Modeling the Contribution of Accident Investigation to Airplane Safety

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Although accident investigation has significantly contributed to safety and reliability improvement of airplanes over decades, its contribution has not been quantified and compared to that of other safety measures. In this paper, a cost effectiveness measure is proposed in terms of the cost and the number of likely future accidents in similar aircraft which could potentially be prevented by the investigation. We concluded that a crucial role of an investigation is to distinguish accidents caused by errors (such as failure to consider a failure mode) a rare combination of circumstances, such as an extremely strong gust hitting a damaged plane on its way to the repair depot. Errors are common to a large number of airplanes and the same accident is likely to happen to other airplanes, while a rare event is unlikely to happen again. We first analyzed past accidents in order to shed light on a key factor—the probability of reoccurrence of an accident. Then, we introduced a concept of cost effectiveness measurement, cost per life saved, and threshold of cost effectiveness. Past accidents with different types of cause were selected as examples, and we examined how the probability of reoccurrence affects cost effectiveness. Finally, we performed a comparison in cost effectiveness between accident investigation and structural design change intended to reduce the probability of failure due to fatigue of a fuselage panel. We found that for the example the safety improvement implemented by the accident investigation was clearly more cost effective.

I. Introduction

The safety and reliability of airplanes have been improved over decades by refining not only design technologies but also post-design and post-production processes, such as testing, health monitoring, inspection, and maintenance (THIM). A key concept for ensuring airplane safety is to understand and predict the uncertainty of the system; uncertainties should be appropriately controlled through the entire lifecycle. Simulation-based design, which has evolved dramatically, greatly contributes to improving prediction accuracy. As simulation often

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has substantial errors, especially when modeling failures, the THIM processes compensate for such errors. For example, structural design of aircraft proceeds through a building-block series of tests to discover unmodeled failure modes and correct errors in models of increasingly more complex structural components (Fig. 1). Besides tests, airliners go through regular schedules of inspection and maintenance in order to reduce the chance of life-threatening or expensive malfunctions.

Most accidents occur due to causes that were not identified or predicted in advance. In this sense, accident investigation identifies missed failure modes and substantially improves safety. Once an accident occurs, an investigation is held not only by the aircraft builder and airliner but also mainly by government agencies, e.g., the National Transportation Safety Board (NTSB) in the U.S. Important roles of accident investigation are to identify accident causes and to accordingly issue recommendations in order to prevent similar accidents from reoccurring in the future.

Historically, THIM have been incorporated based on experience into the conventional safety-factor-based design practice without quantifying their contribution to the system safety. Therefore, they have not been traditionally compared with respect to their cost effectiveness (cost for achieving a given safety level). More recently, researchers have begun to quantify their contribution to safety over the life cycle of the product. Dhillon et al. (Ref. 1) incorporated the THIM processes into evaluating the reliability of industrial robots. Garbatov and Guedes Soares (Ref. 2) used variable inspection schedules to maintain a constant level of reliability throughout the lifecycle. Kale et al. (Ref. 3) traded off life-cycle costs of safe-life design with safety factor against a simultaneous design of structure and inspection. Acar et al. (Ref. 4) quantified the effectiveness of safety measures taken during airplane structural design, such as error or variability reduction and certification tests. Kulkarni and Achenbach (Ref. 5) modeled the effects of inspection schedule on the probability of failure using the probability of damage detection when uncertainty comes from the initial crack distribution. There has not been similar work on the contribution of accident investigation in terms of cost effectiveness.

The objective of this paper is to model the cost effectiveness of accident investigation in terms of the cost and the number of future accidents in similar aircraft which could potentially be prevented by the investigation. We analyze the cost of accident investigation and a trend of accident causes in order to shed light on a key factor—the probability of reoccurrence of an accident. Then, we introduce a concept of cost effectiveness measurement and show how to utilize this measurement with a socially accepted value of investment in safety improvement. Past accidents with different types of causes are selected as examples, and we examine how the probability of reoccurrence affects cost effectiveness. Finally we perform a comparison in cost effectiveness between accident investigation and a structural design change intended to reduce the probability of failure due to fatigue of a fuselage panel.

