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Risk Formulation of Hull Loss Accidents in Narrow-Body Commercial Jet Aircraft (Boeing 737, Airbus A320, McDonnell Douglas MD82, Tupolev TU134 and TU154 and Antonov AN124)

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ABSTRACT

Accidents involving narrow-body aircraft were evaluated statistically for six families of commercial aircraft: Boeing B737, Airbus A320, McDonald Douglas MD80, Tupolev TU134 and TU154 and Antonov AN124. A risk indicator (I_f) for each flight phase for these families of narrow-body aircraft was developed based on motion characteristics, duration time and the presence of adverse weather conditions. An estimated risk level was developed based on these risk indicators. Regression analysis indicated very good agreement between the estimated risk level and the accident ratio of hull loss cases per number of delivered aircraft. The effect of time on the hull loss accident ratio per delivered aircraft (HLAR) was assessed for the B737, A320 and MD80 families. Equations representing the effect of time on the HLAR were developed for the B737, A320 and MD80 families, while average values of HLAR were found for the TU134, TU154 and AN 124 families. Estimated risk equations were developed for each family of aircraft, allowing the HLAR to be estimated for any aircraft family, flight phase, presence of adverse weather factor, time of day, day of the week, month of the year, pilot age and pilot flight hour experience. A simplified relationship between the estimated HLAR and unsafe acts by humans was proposed, with numerical investigation of the relationship suggesting that the HLAR was dominated primarily by the flight phase media.

Keywords: narrow-body aircraft, aircraft accident, hull loss accident, flight phase, risk estimation

INTRODUCTION

Aircraft accidents involving commercial aircraft are often disastrous and extremely costly. It would be useful if a simple model for accident probability estimation could be developed, so that the likelihood of an accident could be predicted and used as additional information for the pilots, air traffic controllers and airport managers, so that more effective decisions can be made to enhance safety and prevent accidents. This paper reports on a model for hull loss accident probability and risk estimation. Hull loss is defined as an accident that causes severe damage to the aircraft, such that the aircraft is completely written off. Usually, accident risk is defined as a measure of how frequently an accident is likely to occur, that is, the probability multiplied by the hazard. The level

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of hazard may be described in any appropriate unit, such as the number of fatal accidents or the number of hull loss accidents.

Therefore, the level of risk for one hull loss accident is the product of the probability of a hull loss accident per flight and the number of flights, or the product of the probability of a hull loss accident per unit of airplanes delivered at the time of the accident.

Accidents can be classified as minor, hull loss and fatal. The present investigation focused on hull loss accidents, using the apparently clear definition of Tiabtiamrat *et al*. (2008): a hull loss accident is an accident that effects severe damage to the aircraft, such that the aircraft is completely written off. There are many indicators that may be used to represent the frequency of accident, such as the ratio of fatalities per million passenger kilometers, and the number of accidents per number of flight hours, as used by Janic (2000) and the ratio of hull loss per million flight departures, as used by Baksteen (1995). There are many different units for measuring accidents, each with its own advantages and disadvantages. The present investigation, aiming for clarity and simplicity, used the hull loss accident ratio (HLAR), which is the number of aircraft of a certain family written off as the result of accidents per delivered number of aircraft units in that family. The HLAR is particularly interesting, since it is relatively easy to determine. In addition, Boeing uses the HLAR, as well as the number of accidents per hours of flying time, to describe accident statistics concerning the Boeing 737 family of aircraft (Boeing Company, 2007; 2008).

Six of the existing commercial narrow-body families of aircraft for medium range flights were considered, namely, the Boeing 737, Airbus A320, McDonnell Douglas MD80, Tupolev TU134 and TU154 and Antonov AN124. It should be noted that the Boeing 737 is the most used aircraft family and the number of accidents involving these aircraft is sufficient for statistical analysis, while the Airbus 320 is a relatively new aircraft and therefore, the number of accidents is smaller. Aircraft production of the MD80 aircraft ceased when Boeing took over the McDonnell Douglas Corporation, but many MD80 family airplanes are still flying. Despite the scarcity of available information, the Russian-made Tupolev TU134, TU154 and Antonov AN124 were also studied, to provide a more complete picture regarding accidents involving narrow-body commercial aircraft.

