Hull loss accident model for narrow body commercial aircraft

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Abstract

Accidents with narrow body aircraft were statistically evaluated covering six families of commercial aircraft including Boeing B737, Airbus A320, McDonnell Douglas MD80, Tupolev TU134/TU154 and Antonov AN124. A risk indicator for each flight phase was developed based on motion characteristics, duration time, and the presence of adverse weather conditions. The estimated risk levels based on these risk indicators then developed from the risk indicator. 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 was assessed for B737, A320 and MD80. Equations representing the effect of time on hull loss accident ratio per delivered aircraft were proposed for B737, A320, and MD80, while average values of hull loss accident ratio per delivered aircraft were found for TU134, TU154, and AN 124. Accident probability equations were then developed for each family of aircraft that the probability of an aircraft in a hull loss accident could be estimated for any aircraft family, flight phase, presence of adverse weather factor, hour of day, day of week, month of year, pilot age, and pilot flight hour experience. A simplified relationship between estimated hull loss accident probability and unsafe acts by human was proposed. Numerical investigation of the relationship between unsafe acts by human and fatality ratio suggested that the fatality ratio in hull loss accident was dominated primarily by the flight phase media.

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

1. Introduction

Accidents involving commercial aircraft are often disastrous and extremely costly. It will be useful if a simple model for accident probability and risk can be developed so that the likelihood of accident can be predicted more effectively decision can be made to enhance safety. In this paper, a model for hull loss accident probability and risk will be reported. Hull loss is defined as the accident that causes severe damage to the aircraft the aircraft is. Accident risk usually defined as a measure of how frequently an accident is likely to occur probability multiplied by hazard. The level of hazard may be described in any appropriate unit such as number of fatal accidents or number of hull loss accidents. The level of risk for one hull loss accident is therefore the product of the probability of hull loss accident per flight and the number of flight, or the product of the probability of hull loss accident per unit airplane delivered multiplied by the number of delivered at the time of accident.

In this investigation the authors focus on the hull loss accidents as used in an earlier work (Tiabtiamrat, 2008). There are many indicators may be used to represent the frequency of accidents such as the ratio of fatality per million of passenger kilometers, the number of accidents per number of flight hours as used by Janic (2000). The ratio of hull loss per million departure flights was used by Baksteen (1995). The hull loss accident ratio (H), which is the number of aircraft of a certain family written off as the result of accident per number of aircraft unit in that family delivered, and the number of accidents per hour time, were used by Boeing in

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Boeing 737 (http://www.b737org.uk/accident_reports.htm, November 2008). In this study, the authors chose to use the hull loss accident ratio (HLAR) to represent the frequency of accidents due to its simplicity.

The narrow body type is the most used aircraft in commercial aviation, therefore needs special attention of the existing commercial narrow body families of aircraft for medium range flights are considered, i.e. Boeing (B737), Airbus (A320), McDonnell Douglas (MD80), Tupolev (TU 134 and TU154) and Antonov (AN124). B737 is the most used aircraft family and the number of accident cases are sufficient for statistical analysis, while A320 airplanes are relatively new and the number of accident are therefore. The production of MD80 family aircraft has been stopped since Boeing took over McDonnell Douglas however, many MD80 family airplanes are still flying. or more complete picture of narrow body commercial aircraft families the Russian made TU134, TU154 and AN124 will also be studied.

It has been recognized that the flight phase of an aircraft as well as the exposure time may affect the risk and cause of aircraft accident (Janic, 2000). Besides the flight phase of aircraft and the exposure time, many factors also be involved in an aircraft accident. It would be useful if aircraft accident probability and risk can be estimated in a simple way with a reasonable degree of accuracy. In developing risk indicators it is inevitable that past accident statistics have to be studied. However, proactive safety prevention rather than cure and not too much should be given to the past statistics (McFadden and Towell, 1999).