The paper is organized as follows. In Section II, the analysis of past accidents in terms of cost and accident causes is described. Then, in Section III, the definition of cost effectiveness is discussed. Section IV shows examples of cost effectiveness of past accident investigations with different types of accident causes and a comparison in cost effectiveness between accident investigation and other reliability improvement measures.
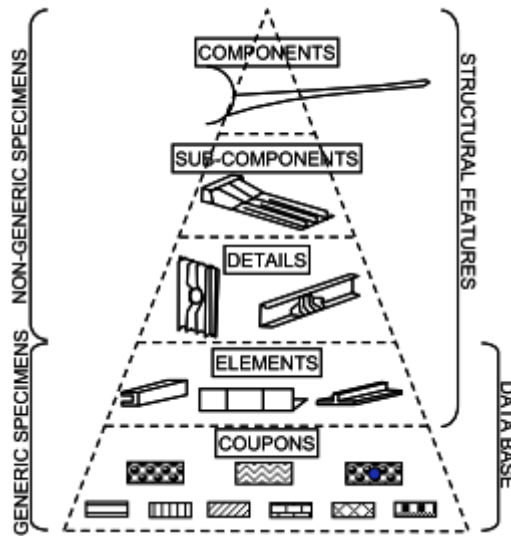
Figure 1 Building-block approach for testing airplane structural components

II. Accident investigation

NTSB is an independent U.S. government agency responsible for accident investigation of civil transportation. It has investigated more than one hundred thousand aviation incidents since its establishment in 1967. The main focus of the accident investigation is basically to identify the cause of accidents and to provide necessary recommendations for preventing similar accidents in the future (Ref. 6). An investigation by NTSB is categorized as either "major investigation" or "others." The label "major investigation" is selected according to the severity of the accident and the complexity of the issues involved. When an accident needs major investigation, a group of investigators called a Go Team, who are on call for immediate assignment, is organized. After the investigation, a detailed report is published. This team "should be strongly encouraged to submit their proposed conclusion, recommendation, and probable cause (Ref. 7)." Other investigations are conducted by NTSB field offices. In the following subsections, we analyzed current trends of accident investigations in terms of cost and accident causes in order to shed light on a key factor for the quantification of its contribution.

A. Cost of accident investigation

Figure 2 shows government budget for NTSB's "Aviation safety (Ref. 8)." It can be seen that government budget has been increased over the years. Notice that a sudden budget increase seen in 1997 is because NTSB required one-time cost for TWA 800 accident investigation which started in 1996.

However, when it comes to cost of accident investigation, we cannot ignore the cost spent by industries and other parties. Aircraft makers and airliners are involved in investigation and play crucial roles. The military participate if needed. As we mentioned previously, the purpose of accident investigation is to prevent a similar accident from occurring in the future, so implementation cost should be taken into account to accomplish the safety improvement. For instance, implementation cost includes not only one-time redesign cost but also operational cost, such as additional periodical inspection cost. Thus, the cost of NTSB investigation should be considered as only one part of the entire cost for a safety improvement.
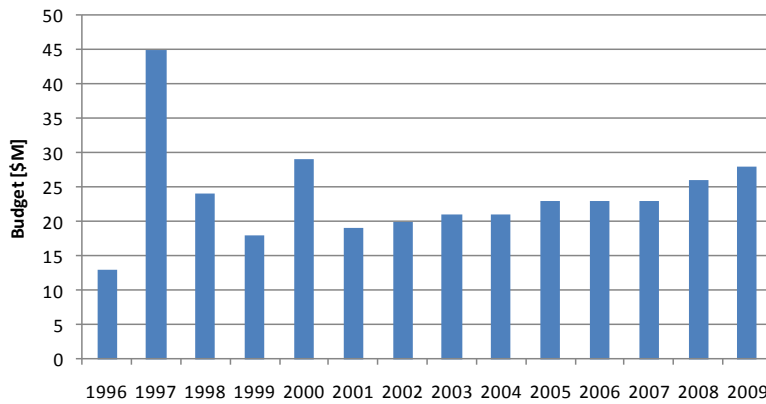
Figure 2 NTSB budget for aviation safety from 1996 to 2009 (current dollars)