It has been recognized that the movement of aircraft, as well as the exposure time is a factor in determining the risk of an aircraft accident (Janic, 2000). However, the focus of Janic (2000) was on fatal accidents and used regression analysis to find the relationship between the global fatality rate (the number of deaths per passenger-kilometers), with a very good correlation of R^2 = 0.901. The present paper considered that the movement, or motion, of the flight phase and the duration time should be taken into consideration.

Many factors could be involved in an aircraft accident (Reason, 1990), and the relationships between them are likely to be complicated. However, it would be useful if a relatively simple way of risk estimation, with a reasonable degree of accuracy, could be developed for practical uses. In developing risk indicators, it is inevitable that past accident records and statistics have to be studied. However, it is necessary to emphasize “proactive safety” or prevention rather than cure and thus, not attach too much importance to past statistics (McFadden and Towell, 1999). It may be more productive to focus more effort on determining potential hazards and the causes of accidents and initiating preventive, as well as corrective actions.

There are two approaches in assessing aviation risk and safety (Shyur, 2008). The first approach is to study the number of accidents carefully and then suggest some indicators for improvement in safety. The second approach is to build a mathematical model of accidents by assuming that the occurrence of accidents follows a Poisson distribution. Generally, it is accepted that an accident is a complex process that may need sophisticated analytical techniques. However, when it comes to applying the results of analysis, not only simplicity, but also quantification is needed (Braithwaite *et al.*, 1998). The second approach was used by Shyur (2008) to develop a probabilistic model which seemed rather complicated. The present paper combined both approaches, with the further study of statistical data linked with an attempt to quantify the relationships between factors and so produce a useful model.

Many possible alternatives in risk estimation have been mentioned (Bird Strike Committee USA, 2006) using historical data, modeling, breaking down the system into known subsystems using techniques such as event trees or fault trees, comparing by analogy with similar situations or by comparison with similar activities. There are a wide range of possible approaches and all approaches seem acceptable.

Tiabtiamrat *et al.* (2008) developed a model of a risk indicator for aircraft hull loss accidents for the Boeing 737 family of aircraft based on the motion of the flight phase. The present paper considered a more refined model that was extended to cover not only Boeing 737 aircraft, but also all narrow-body commercial aircraft families.

MATERIALS AND METHOD

Hull loss accident probability model

Aircraft accident investigation is a difficult task due to the scarcity of evidence, difficulty due to geographical accessibility, destroyed evidence and time and cost constraints. Often, the final accident report conclusions are unclear and many questions remain unanswered. Many investigations are still presented in a preliminary form only. From the final and preliminary accident reports available, statistical methods were used to analyze and interpret the results and to develop a risk estimation model for hull loss accidents of narrow-body commercial aircraft. The effect of many relevant factors has been reported by the National Transportation Safety Board (NTSB), such as the monthly effect, weekly effect and time of day effect (National Transportation Safety Board, 1999).

Probability of hull loss accident in each flight phase

It is generally accepted that different flight phases are associated with different degrees of probability of an accident, as noted by the NTSB (National Transportation Safety Board, 1999, 2003). For example, the landing flight phase is known to have higher probability of an accident than standing or taxiing. The major flight phases considered were: stand, pushback, taxi, take off, climb, cruise, approach and landing (Commercial Aviation Safety Team, 2006). Minor flight phases were combined with the most similar phase, for example 'descend' was combined with 'cruise', and 'maneuver' was combined with 'approach'.

