Effectiveness of Accident Investigations of the Space Shuttle for Safety Improvement

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Accident investigation has been playing a crucial role for improving aviation safety by identifying unknown accident causes and leading to corrective actions. While the cost effectiveness of accident investigations for airliners has been studied, such studies are lacking for spacecraft. We study the cost effectiveness of the investigations of the Space Shuttle disasters. We find that for airliners we can ignore risks that were not involved in the accident, but for spacecraft this approximation is not accurate enough, and the effect of the corrective actions on the system failure probability must be accounted for. We evaluate the cost effectiveness of the Space Shuttle investigations by using the Department of Transportation guidelines for the value of saving lives in public transportation. According to the guidelines, the accident investigations of the Space Shuttle disasters are not cost effectives in terms saving lives. The cost effectiveness is also examined from the point of view of program sustainability (monetary value of the vehicle). We find that the Challenger case is substantially cost effective and the Columbia case is worth spending more than $100 million.

I. Introduction

The safety of airplanes and space vehicles have been improved alongside the evolution of design, manufacturing and maintenance [1, 2]. In addition, safety improvements triggered by accidents have been playing a crucial role. Investigation following an accident or incident identifies failure modes which were not recognized by designers and operators. Then safety recommendations are issued in order to prevent similar accidents in the future. Safety remedies following investigations consist not only of modifications of design and maintenance procedures but also of improvements in regulations and design philosophies, which make a significant contribution to risk reduction by being applied to entire communities. These are not limited to current fleets, but also to yet-to-developed vehicles in the future.

For commercial aviation, there is an independent organization responsible for accident investigation, i.e., the National Transportation Safety Board (NTSB). The annual budget of NTSB for aviation safety is around $30 million [3]. The actual cost of an investigation is much higher than the NTSB cost (at least by a factor of four) when the cost of other agencies and private sector is taken into account [4]. In comparison, the space community often organizes an independent committee responsible for investigation in case of disaster (e.g., Columbia Accident Investigation Board (CAIB) for the Space Shuttle Columbia accident in 2003). The investigation reportedly costed more than $100 million. Thus, cost for accident investigation of a space vehicle is substantially higher than for an airplane accident.

While the cost effectiveness of safety implementations after accidents is usually examined, e.g., FAA's airworthiness directives, there are few studies on cost effectiveness of accident investigations in the open literature. Matsumura et al. [5] demonstrated the ease of estimating cost effectiveness of a single accident investigation for commercial airplanes. It was shown that two past accident investigations for commercial airplanes were considered cost effective according to the Department of Transportation (DOT) guideline for public transportation about monetary value of life saved ($6.2 million [6]).

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This paper extends the previous work to examine cost effectiveness of accident investigation for space vehicles, which have small fleets, a small crew size, and a much higher vehicle cost. In order to shed light on key factors that determine cost effectiveness, we study the Space Shuttle disasters. Then, cost effectiveness is compared to the effectiveness threshold of the DOT guideline for public mass transportation. Since the threshold is established based on the concept that "how much people are willing to pay to decrease risk in the future," this study gives us an idea about if the accident investigation for space vehicles is cost effective from the society's point of view.

In the previous work, the cost effectiveness of accident investigation was defined based on safety improvement of a direct accident cause ignoring an impact on system level safety. As shown in this work, this assumption is justified for airliners because of the large fleet size and the very low probability associated with almost all accident causes. We first redefine the cost effectiveness based on system level safety, and then investigate the discrepancy between the two approaches of the effectiveness estimate (system or direct cause). Then, the accident investigations for the Space Shuttle accidents, such as the Challenger and the Columbia, are discussed. We also examine the effectiveness of the accident investigations based on the contribution to sustaining the Space Shuttle program as well as to saving lives in the future.

The paper is organized as follows: Section II describes cost effectiveness measurement. Cost effectiveness of safety improvement by Space Shuttle's accident investigations is examined and discussed in Section III. Conclusions and remarks are addressed in Section IV.

II. Definition of Cost Effectiveness of Accident Investigation

Definition of cost per life saved

Cost effectiveness of an accident-related safety enhancement centers on the notion of the monetary value of statistical life (VSL), defined as the value of improvements in safety resulting in a reduction by one in the expected number of fatalities. VSL is estimated from the amount of the wealth the society is willing to give up in exchange for a small decrease in risk [7]. In the same fashion, Matsumura et al. [5] defined cost effectiveness of accident investigation by computing how much we spend to prevent the loss of one life in the future. In Ref. [5], the cost effectiveness of airplane accident investigations is discussed based on the improvement in the probabilities of individual accident causes. In this section, we redefine the cost effectiveness by considering an impact on system level safety.