B. Trend of accident causes

We look into the trend of aviation accidents reflected in statistical data provided by NTSB (Ref. 9). The annual number of accidents is shown in Fig 3. We examined statistical data of recent 20 years. It can be seen that the number of accidents has decreased over the decades. Furthermore, fatal accident rates in terms of flight hours are shown Fig 4. Airplanes are categorized into two types; jet airplanes usually used for major airliners (operated under 14 CFR Part 121) and turboprop commercial air carriers commonly referred to as commuter airlines (operated under 14 CFR Part 135). It is observed that the fatal accident rates also have been decreasing for both types, but the accident rates of commuters are more than 10 times higher than that of jet airplanes.
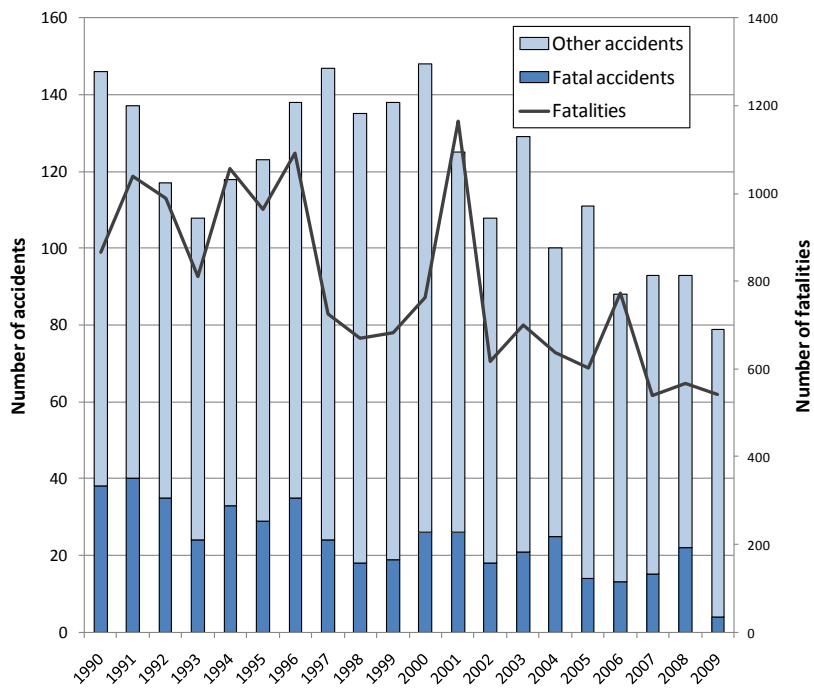

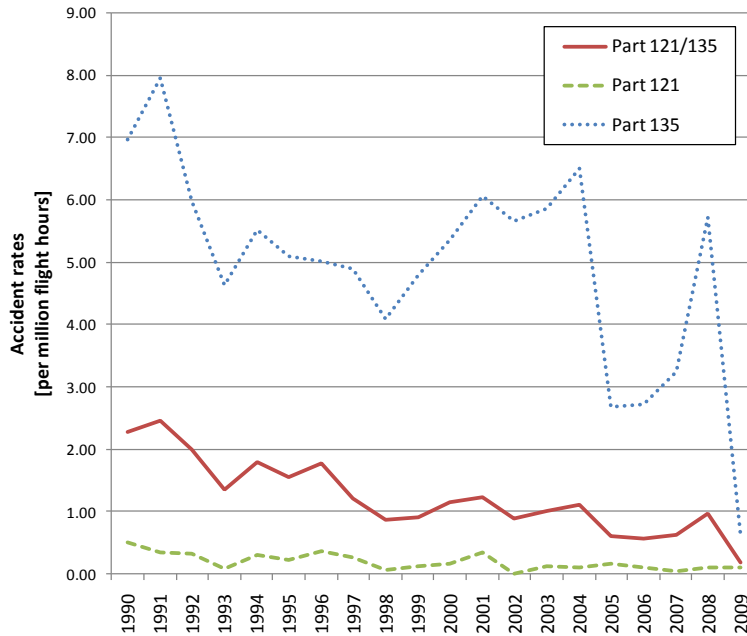**Figure 3 Number of accidents from 1990 to 2009**

Figure 4 Accident rates from 1990 to 2009

Part 121: Airplanes operated under Title 14, Part 121 (Jet aircrafts used for major airlines and cargo carriers)

Part 135: Airplanes operated under Title 14, Part 135 (Turboprop commercial air carrier commonly referred to as commuter airlines)

For further examination, we looked into the trend of the causes of accidents. The causes of accidents in past major investigations were categorized into three classifications – Rare event, Error, or Human. "Rare event" is an unexpected event that is not likely to happen in normal operation, e.g., extreme wind gust. Also, there were several events for undetermined reasons, e.g., loss of cabin pressurization, that were also categorized as "Rare events." On the other hand, "Error" is a failure to consider a failure mode, meaning a similar accident is likely to happen in the same situation. For example, if the phenomenon of fatigue crack growth fails to be recognized, all airplanes in the fleet will have the same risk. Similarly, there could be errors in manufacturing and inspection processes and operation manuals. The last category is "Human-related." This is an accident due to pilot action or inaction, and due to an inappropriate action of operator, such as a mistake, ignoring standard procedures, etc. Whether or not the required procedures were documented, if they did not follow them, we categorize such accident causes as "Human-related."