For the flight phase effect, which appears to be the most dominant effect, a risk indicator for each flight phase was developed by considering the effect of media and flight environment, aircraft airspeed, acceleration and altitude change. For each flight phase, the risk factor (V_i) was assigned a number from 1 to 5 on a Likert scale to represent the degree of risk, where 1, 2, 3, 4 and 5 represent no risk, little risk, medium risk, high risk and very high risk, respectively. A multiplicative model was used, where the assigned value of each motion factor was multiplied to get the value of the risk indicator (Equation 1):

$$I_i = \prod_{j=1}^{6} V_{ij} \quad (1)$$

where: I_i is the risk indicator for flight phase *i*. Then *i* = 1, 2, 3, 4, 5, 6, 7, and 8 represent the phases of stand, pushback, taxi, take off, climb, en route, approach and landing, respectively. V_{ij}

stands for the risk value of the media and environment of the flight phase, aircraft speed, acceleration, altitude change, phase duration time and the relative weighting of the flight phases which had not been completely accounted for by the first five variables. Each of the values of each risk factor V_{ij} was assigned a value between 1 and 5, according to the perceived risk for any narrow-body aircraft. The estimated risk level L_i for each flight phase, which is the estimation of the relative accident probability for each flight phase, can be computed from the risk indicators I_i by Equation 2:

$$L_i = \frac{I_i}{\sum_{i=1}^{8} I_i} \quad (2)$$

The details of values assigned and computed are given in Table 1. Using data from Harro (2009), the relative accident probability for each flight phase was plotted against the estimated risk level and a linear regression line through the origin was fitted to the plot. A very good fit for a curve was found for the Boeing 737 family and for the combination of all families of aircraft with R^2 values as high as 0.9260 and 0.8937, respectively, (Figures 1 and 2).

Table 1 Risk factors, risk indicators and risk levels for each flight phase.

Flight phase		Risk factor						Risk indicator	Risk level
	i	V_1	V_2	V_3	V_4	V_5	V_6	I_i	L_i
Stand	1	1	1	1	1	1	1	1	0.00190
Pushback	2	1	1	1	1	1	1	1	0.00190
Taxi	3	1	1	1	1	1	1	1	0.00190
Take off	4	5	3	2	3	1	1	90	0.17143
Climb	5	3	2	2	3	1	1	36	0.06857
Cruise	6	2	1	5	1	5	1	50	0.09524
Approach	7	3	1	4	4	1	2	96	0.18286
Land	8	5	1	5	5	1	2	250	0.47619
							Sum =	525	1.00

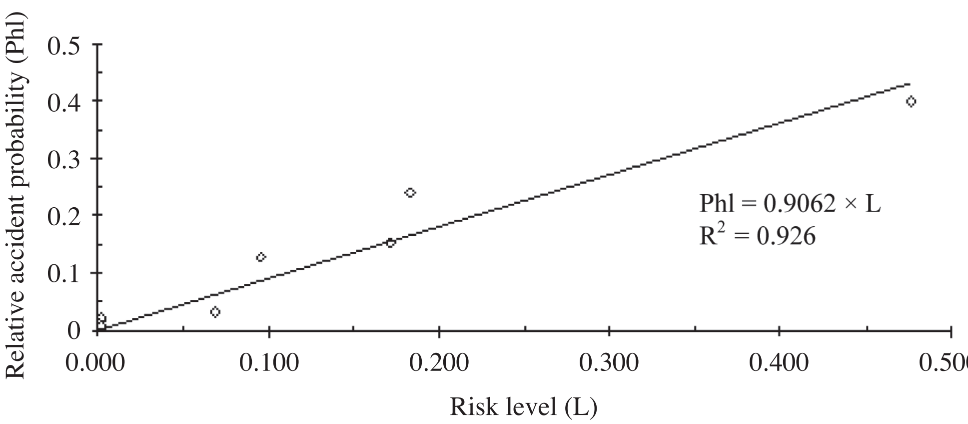

Figure 1 Relationship between accident probability and risk level for Boeing B737 family of aircraft.

