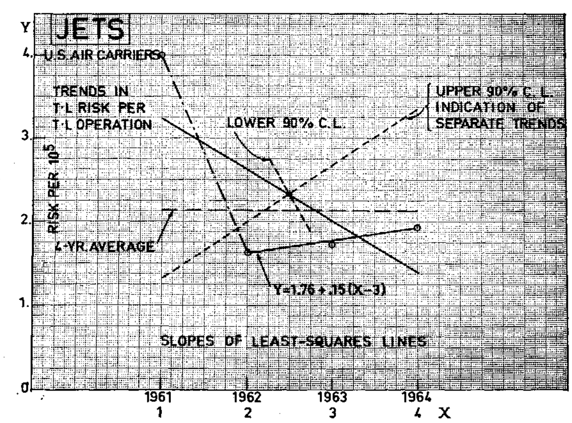

Fig. 16 Trends for jets in takeoff and landing.

† Only unofficial estimates for 1965 were available at the time of this analysis, but these indicated that the jet landing rate in 1965 would be appreciably higher than in 1964, and thus an upward trend in risk greater than we have computed for 1962–1964.

Summary and Discussion

1. Based upon Intrinsic Rates for the 4-Yr Interval 1961–1964

a) When cruise risk rates are based upon cruise miles, then all three winged-aircraft types have equal cruise risk.

b) The takeoff-landing risk shows the jets to be the most dangerous of all four types of aircraft in this combined flight phase, roughly about 2 to 1 compared with pistons and turboprops. Helicopters are also somewhat safer than jets in the takeoff-landing phase.

c) Each of the four aircraft types exhibits about a 2 to 1 ratio of higher accident rate in landing compared with takeoff. Piston aircraft are the safest of all four types in landing. The jets are the most dangerous of all four types both in landing and also in takeoff, separately. The turboprop is the safest of all four types in takeoff. It might prove instructive to study the turboprops' takeoff phase in detail to ascertain why it has proven to be so exceptionally safe in takeoff, compared with all other types.

It is possible that the higher intrinsic accident rates of jets compared with turboprops or pistons may be due, at least in part, to "learning curve" troubles prevalent for newer jet models, whereas the operators and pilots of the older pistons and turboprops have already accumulated sufficient experience to fly these at their full safety potential. To whatever extent this factor may be significant, it would then follow with the same significance that new models and radical design changes in jets should be introduced less frequently and with greater caution in the future. It must be expected that these higher risk rates for jets, regardless of the causes, will be brought down *at least* to the level of pistons and turboprops before the time arrives when jets take over all winged-aircraft air carrier services.

d) The strong domination of total accident risk by the takeoff-landing risk suggests that the policy of some airlines to assign their best and most experienced pilots to longhaul nonstop routes, while the local multistop services are reserved for other pilots, may not be the optimal policy from a safety viewpoint.

e) The statistical relationship between landing accident rate and average landing speed is strongly nonlinear. An independent study of all U.S. Air Force landing accidents, with more statistical reliability, shows that the correlation is very high, and that the relationship is actually cubic.

f) When each intrinsic accident rate is recalculated, taking into account the severity of the accidents, the quantitative comparisons among the aircraft types do not change appreciably, except for helicopters in landing risk. On this basis helicopters are the safest of all four aircraft types in landing.

g) In generalities, some results of our analysis are 1) that helicopters (and by implication, future V/STOL aircraft in commercial operation) are very much safer aircraft than is generally believed, 2) that jets are not relatively as safe as is generally believed, and 3) that no single (utilization) rate can give an accurate safety evaluation. In fact, among conventional rates, accidents per flight hour gives comparisons essentially the reverse of actual conditions. Compared with this, the single utilization rate taken as accidents per flight segment is far less misleading.

2. Based upon Significant Trends within the Period 1961–1964

a) The jets became significantly safer in cruise, the accident rate having decreased approximately 40% between the first and second halves of the 4-yr period.

b) The jets exhibited a major safety improvement in landing rate between 1961 and 1962. Subsequently, however, there has been an upward trend in the takeoff-landing risk, particularly in the landing risk. The takeoff-landing rate, therefore, ended in 1964 at a value not better than the over-all 4-yr rate.

c) The pistons exhibited no significant trends, and turboprops showed no trends in takeoff or landing risk. Their safety characteristics have stabilized.

d) Helicopters showed no significant trend in the takeoff-landing risk.

3. Risk for a Specific Flight

The method proposed here using intrinsic rates permits accurate calculation of the total risk involved in any specific flight: of given total duration, given number of intermediate stops, and for a given type of aircraft.

4. Possible Explanations

It would be altogether premature at this point to hazard guesses to explain the relative safety characteristics of the four aircraft types analyzed, or to explain why certain trends are occurring in these rates. Our present statistical analysis reveals only where the detailed improvements and deteriorations in safety are occurring. In particular, for the dominant accident risk which is the total landing phase, although some landing accidents may have no conceivable relationship to landing speed, the strong correlation and rapid variation revealed between risk and speed, considered statistically, are unmistakable. A detailed study will be required to examine all factors involved in each landing accident and to determine how these factors may interact with speed, or how performance may be associated with speed, to cause accidents.

5. Future Application

Our primary purpose is not to emphasize comparisons or to exhibit the trends during 1961–1964. Rather, our primary purpose is to reveal the necessity for analyzing all future air safety statistics on the basis of a set of intrinsic rates, instead of continuing to rely upon the conventional utilization rates. Intrinsic rates permit a separation of different risk effects which otherwise can mask each other and escape detection.

A possible expansion of our analysis would be to separate flight into five phases instead of three, putting initial climb and final descent into separate phases. If such additional subdivision is employed, however, this will reduce statistical reliability when the data are made more scarce by further splitting.

This paper consists only of a statistical analysis of accident data undertaken by the author while an employee of the Federal Aviation Agency; it does not include any examination of specific causes, or of all operational factors involved in each accident, which might tend to confirm or negate some implications of the statistical results. Therefore this paper does not necessarily reflect the views of the Federal Aviation Agency, nor does the Agency necessarily concur in all of the statements and conclusions.

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