There are two major approaches used by researchers in assessing aviation risk and safety as noted by Shyur (2008). The first approach is to study the number of accidents carefully and then offer some indicators for improvement in safety using deterministic models. This approach was used by Braithwaite (1998). The second approach is to build a probabilistic mathematical model of accident by assuming that the occurrence of accident follows the Poisson process. The second approach was used by Shyur. However, when it comes to application, simplicity and quantification is necessary. The authors chose to follow the first approach by studying relevant statistical data and quantifying the relationships between factors in a simplified deterministic model.

Many possible alternatives in probability and risk estimation have been mentioned in http://www.birdstrike.org/comlink/risk.faq.htm (February 1, 2009) using historical data, modeling, breaking down the system into known subsystem using techniques event trees or fault trees, with similar situations, or compare with similar activities. There are a wide range of possible approaches and all approaches seem acceptable to some degree. In this paper a more refined model than the former one (Tiabtiamrat, 2008) will be developed. The hull loss accident model will also be extended to cover not only B737 family but also six of the narrow body commercial aircraft families.

2. Methodology

Aircraft accident investigation process is a difficult task due to the scarcity of evidence, the difficulty due to geographical accessibility, destroyed evidence, time and cost constraints. Often the final accident report are left unclear and questions remained unanswered. Many accident investigations presented the accident reports in a preliminary or interim form only. From the final, interim, and preliminary accident reports available, the authors will use statistical methods to analyze and interpret the results and then will propose an accident probability estimation model for hull loss accident of narrow body commercial aircraft. any relevant factors reported by the National Transportation Safety Board (NTSB, 1998) will be included in the model.

2.1 The probability of hull loss accident in each flight phase

It is generally accepted that different flight phase are associated with different degree of probability of accident (NTSB, 1999/1). For example the landing phase is known to higher probability of accident than standing or taxiing. The major flight phases considered are as: standing, pushback, taxiing, take off, climbing, cruising, approaching and landing. Minor flight phases are combined to the most similar phase i.e. descending is combined with cruising, and maneuver is combined with approaching.

For the flight phase effect which appears to be the most dominant effect, a risk indicator for each flight phase is developed by considering the effect of media and environment, aircraft speed, acceleration, and altitude change. For each flight phase the risk factor \( V_i \) is assigned a number of 1 to 5 on Likert scale to represent the degree of risk. The scale 1, 2, 3, 4 and 5 represents no risk, risk, medium risk, high risk and very high risk respectively. A multiplicative model is used where the assigned value of each motion factors are multiplied to get the value of risk indicator, i.e.

\[
I_i = \prod_{j=1}^{8} V_{ij}
\]

where \( I_i \) is the risk indicator for flight phase \( i \). Then \( i = 1, 2, 3, 4, 5, 6, 7, \) and 8 represents the phase stand, pushback, taxi, take off, climb, cruise, approach, and land 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 has not been completely accounted for by the first variables. Each of the value of each risk factor \( V_{ij} \) was assigned 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 relative accident probability for each flight phase can be computed from the risk indicators \( I_i \) by the following equation:

\[
L_i = \frac{I_i}{\sum_{i=1}^{8} I_i}
\]
Using data from Accident Statistics 2008, the relative accident probability for each flight phase was plotted against the estimated risk level, and the linear regression line through the origin was fitted to the data. A very good curve fitting was found for the B737 aircraft family with $R^2 = 0.9260$ as illustrated in Figure 1, and for combined families of aircraft with $R^2 = 0.8937$ as illustrated in Figure 2.

### 2.2 Effect of weather

The effect of weather on hull loss accident is. The weather alone may be considered the cause of accident, or weather may be a factor acts in association with other causes such as pilot error, mechanical failure and . The weather factor 45.46% narrow body commercial aircraft (Accident Statistics, 2008 close to the weather effect in general aviation 47.56% (NTSB, 1999). information for narrow body aircraft. For simplification, the partial probability of hull loss accident due to weather $P_w$ is then assigned as:

$$P_w = 0.5 + 0.5(0.4546) = 0.7273,$$

and the probability of hull loss accident related to pilot experience $P_{pe}$ is known by:

$$P_{pe} = 1.737 \times 10^{-14.27} h_p^{1.427},$$

where total number of pilot flight hour ($h_p$) represents the pilot experience. This equation yields a very good fit the data with $R^2 = 0.9713$.