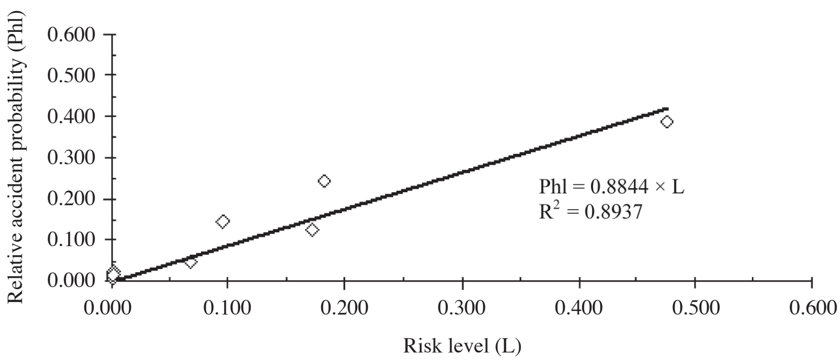

Figure 2 Relationship between relative accident probability and risk level for all families of narrow-body aircraft.

Effect of weather

The effect of weather is rather complicated. The weather alone may be considered the cause of an accident or weather may be a factor which acts in association with other causes, such as pilot error and mechanical failure amongst others. The weather factors have been identified as a cause in 45.46% of accidents involving narrow-body commercial aircraft (Boeing Company, 2007), which is very close to the weather effect in general aviation of 47.56% (National Transportation Safety Board, 2007).

For simplification, the partial probability of a hull loss accident due to weather (I_7) can be determined by Equation 3 if there is at least one weather factor present:

$$P_w = 0.5 + 0.5(0.4546) = 0.7273 \quad (3)$$

and by Equation 4 if there is no weather factor present:

$$P_w = 0.5 - 0.5(0.4546) = 0.2727 \quad (4)$$

Effect of time

There appeared to be a time effect in general aviation accidents (National Transportation Safety Board, 1998). Applying curve fitting to the data in the report produced the following relationships. The partial probability of an accident due to the effect of the hour of day can be represented by Equation 5:

$$P_{hd} = 0.045 + 0.045 \sin \pi(\frac{h}{12} - 1.25) \quad (5)$$

where: h = the hour of day,

P_{hd} = the partial probability due to the time of day from 00.01 to 24.00 hour.

Equation 5 fitted well with the data and had an R^2 value of 0.9713. The effect of day of the week is represented by Equation 6:

$$P_{dw} = 0.15 + 0.045 \sin \frac{2\pi}{7}(d + 1) \quad (6)$$

where: d = day of the week, with 1 to 7 for Monday to Sunday, respectively,

P_{dw} = the partial probability due to day of week.

Equation (6) provided a fair fit with the data, with an R^2 value of 0.7111. The effect of the month is shown by Equation (7):

$$P_{my} = 0.038 \sin \frac{\pi}{12}(2m - 7) + 0.085 \quad (7)$$

where: m = month of year from 1 to 12 for January to December, respectively,

P_m = the partial probability due to the month of year.

Equation (6) fitted well with the data with an R^2 value of 0.8532. Although Equations 5, 6 and 7 were based on general aviation data, they were assumed to be applicable to narrow-body commercial aircraft.

Effect of the pilot

The effect of pilot age on all types of accident has been reported for general aviation by the NTSB (National Transportation Safety Board, 1998). The relationship between pilot age and probability of accident can be represented by Equation 8:

$$P_{pa} = -0.038 + 2.613\times10^{-2}y - 2.679\times10^{-4}y^2 \quad (8)$$

where: y = the age in years of the pilot,

P_{pa} = the partial probability of an accident due to pilot age.

Equation (8) fitted satisfactorily with data with an R^2 value of 0.8532. The partial probability of an accident due to pilot experience (P_{pe}) is related to the pilot flying hours (h_p) by Equation 9:

$$P_{pa} = 1.737\times10^{-1.427}h_p^{-1.427} \quad (9)$$

This equation provided a very good fit to the data, with an R^2 value of 0.9713.