Potential future fatalities related to an accident are calculated by the product of the expected number of fatalities $\mathrm{N_f}$ that would result from a fatal accident., the number of vehicles (airplanes) $\mathrm{N_v}$ that have the same failure potential, and the probability of reoccurrence of the accident in the remaining lifetime. For estimating $\mathrm{N_v}$, one may take into account not only existing space vehicles (airplanes), but also not-yet-built ones which will potentially benefit in the future from the improvement. Of these three parameters, accident investigation has the potential to change the probability of accident reoccurrence, through implementation of the recommended safety measures. On this basis, we calculate the cost of the investigation per life saved $\mathrm{C_{1life,sys}}$ as

$$\mathrm{C_{1life,sys}} = \frac{\mathrm{C_{inv}}}{\mathrm{N_f\,N_v(P_{sys,before} - P_{sys,after})}} \tag{1}$$

where $\mathrm{P_{sys,before}}$ is the probability of a fatal accident occurring per remaining lifetime of one space vehicle (airplane) before safety improvement is applied, and $\mathrm{P_{sys,after}}$ is the probability of after improvement is applied. The subscript "sys" represents the system level probability. $\mathrm{C_{inv}}$ is the cost invested in the accident investigation. For analyzing cost effectiveness of a safety improvement triggered by an accident, it would make sense if $\mathrm{C_{inv}}$ includes both the investigation cost and the cost for implementing the safety recommendations. In this study, since we focus on the effectiveness of accident investigations, we only take into account the cost of an investigation for $\mathrm{C_{inv}}$.

How much society should invest in preventing fatalities is controversial, as seen in many ongoing discussions in different communities, e.g., health care, transportation, environment, etc. Viscusi [8] analyzed data on worker deaths across different industries, and suggested the value of life in the range of \$4.7 to \$8.7 million. In commercial aviation, economic values used in investment and regulatory decisions of the U.S. Department of Transportation (DOT) were analyzed and determined [6]. The latest guidance led to the value of \$6.2 million per fatality averted. However, there is no relevant investigation for human-related space transportation. The willingness of society to invest in saving lives of astronauts may be higher, at least in part, because of the high investment in training them, and their high visibility.

Cost per life saved - System safety based vs. individual cause based –

The degree of system level safety improvement might not be available, because it requires probabilities of failure of the all potential failure modes. In this section, we investigate when the cost effectiveness estimate based only on the probability of the direct accident cause is an accurate approximation to the cost effectiveness based on the system level safety. This boils down to the question when is the change in probability of the direct cause of the accident is a good approximation to the change in the system level probability of an accident.

It is assumed that there are N remaining failure modes besides the direct cause of accident in a system. The probabilities of failure of the direct cause are denoted as $\mathrm{P_{d,before}}$ and $\mathrm{P_{d,after}}$. The probability of failure of *i*th mode among N modes is P_i. There are many articles describing how to calculate system level reliability, e.g., Refs. [9-11]. Here, we assume that all N+1 failure modes are independent and form a series system. Then, the system level probabilities before and after the corrective action to the direct cause is applied, $\mathrm{P_{sys,before}}$ and $\mathrm{P_{sys,after}}$, are obtained as

$$\mathrm{P_{sys,before}} = 1 - (1 - \mathrm{P_{d,before}})\prod_{\mathrm{i=1}}^{\mathrm{N}}(1 - \mathrm{P_i}) \tag{2}$$

$$\mathrm{P_{sys,after}} = 1 - (1 - \mathrm{P_{d,after}})\prod_{\mathrm{i=1}}^{\mathrm{N}}(1 - \mathrm{P_i}) \tag{3}$$

The improvement in the system level probability is determined by the difference between $\mathrm{P_{sys,before}}$ and $\mathrm{P_{sys,after}}$ as

$$\mathrm{P_{sys,before}} - \mathrm{P_{sys,after}} = (\mathrm{P_{d,before}} - \mathrm{P_{d,after}})\prod_{\mathrm{i=1}}^{\mathrm{N}}(1 - \mathrm{P_i}) \tag{4}$$