### 2.3 Effect of the pilot age and experience

The effect of pilot age all types of accident has been reported for general aviation by NTSB (1999). The relationship between pilot age and probability of accident can be represented by:

$$P_{pa} = -0.038 + 2.613 \times 10^2 y - 2.679 \times 10^4 y^2$$

where $y$ is the age in year of the pilot and $P_{pa}$ is the partial probability of accident due to pilot age. Equation satisfactorily data with $R^2 = 0.8532$. The partial probability of hull loss accident related to pilot experience ($P_{pe}$) is known by:

$$P_{pe} = 1.737 \times 10^{-14.27} h_p^{1.427}$$

where total number of pilot flight hour ($h_p$) represents the pilot experience. This equation yields a very good fit the data with $R^2 = 0.9713$.

### 2.4 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 week, month of year, pilot age, and pilot flight hour experience can be taken into account by successive multiplications resulted in the relative probability due to combined factor $P_{cb}$

$$P_{cb} = P_f P_w P_{bd} P_{dw} P_{my} P_{pa} P_{pe}$$

### Figures

- **Figure 1.** Relationship Between Relative Accident Probability and Risk Level for Boeing B737 Family of Aircraft
- **Figure 2.** Relationship Between Relative Accident Probability and Risk Level for Six Narrow Body Families of Aircraft
The trend of hull loss accident ratio (H) for each family of narrow body commercial aircraft against time in year of accident occurrence after 1900, i.e. (t = year - 1900), can be found by regression analysis and curve fitting of reported data (http://www.planecrashinfo.com/cause.htm, February 16, 2009). The index l = 1, 2, 3, .., 6 represents B737, A320, MD80, TU134, TU154, and AN124 respectively.

The curve of H against t for B737 is illustrated in Figure 3. H decreases initially sharply with time and then levels off, which reflects the increasing safety in commercial aircraft operations. Similar trends are found for A320 and MD80 families. The equations for H as functions of time and their \( R^2 \) are summarized in Table 3.

For Russian aircraft we could only find the average values for H. The average values of H for Russian narrow body aircraft families in the year 2008 (http://www.aviation-safety.net/database.html, April 23, 2008) were also shown in Table 3. The equations representing the relationship between H and t for B737 family with coefficient of determination \( R^2 = 0.8265 \) suggests a good fit to data. The equation representing A320 and MD80 families indicate lower \( R^2 \) values which is apparently the result of the abnormal sharp initial drop of H with time.

### 2.7 Estimation of the probability of an aircraft involving in a hull loss accident

For the estimation of the probability of an aircraft involving in a hull loss accident, the average probability of an aircraft involving in a hull loss accident is equal to the hull loss accident ratio H as shown in Table 3. When the combined effect of aircraft family, flight phase, weather, time of day, day of week, month of year, pilot age, and pilot flight hour experience is considered, the probability of hull loss accident for each flight phase is estimated. The results are summarized in Table 2.

### Table 1. Risk Factors, Risk Indicators and Risk Levels for Each Flight Phase

<table>
<thead>
<tr>
<th>Flight Phase</th>
<th>Risk Factor</th>
<th>Risk Indicator</th>
<th>Risk Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>i V_1 V_2 V_3 V_4 V_5 I L</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stand</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Pushback</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Taxi</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Take off</td>
<td>4</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Climb</td>
<td>5</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Cruise</td>
<td>6</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Approach</td>
<td>7</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Land</td>
<td>8</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Sum</td>
<td>525</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 2. Relative Probability of Accident at Each Flight Phase for Six Families of Narrow Body Aircraft