These categories are key factors in determining a likelihood of reoccurrence of an accident and therefore the cost effectiveness of investigation. If an accident cause is likely to happen to other similar airplanes, i.e., error, recommendations based on investigation will potentially prevent many accidents in the future. On the other hand, if large amounts of money are spent for an investigation about an extremely rare event accident, it contributes less effectively to future safety. An accident caused by human-related causes can be considered as either error or rare event. In terms of likelihood, it should be carefully investigated if it is likely to happen in other planes.

Table 1 shows the categorized accident causes of major accidents from 1996 to 2005. It can be seen that 46% are due to errors, indicating that they could have been prevented by appropriate design, manufacturing and maintenance procedures, and operation manuals. On the other hand, rare event is less dominant, 9% including terror attacks. Human-related cause is a factor in 65% of the accidents. Human-related causes can be categorized into error and rare event. However, since it is difficult to clearly distinguish between them, careful investigation is needed for the classification. Also when we look at the type of causes, 35% of the accidents are due to a combination of two or

three types of causes. These observations indicate that the causes of accidents are complex rather than due to a simple single cause such as unexpected extreme flight condition. In this sense, accident investigation plays a crucial role in examining how they contribute to the accident in order to effectively prevent them through recommendations.

Table 1 Classification of accident causes (from 1996 to 2005)

Types of accident	Types of accident causes			Total number of accidents	
	Rare event	Error	Human		
Single cause	○	-	-	4 [a]	11%
	-	○	-	7	19%
	-	-	○	13	35%
Combination of causes	○	○	○	0	0
	○	○	-	2	5%
	○	-	○	3	8%
	-	○	○	8	22%
	9 (24%)	17 (46%)	24 (65%)	37	

Note: [a] These are accidents due to terror attack.

III. Modeling the Cost Effectiveness of Accident Investigation

A. Definition of cost effectiveness (Cost per life saved)

In this paper, we focus on the contribution of accident investigation to preventing fatalities in the future. To quantify this contribution, the number of fatalities per accident and the likelihood of reoccurrence of an accident are taken into account. Since there is a possibility that a similar accident may happen to aircraft of the same model, the number of airplanes in the fleet is also considered. Moreover, recommendations issued by NTSB are applied not only to the same aircraft model but also to related fleets which have the same failure potential. Thus, the number of airplanes in the related fleets can be considered for estimating potential future fatalities.

Finally, we define the equation of the cost effectiveness of the accident investigation as

$$C_{1\text{life}} = \frac{C_{\text{inv}}}{N_f N_a P_{1r}}$$
(1)

where $C_{1\text{life}}$ is "cost per life saved". This value represents how much is invested to prevent one fatality in the future. Also, C_{inv}, N_f, N_a, and P_{1r} are the cost for the accident investigation, the number of fatalities in that accident, the number of airplanes in fleet (or related fleets), and the probability of reoccurrence of an accident in lifetime per airplane, respectively. Notice that the unit of the cost per life saved in the lifetime of fleet (or related fleets) expressed in Eq. (1) is dollars.

B. Effective cost for future safety and threshold of cost effectiveness

How much society should invest in preventing fatalities or extending life is controversial and there are many ongoing discussions in different social communities, e.g., health care, fire, natural disaster, transportation, etc. In aviation, economic values used in investment and regulatory decisions of the Federal Aviation Administration

(FAA) were analyzed (Ref. 10). Ref. 11 specified that values of life and injury be based on the "willingness to pay" by society for reduced risks of fatalities and injuries. The latest guidance in 2004 provided a minimum value of $3 million per fatality averted. This means that people would be willing as a group to pay $3 million to prevent one fatality. We can use this value for C_{1life} in Eq. (1) and calculate the corresponding investigation cost. Similarly, in Europe, an aviation fatality saved is valued 4.05 Million EURO by European Transport Safety Council in 2003 (Ref. 11). Thus, a value of several million dollars per fatality adverted can be considered as common sense currently in the community.