Combined aircraft family, flight phase, weather, time and pilot effect

The combined effect of aircraft family and flight phase has already been accounted for by P_f in Table 2. The effect of weather, time of day, day of the week, month of the year, pilot age and pilot flight hour experience can be taken into account by successive multiplications resulting in the relative probability due to combined factors P_{cb} as Equation 10:

$$P_{cb} = P_f\, P_w\, P_{hd}\, P_{dw}\, P_{my}\, P_{pa}\, P_{pe} \quad (10)$$

RESULTS AND DISCUSSION

Hull loss accident ratio of narrow-body aircraft

The trend of the hull loss accident ratio for each family of American and European narrow-body commercial aircraft (H_l) against the time of the accident in years after 1900 (t = year - 1900), can be found by regression analysis and curve fitting of data reported on a well known aircraft accident information website (Harro, 2008). The index l = 1,2,3,4,5,6 represents the Boeing 737, Airbus A320, McDonnell Douglas MD80, Tupolev

Table 2 Relative probability of an accident at each flight phase for narrow-body families of aircraft.

Flight phase	i	Risk level L	737 P_f	A320 P_f	M80 P_f	TU134 P_f	TU154 P_f	AN124 P_f	All P_f
Stand	1	0.0019	0.0085	0.1333	0.0909	0.0000	0.0189	0.0000	0.0228
Pushback	2	0.0019	0.0170	0.0000	0.0000	0.0000	0.0000	0.0000	0.0076
Taxi	3	0.0019	0.0085	0.0667	0.0454	0.0196	0.0000	0.0000	0.0152
Take off	4	0.1714	0.1610	0.0667	0.0909	0.0784	0.1321	0.0000	0.1255
Climb	5	0.0686	0.0339	0.0667	0.1364	0.0588	0.0377	0.0000	0.0494
Cruise	6	0.0952	0.1186	0.0000	0.0909	0.1569	0.2642	0.2500	0.1483
Approach	7	0.1829	0.2458	0.2667	0.2364	0.3137	0.2075	0.2500	0.2433
Land	8	0.4762	0.4068	0.4000	0.4090	0.3725	0.3396	0.5000	0.3878
Number of hull loss cases		n	118	15	22	51	53	4	263
k in regression equation P_f = kL		k	1.0467	0.8426	0.8359	0.8809	0.6983	1.1014	0.8844
		R^2 =	0.9419	0.8153	0.9606	0.7519	0.5037	0.7477	0.8937
Remarks on curve fitting between L and P_f			Very good	Good	Very good	Good	Fair	Fair	Good

TU134, Tupolev TU154 and Antonov AN124, respectively. The curve of H_l versus time for Boeing 737 aircraft is illustrated in Figure 3. Initially, H_l decreases sharply with time and then levels off, which reflects the increasing safety in commercial aircraft operations. Similar trends were found for the Airbus A320 and McDonnell Douglas MD80 families. Only average values for H_l were available for Russian aircraft.The equations for H_i as functions of time and their R^2 values are summarized in Table 3. The average values of H_l for the Russian narrow-body aircraft families in 2008 are also shown in Table 3. The equation representing the relationship between H_l and t for the Boeing 737 family had a coefficient of determination (R^2) value of 0.8265, which suggests a good fit to the data. The equations representing the Airbus 320 and MD80 families had lower R^2 values due to the extremely sharp initial drop of H_l with the time when these families of aircraft began operations.

Estimation of probability of an aircraft being involved in a hull loss accident

The average probability of an aircraft being involved in a hull loss accident is the hull loss accident ratio H_l as shown in Table 3. When the combined effect of aircraft family, flight phase, weather, time of day, day of the week, month of the year, pilot age and pilot flight hour experience is accounted for, then the probability of an aircraft involved in a hull loss accident is the product of H_l and P_{cb} as shown in Equation 11:

$$P_{hl} = H_l P_{cb} \quad (11)$$

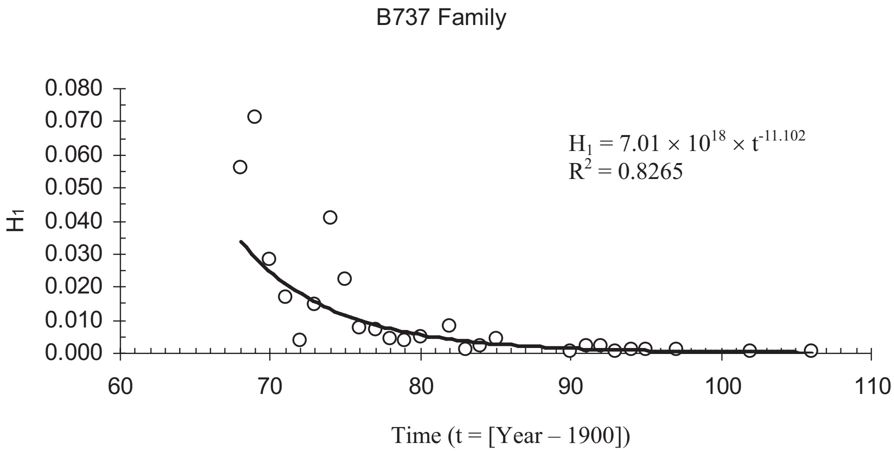

Figure 3 Hull loss accident ratio (H_l) over time (t = [Year – 1900]) of Boeing 737 family aircraft.

Table 3 Relationship between hull loss accident ratio (H_l) and time (t = [Year – 1900]) for each family of aircraft.

Aircraft family	Hull loss accident ratio equation	R^2
Boeing 737	$H_1 = 7.00\times10^{18}\ t^{-11.102}$	0.8265
A320	$H_2 = 3.00\times10^{16}\ t^{-9.3634}$	0.6222
MD80	$H_3 = 1.00\times10^{22}\ t^{-12.386}$	0.4572
TU134	$H_4 = 0.05986$	-
TU154	$H_5 = 0.05669$	-
AN124	$H_6 = 0.07018$	-

Equation 11 can be expanded to Equation 12:

$$P_{hl} = H_l P_f P_w P_{hd} P_{dw} P_{my} P_{pa} P_{pe} \quad (12)$$

The unit of probability of an accident P_{hl} in Equation 12 is unit of aircraft involved in a hull loss accident per number of aircraft in the same family delivered. P_{hl} is also the value of the risk of an aircraft involved in one hull loss accident.

Evaluation of hull loss aircraft accident risk model

Equation 10 suggested that an accident is a combination of latent unsafe conditions and unsafe acts. A simplified interpretation model is proposed as shown in Figure 4.

If the relationship is interpreted to be a multiplicative model, then latent unsafe conditions are represented by the probability of an aircraft involved in one hull loss accident P_{hl} as expressed in Equation 12 multiplied by the severity of unsafe acts by humans (UA). Since each case represents one actual hull loss accident, the numerical value of UA is simply the inverse of P_{hl} (Equation 13):

$$P_{hl} \times UA = 1 \quad (13)$$

where: UA = severity of unsafe acts by humans.

Numerical investigation of the model

From the 23 cases of accidents involving hull loss accidents of narrow-body aircraft, information for which there was either a completed report or a relatively complete interim report available, information was used to evaluate the variables in the model. A further attempt was made to use the risk model to investigate the possible relationship between the fatality ratio (FR, defined as the ratio between fatalities and the number of people on board the aircraft), UA and flight phase. Plotting FR against UA (Figure 5) showed two distinct clusters. One cluster involved low FR

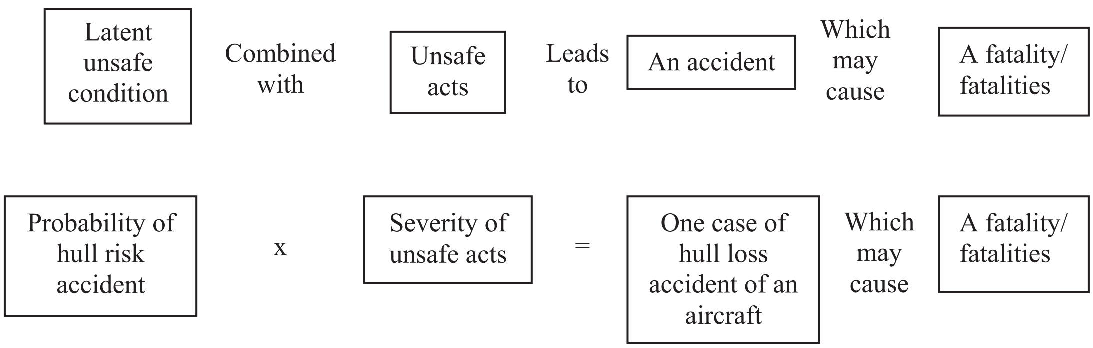

Figure 4 Simplified hull loss accident model.