<table>
<thead>
<tr>
<th>Flight Phase</th>
<th>Risk Level</th>
<th>Probability of Hull Loss Accident Due to Flight Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>B737</td>
<td>A320</td>
<td>M80</td>
</tr>
<tr>
<td>i L</td>
<td>P_f</td>
<td>P_f</td>
</tr>
<tr>
<td>Stand</td>
<td>1</td>
<td>0.0019</td>
</tr>
<tr>
<td>Pushback</td>
<td>2</td>
<td>0.0019</td>
</tr>
<tr>
<td>Taxi</td>
<td>3</td>
<td>0.0019</td>
</tr>
<tr>
<td>Take off</td>
<td>4</td>
<td>0.1714</td>
</tr>
<tr>
<td>Climb</td>
<td>5</td>
<td>0.0686</td>
</tr>
<tr>
<td>Cruise</td>
<td>6</td>
<td>0.0952</td>
</tr>
<tr>
<td>Approach</td>
<td>7</td>
<td>0.1829</td>
</tr>
<tr>
<td>Land</td>
<td>8</td>
<td>0.4762</td>
</tr>
<tr>
<td>Hull Loss Cases</td>
<td>n</td>
<td>118</td>
</tr>
<tr>
<td>k In Equation P_f = k L</td>
<td>k</td>
<td>1.0467</td>
</tr>
<tr>
<td>( R^2 )</td>
<td>0.9359</td>
<td>0.6587</td>
</tr>
</tbody>
</table>

### 2.6 The hull loss accident ratio of narrow body aircraft

The trend of hull loss accident ratio (H) for each family of narrow body commercial aircraft against time in year of accident occurrence after 1900, i.e. (t = year - 1900), can be found by regression analysis and curve fitting of reported data (http://www.planecrashinfo.com/cause.htm, February 16, 2009). The index l = 1, 2, 3, .., 6 represents B737, A320, MD80, TU134, TU154, and AN124 respectively. The curve of H against t for B737 is illustrated in Figure 3. H decreases initially sharply with time and then levels off, which reflects the increasing safety in commercial aircraft operations. Similar trends are found for A320 and MD80 families. The equations for H as functions of time and their \( R^2 \) are summarized in Table 3.
accounted for, then the probability of an aircraft involved in a hull loss accident is the product of $H_l$ and $P_{cb}$ as follows:

$$P_{hl} = H_l P_{cb}$$

or

$$P_{hl} = H_l r_w d_w m_y p_u p_c$$

The unit of probability of accident $P_{hl}$ in equation (15) is unit of aircraft involved in a hull loss accident per number of aircraft in the same family delivered.

3. Evaluation of the hull loss aircraft accident model

Reason (1990) suggested that an accident was a result of combined effect of latent unsafe conditions and unsafe acts by human. A simplified hull loss accident model following Reason’s reasoning is as shown in Figure 4. To quantify the relationship, an assumption is made that a hull loss accident occurs when the estimated accident outcome (AO), which is the product of probability of hull loss accident ($H_l$) and the severity of unsafe acts (UA) reaches or surpasses unity, as represented by equation (16).

$$AO = P_{hl} \times UA > 1$$

Once a hull loss accident happens, there may or may not be fatality. Fatality is represented by fatality ratio (FR), i.e. the ratio of people, on board the aircraft and on the ground, losing life divided by the number of people on board. At this stage it is not possible to theoretically relate hull loss accident to FR.

3.1 Numerical investigation of the model

The accident probability model will now be used to investigate what factors that can affect FR. On-line search discovers 24 cases of hull loss accident final and relatively

<table>
<thead>
<tr>
<th>Aircraft Family</th>
<th>Equation for $H_l$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boeing 737</td>
<td>$H_l = 7.00 \times 10^{18} t^{-11.102}$</td>
<td>0.8265</td>
</tr>
<tr>
<td>Airbus A320</td>
<td>$H_l = 3.00 \times 10^{16} t^{-9.3634}$</td>
<td>0.6222</td>
</tr>
<tr>
<td>McDonnell Douglas MD80</td>
<td>$H_l = 1.00 \times 10^{22} t^{-12.386}$</td>
<td>0.4572</td>
</tr>
<tr>
<td>Tupolev TU134</td>
<td>$H_l = 0.059,86$</td>
<td>-</td>
</tr>
<tr>
<td>Tupolev TU154</td>
<td>$H_l = 0.056,69$</td>
<td>-</td>
</tr>
<tr>
<td>Antonov AN124</td>
<td>$H_l = 0.070,18$</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 3. Hull Loss Accident Ratio of B737 Family Aircraft