Here we introduce the concept of cost effectiveness threshold, such as threshold of cost being invested. Once we estimate a probability of reoccurrence of an accident, we can calculate the threshold for effectiveness of the cost being invested, C_{inv_th}, by using Eq. (1) and $3M per fatality which is recommended by FAA.

$$C_{inv\_th} = 3 \times 10^6 N_f N_a P_{1r} \qquad (2)$$

The advantage of having a threshold value is that after we determine the probability of reoccurrence by accident investigation, we can judge whether or not implementation plan for recommendation is cost effective. Even during investigation, once the probability of reoccurrence is determined, we can see if the investigation is cost effective and whether or not we need to go further into detail of the accident.

IV.   Examples of Cost Effectiveness of Accident Investigation

A. Cost effective of accident investigation

As examples of the measurement of investigation cost effectiveness, we use two past accidents with different types of causes--error and rare event. The example of an accident due to error is from Alaska Airlines Flight 261, which occurred on January 31, 2000. Casualties were two pilots, three cabin crewmembers, and 83 passengers on board, and the airplane, MD-83, was destroyed by impact forces (Ref. 12). Table 2 shows related information of the accident and the airplane.

Looking into the detail of causes of the accident, NTSB concluded that the probable cause is "a loss of airplane pitch control resulting from the in-flight failure of the horizontal stabilizer trim system jackscrew assembly's acme nut threads. The thread failure was caused by excessive wear resulting from Alaska Airlines' insufficient lubrication of the jackscrew assembly." According to the NTSB report, several factors contributed to the accident. First, lubrication of the nut threads was not adequately performed. The investigation also revealed that there was an inappropriate lubrication interval, so that the excessive wear due to the insufficient lubrication became critical before the following lubrication time. It is also reported that the periodic inspection interval for the wear condition was also too wide to catch the excessive wear before causing failure. Furthermore, there was no fail-safe mechanism to prevent the catastrophic effect from the nut thread loss. These observations lead us to conclude these inappropriate maintenance procedures and the aircraft design as errors, meaning that once insufficient lubrication happens, a similar catastrophic accident is likely to happen to other airplanes. When we look at the inadequate lubrication, it is concluded that "more than just the last scheduled lubrication was missed or inadequately performed." The report also notes that "inadequate lubrication of the accident jack screw assembly was not an isolated occurrence" and "deficiencies continue to exist in Alaska Airlines' lubrication practices," indicating that there was a possibility of other locations with insufficient lubrication. In fact, NTSB issued recommendations on improving Alaska Airlines' lubrication process. Based on these facts, we estimate that the probability of reoccurrence is between one per hundred and one per thousand. That is, in a fleet of 1,000 planes, the same kind of accident is very likely to reoccur over the lifetime of the airplanes (Design lifetime of MD-83 =

50,000 flight hours (Ref. 13)), and possibly even in a fleet of 100 airplanes. By using Eq. (2), corresponding cost effective threshold range is determined to be \$2,950M-\$295M (Table 3). If the cost for the accident investigation and implementation is less than this cost range, these safety improvement activities can be considered as cost effective measures.

Table 2 Number of fatalities and airplanes in fleet, Alaska Airlines Flight 261, in 2000

	Quantity	Remark
Number of fatalities, N_f	88	All crews and passengers
Size of fleet, N_a	1,191	MD-83 (Delivered from 1980 to 1999)

Table 3 Cost effectiveness threshold, Alaska Airline Flight 261

Cost effectiveness threshold, C_{inv_th}	Probability of reoccurrence, P_{1r}
\$2,950M	$P_{1r} = 1.0 \times 10^{-2}$ (once in 100 lifetimes of airplane)
\$295M	$P_{1r} = 1.0 \times 10^{-3}$ (once in 1,000 lifetimes of airplane)

Design lifetime of MD-83: 50,000 flight hours

An example of a rare-event accident is from United Express Flight 5925 which occurred on Nov 19, 1996. The airplane, a Beech 1900, crashed while landing at the Quincy airport, Illinois, colliding with a Beechcraft King Air. All 12 aboard the Beech 1900 and 2 aboard the King Air were killed in the accident (Ref. 14). Table 4 shows the related information of the accident.