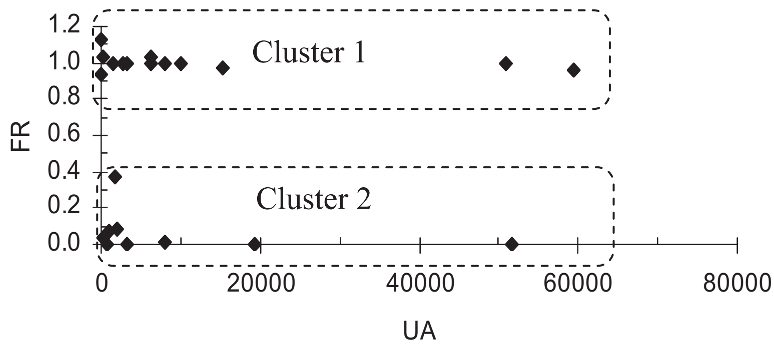

Figure 5 Relationship between fatality ratio (FR) and severity of unsafe act (UA).

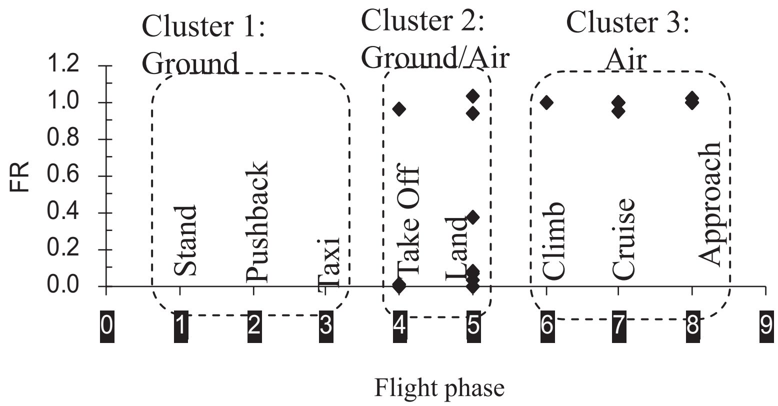

Figure 6 Relationship between fatality ratio (FR) and flight phase.

values, where FR was approximately 0 and the other cluster involved high FR values, where FR was approximately 1. Plotting FR against the flight phase sequence number in the order of flight media and flight sequence, it became apparent that there were three clusters of data according to the flight phase media. The accident cases with FR approximately equal to 1 involved the climb, cruise and approach phases, and had "air" as the medium. The accident cases with FR approximately 0 or equal to 1 were those involved in the take off and land phases with the medium of 'ground/air interphase'. While there was a lack of hull loss accident data concerning the stand, pushback and taxi phases, this implied that these phases, where the aircraft is firmly on the 'ground' medium, represented a negligible number of hull loss accidents and therefore no fatalities were reported in the aircraft accident investigation reports, which implies FR was approximately equal to 0. These explanations appeared to be logical and straightforward.

The risk model proposed was not able to link UA to FR. However, it suggested that the flight phases and flight media had an important effect on FR. Further investigation is needed into the factors that may affect FR besides flight phase, which may be related to human factors.

CONCLUSION

A risk model for a narrow-body commercial aircraft involved in a hull loss accident was presented. The model seemed to fit well with aircraft accident data. The model was not able to link the estimated HLAR to FR, but instead it suggested that flight phase had an effect on FR.

Factors that affect FR, which apparently were closely associated with human factors, need further study. Further investigation should be carried out on more types of aircraft. The accident types should be expanded to cover all types of accidents and incidents to get a more comprehensive understanding of aircraft accidents.

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