![Figure 3. Hull Loss Accident Ratio of B737 Family Aircraft](image)

Figure 4. A simplified hull loss accident model based on Reason’s accident model.
completed interim reports concerning narrow body commercial aircraft, which provide data and information that can be used. The sources of data and information are very briefly listed in Table 4 and more details are given in the references. These data and information are used to evaluate variables in the model.

The accident probability model is used to investigate the possible relationship between fatality ratio (FR) and the severity of unsafe act UA and flight phase. Plotting FR against UA as illustrated in Figure 5, two distinct clusters appears. One cluster involves low FR i.e. FR ≈ 0, and another involves high FR i.e. FR ≈ 1. Plotting FR against flight phase sequence number in the order of flight media and flight sequence, three clusters of data becomes apparent as shown in Figure 6. The accident cases with FR ≈ 1 involved climb, cruise, and approach phases which involved “air” as the medium. The accident cases with FR values in between, i.e. 0 < FR < 1, are those involved take off and land phases with the medium of “ground/air interphase”. Lacking hull loss accident data concerning standing, pushback, and taxiing implies that these phases, where the aircraft is firmly on the “ground”, represent negligible number of hull loss accident and therefore no fatalities, which implies FR ≈ 0. These explanations seem very logical. Although this accident probability model has not been able to link UA to FR, it suggests the important effect of flight phase on FR.

6. Conclusions

A hull loss accident model for narrow body commercial aircraft has been presented and it seems to fit well with aircraft accident data. The model was used with Reason’s accident model to investigate the relationship between probability of an aircraft involving in a hull loss accident, unsafe acts, accident occurrence, and fatality ratio. The model

<table>
<thead>
<tr>
<th>Source</th>
<th>Year</th>
<th>Source</th>
<th>Year</th>
<th>Source</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accident Investigation Branch, Yugoslavia</td>
<td>1973</td>
<td>Aeronautical Accident Investigation and Prevention Center, Brazil</td>
<td>2008</td>
<td>Aeronautical Development Agency, India</td>
<td>2001</td>
</tr>
<tr>
<td>Agenzia Nazionale Per La Sicurezza Del Volo, Italy</td>
<td>2004</td>
<td>Air Accident Investigation and Aviation Safety Board, Greece</td>
<td>2006</td>
<td>Air Accidents Investigation Branch, UK</td>
<td>1990</td>
</tr>
<tr>
<td>Main Commission Aircraft Accident Investigation Warsaw, Poland</td>
<td>1995</td>
<td>NTSB, USA</td>
<td>1982</td>
<td>NTSB, USA</td>
<td>1997/1</td>
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<td>NTSB, USA</td>
<td>1997/2</td>
<td>NTSB, USA</td>
<td>1999</td>
<td>NTSB, USA</td>
<td>2001/1</td>
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<tr>
<td>NTSB, USA</td>
<td>2001/2</td>
<td>NTSB, USA</td>
<td>2002</td>
<td>National Transportation Safety Committee (NTSC), Indonesia</td>
<td>2003</td>
</tr>
<tr>
<td>NTSC, Indonesia</td>
<td>2008/1</td>
<td>NTSC, Indonesia</td>
<td>2008/2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: See references for more details.
suggests the important effect of flight phase media on fatality ratio.

Effect of unsafe acts by human (human error) on fatality ratio has not been detected by the proposed accident model. A more refined model that can link human error to accident risk, accident occurrence, and fatality ratio should be attempted.

Further investigation should also 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 accident. A more refined model that can link human error to accident risk, accident occurrence, and fatality ratio should be attempted.

Acknowledgment

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http://www.planecrashinfo.com/cause.htm [February 16, 2009]


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