For commercial airplanes, probability of lifetime service without having a fatal accident is roughly estimated at 0.99 from the fatal accident rate in the U.S. in 2002-2009 (1.9x10-7 per aircraft departure [12]) and a typical design lifetime of airplanes of 40,000. This implies that the term $\prod_{\mathrm{i=1}}^{\mathrm{N}}(1 - \mathrm{P_i})$ is greater than 0.99. Then, the improvement in system probability $\mathrm{P_{sys,before}} - \mathrm{P_{sys,after}}$ in Eq. (4) can be accurately approximated by $\mathrm{P_{d,before}} - \mathrm{P_{d,after}}$. This approximation is useful because system level probabilities of airplanes are rarely available and the estimates of the system probabilities would not be very accurate. If, on the other hand, the safety level of a system is poor (some of $\mathrm{P_i}$s are very high), like the Space Shuttle discussed later, the approximation is not useful and the system probabilities need to be carefully evaluated.

III. Cost Effectiveness of Accident Investigation for the Space Shuttle Disasters

In this section, the cost effectiveness of accident investigation of past Space Shuttle accidents is examined. Throughout 30-year-operation of the Space Shuttle on 135 missions, NASA experienced two catastrophic failures, Challenger (STS-51L) in 1986 and Columbia (STS-107) in 2003. After the Challenger disaster, where the vehicle exploded during the ascent phase, the Rogers Commission was formed for the accident investigation. The commission found that the accident was caused by a failure in O-ring sealing of a joint of the solid rocket motor (SRM) aimed at preventing the pressurized hot gases from leaking. The Columbia orbiter was destroyed during atmospheric reentry. The Columbia Accident Investigation Board (CAIB), an independent investigation committee, determined that a piece of insulating foam which separated right after the liftoff from the left bipod ramp section of the External Tank made a breach in the Thermal Protection System on the leading edge of the left wing, resulting in deterioration of heat shielding function.

Parameter estimation for Eq. (1) and the cost effectiveness of these accident investigations are discussed as follows.

Parameter estimation

Four orbiters remained after the Challenger mission, and three orbiters after the Columbia mission ($\mathrm{N_v}$=4 or 3). The numbers of fatalities were determined by the average crew size of the actual missions. For Challenger the average crew size was 6.2 based on total 685 crewmembers for 110 remaining ascent missions. 6.6 is the average number of crewmembers after the Columbia accident calculated from total 145 crewmembers for 22 reentry flights.

Since the costs of the accident investigations are not publicly available, we estimated them from news sources. The investigation cost for the Challenger disaster was reportedly \$175 million [13]. This is substantially beyond the

NASA's estimate in the middle of the investigation (between \$40 million to \$65 million) [14]. For the Columbia accident investigation, it was estimated at \$152 million [15]. These costs are substantially larger than for aircraft accidents as evidenced by comparing to annual NTSB budget for aviation safety of about \$30 million [3], and a report which estimated the investigation cost of a major commercial airplane accident at \$8.5 million [4], including costs of other government agencies, e.g., Federal Aviation Administration, and private sectors.

NASA reported the latest results of Space Shuttle Probabilistic Reliability Assessment (PRA) [16]. This study tracks changes in risks, probability of loss of crew and vehicle (LOCV), of dominant failure causes of the Space Shuttle over the missions. Since these risks are expressed as LOCV per mission, we need to convert them to probability of LOCV in lifetime to be applicable to Eq. (1). After the Challenger mission (25th mission), 110 missions remained and were operated by four remaining vehicles (Atlantis, Columbia, Discovery, and Endeavour). For simplicity, we assume that each vehicle has an average 27.5 missions in its lifetime. Then, the probability of LOCV for each remaining vehicle is calculated as $\mathrm{P_{life}} = 1 - (1 - \mathrm{P_{mission}})^{27.5}$, where $\mathrm{P_{mission}}$ represents probability per mission and $\mathrm{P_{life}}$ is the probability in lifetime. In the same manner, the average missions of each vehicle after the Columbia accident (113th mission) was obtained by during 22 total remaining missions by three vehicles, resulting with $\mathrm{P_{life}} = 1 - (1 - \mathrm{P_{mission}})^{7.3}$.