NTSB concluded that "contributing to the severity of the accident and the loss of life were the lack of adequate aircraft rescue and firefighting services and the failure of the air stair door on the Beech 1900C to be opened", but the direct cause of the collision was a combination of human errors. While Beech 1900 was approaching the runway, the pilot on Beech 1900 mistook an interrupted transmission from another airplane on runway, a Piper Cherokee, as a response from the King Air pilots that they were not planning to take off. The response from the Cherokee to Beech 1900 was unnecessary and inappropriate. Also, the pilots on the King Air failed to announce their intention to take off and missed their duty to "see and avoid" other traffic. Furthermore, the pilot of the King Air did not hear the transmissions from the Beech 1900; it was reportedly likely that either they did not properly configure the radio receiver switches, or they were preoccupied, distracted, or inattentive. As a result, the collision occurred on the runway when the King Air had begun its takeoff while the Beech 1900 was landing. This can be considered as an extremely rare event; it is not likely to happen to other airplanes. In fact, some recommendations about evacuation after a collision were issued, but there was no recommendation intended to prevent the direct causes, i.e., the failure to "see and avoid" and the interrupted transmission[††]. It is not easy to clearly determine the probability of reoccurrence of this human-related rare event, but we estimated the range of it from 10^{-5} to 10^{-7}. This range is equivalent to an accident rate of 3.3×10^{-4} to 3.3×10^{-6} per million flight hours (Design lifetime of

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[††] There was one recommendation to "Reiterate to flight instructors the importance of emphasizing careful scanning techniques during pilot training and biennial flight reviews," but it is not specific to this accident situation.

Beech 1900 = 30,000 flight hours (Ref. 15)). The corresponding cost effectiveness threshold is shown in Table 5. Similarly to the previous example, if the cost being invested for investigation and implementation are less than this cost range, they were held cost effectively.

As seen from these two examples, the proposed model is useful for evaluating cost effectiveness of accident investigation and implementation of recommendations.

Table 4 Number of fatalities and airplanes in fleet, United Express Flight 5925, in 1996

	Quantity	Remark
Number of fatalities, N_f	14	All crews and passengers
Size of fleet, N_a	695	Delivered from 1982 to 2002

Table 5 Cost effectiveness threshold, United Express Flight 5925, in 1996

Cost threshold, C_{inv_th}	Probability of reoccurrence, P_{1r}
$0.292M	$P_{1r} = 1.0 \times 10^{-5}$ (once in 10^5 lifetimes of an airplane)
$0.003M	$P_{1r} = 1.0 \times 10^{-7}$ (once in 10^7 lifetimes of an airplane)

Design lifetime of Beech 1900: 30,000 flight hours

B. Comparison to other reliability improvement measures

In this subsection, we compare cost effectiveness between accident investigation and another reliability improvement measure that is intended to reduce the probability of failure. Kale et al. (Ref. 16) traded off the reliability improvement for fatigue of a fuselage panel against lifecycle cost. In this case, variability in initial crack size, in material properties for crack growth, and in pressure load in flight was considered as uncertainties. For design variables, the thickness of panel, inspection type, and inspection interval in service were optimized to find the minimum lifecycle cost for a given probability of failure. The lifecycle cost is calculated based on structural weight and frequency of inspection in service. Appendix A shows the details of the cost estimate. We selected the case in which the probability of failure is improved from 10^{-7} to 10^{-8} in the lifetime per panel. We assumed to have 1,350 panels design for fatigue per aircraft, which is equivalent to reliability improvement from 1.4×10^{-4} to 1.4×10^{-5} in the lifetime per airplane.

Thus, in the reliability-based design optimization (RBDO) framework, reliability improvement is applied from a certain probability of failure to another. Accordingly, we modify the equation of cost effectiveness in Eq. (1) as

$$C_{1life} = \frac{C_{inv}}{N_f N_a (P_{1before} - P_{1after})} \tag{3}$$

where $P_{1before}$ is a probability of failure in lifetime of each airplane before improvement is applied, and P_{1after} is the probability of failure in lifetime of each airplane after improvement is applied. This equation is the same as Eq. (1) when P_{1after} is zero, where a similar accident is assumed to be completely prevented after accident investigation.

Table 6 shows the cost per life saved by the structural design change. For the number of fatalities, we consider two extreme cases. The first case is that fatigue failure leads to a fatal accident; the number of fatalities is the same as the number of all passengers of Boeing-747 (about 450 passengers). The other case is that there is a single

fatality, like Aloha airlines' accident due to metal fatigue in 1988[‡‡]. Additional lifecycle cost per panel including material manufacturing, fuel, and inspection cost is $0.81M per panel and the resulting total additional cost for the fleet is $1,149M. Cost per life saved is finally calculated as $15M for 450 fatalities and $6,667M for one fatality.

Since we do not know the actual cost for Alaska Airlines case, we estimated a cost which performs the same cost effectiveness as the structural design change case, i.e., cost per life saved = $15M. Table 7 shows the comparison of cost effectiveness between the accident investigation of Alaska Airlines and the structural design change. Cost of Alaska Airlines case is determined to be $14,700M if $P_{1r} = 10^{-2}$, and $1,470M if $P_{1r} = 10^{-3}$. According to the accident report, recommendation issued mainly consists of two improvement measures, such as revising lubrication and maintenance procedures, and design correction for the catastrophic single point of the wear. Considering implementation plan and the amount of NTSB's annual budget previously discussed, it would be apparent that the implementation and investigation cost for this accident can be approximate as quite less than the cost range. Thus, we can conclude that the accident investigation is much more cost effective than that of structural design change.

This comparison can be considered as comparing two types of investment for future safety. While accident investigation reveals and prevents unrecognized failure modes, which are discovered by accident, from reoccurring in the future, the stricter structural design requirements is equivalent to imposing a stricter design rule on already-known failure mode. In this particular case, the investment for protecting against unknown failure modes is much more cost-effective than applying more severe design rules.

Table 6 Cost per life saved, structural design change for fatigue life

(Improvement of probability of failure: from 1.4×10^{-4} to 1.4×10^{-5} in life time in each airplane)

	Quantity		Remark
Additional cost in lifecycle, C_{inv}	$1,149M		for the fleet
Size of fleet, N_a	1,418		delivered as of 2010
Assumed fatalities, N_f	450	1	
Cost per life saved, C_{1life}	$15M	$6,667M	

Table 7 Comparison in invested cost for the same cost per life saved, C_{1life},
between accident investigation and structural design change for fatigue life

	Cost per life saved, C_{1life} [in lifetime for the fleet]	Corresponding cost
Accident investigation (Alaska Airlines Flight 261)	$15M	$14,700M (if $P_{1r} = 10^{-2}$) $ 1,470M (if $P_{1r} = 10^{-3}$)
Structural design change for fatigue life		$1,149M

[‡‡] A small section on the left side of the roof ruptured during the flight, and the resulting explosive decompression tore off a large section of the roof. One of the crewmembers was flown away through the hole.

V. Concluding Remarks

A methodology of quantifying cost effectiveness of accident investigation for saving lives is proposed. We show that the probability of reoccurrence of an accident is a key factor for determining the cost effectiveness, i.e., cost per life saved. Through examples, we illustrated the cost effectiveness of different types of accident causes, such as error and rare event. We conclude that distinguishing accident causes, i.e., error or rare event, is a crucial role of accident investigation not only for issuing appropriate recommendations but also for evaluating cost effectiveness of investigation and implementation. We also performed a comparison in cost effectiveness between accident investigation and a structural design change which intends to reduce probability of fatigue failure. We found that for the example of Alaska Airline case the safety improvement by the accident investigation was clearly more cost effective.

Appendix: Cost model of structural design change for fatigue

The total lifecycle cost is calculated based on the weight of the structure and a frequency of inspection. While a fatigue tolerant structure with thicker panel can reduce a frequency of the inspection, a cost penalty on weight is imposed. Eq. (4) is the model of total lifecycle cost, C_{total}, used in (Ref. 16).

$$C_{total} = C_M W + C_F W S_l + C_I N_I \qquad (4)$$

where C_M is material manufacturing cost per unit weight, W is structural weight, C_F is fuel cost per unit weight per flight, S_l is service lifecycle of airplane, C_I is cost of inspection, and N_I is the number of inspections, respectively. The total lifecycle cost in lifetime per panel is calculated as \$18.66M when $P_{1before} = 10^{-7}$, and \$19.47M when $P_{1after} = 10^{-8}$ so that the additional cost for the improvement is obtained as \$0.81M.

Acknowledgement

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