Table 1 shows the probabilities of LOCV at system level converted to probability in lifetime and Table 2 is the probabilities of the direct causes. The improvement of system level risk is estimated based on the top 10 risks addressed in the NASA report [16]. For example, after the Challenger's accident, the probability of LOCV of the system is improved by 0.124 while the degree of improvement of the direct cause is 0.656. This is a remarkable feature of the safety of the Space Shuttle. The Space Shuttle initially had five potential failure causes whose risks were more than 1 in 1000 missions. Even after the direct cause of the accident of the Challenger (O-ring sealing) became less dominant, other risk drivers remain and cause the probability of LOCV to remain high. For more details of the risk progression, readers refer to Appendix A.

Table 1. Safety improvement at system level

	Probability of LOCV in lifetime *		$\mathrm{P_{sys,before}} - \mathrm{P_{sys,after}}$
	Before improvement	After improvement	
Challenger	0.939 (1 in 10.4 missions)[4]	0.815 (1 in 16.8 missions)	**0.124**
Columbia	0.121 (1 in 57.4 missions)	0.081 (1 in 87.2 missions)	**0.040**

* LOCV: Loss of crew and vehicle.

Table 2. Safety improvement of direct causes

	Probability of LOCV in lifetime *		$\mathrm{P_{d,before}} - \mathrm{P_{d,after}}$
	Before improvement	After improvement	
Challenger	0.675 (1 in 25 missions)	0.018 (1 in 1500 missions)	**0.657**
Columbia	0.055 (1 in 130 missions)	0.012 (1 in 600 missions)	**0.043**

* LOCV: Loss of crew and vehicle.

Cost effectiveness of accident investigations

Using the above determined parameters, the cost effectiveness of the accident investigations were calculated by Eq. (1). The results are summarized in Table 3. As discussed in the previous section, for the Challenger case, the cost effectiveness estimate based on the probabilities of direct accident cause substantially underestimate $\mathrm{C_{1life,sys}}$ because of the fact that other risk drivers remain even after the direct cause vanishes (Table A.1). According to the

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[4] 1 in 10.4 missions corresponds to a 91.2% chance that an accident should have happened before the 25th flight, but it didn't happen. This indicates that 1 in 10.4 missions are likely to be a conservative estimate.

guideline of the DOT, the effectiveness threshold of \$6.2 million for C_{1life}, the investigations of the Space Shuttle accidents are far less cost effective even though the improvement in the probability is very high.

Table 3. Cost per life saved of Space Shuttle's accident investigations

	Cost per life saved	
	Based on probability improvement of direct cause $(P_{d,before} - P_{d,after})$	$C_{1life,sys}$, based on system level safety improvement $(P_{sys,before} - P_{sys,after})$
Challenger	\$10.7 million	\$56.8 million
Columbia	\$179.2 million	\$192.7 million

One might argue that the Space Shuttle program is not commercial passenger transportation. Over the decades, one of the important missions of the Space Shuttle program was to establish and sustain the access to the low earth orbit. From this perspective, contributions of the accident investigations may be defined to prevent not only the loss of astronauts but also the loss of the vehicles in the future. Therefore, the break-even is the balance between investing cost in an accident investigation and the monetary loss of crew members and vehicles shown in Eq. (5).

$$\begin{aligned} C_{inv} &= \text{monetary loss of astronauts} + \text{monetary loss of vehicle} \\ &= (C_{veh} + C_{1life,sys} N_v\, N_f)(P_{sys,before} - P_{sys,after}) \end{aligned} \tag{5}$$

where C_{veh} is the reconstruction cost of the vehicle. By modifying the Eq. (5) for C_{1life}, the cost per life saved accounting for the contribution to the sustainability of the program is obtained as follows

$$C_{1life,sys} = \frac{1}{N_v\, N_f}\left(\frac{C_{inv}}{P_{sys,before} - P_{sys,after}} - C_{veh}\right) \tag{6}$$

Table 4 shows the results of $C_{1life,sys}$ calculation using the same parameters estimated in the previous section. For the cost of reconstructing the Shuttle orbiter, \$2.4 billion is used from the literature [14]. For the Challenger's case, $C_{1life,sys}$ is negative, indicating that the accident investigation is substantially cost effective even without considering the contribution to saving astronauts. On the other hand, the investigation for the Columbia accident is not still cost effective because of the small probability improvement.

Table 4. Cost per life saved considering the sustainability of Space Shuttle program

	Cost per life saved $(C_{1life,sys})$
Challenger	\$-39.5 million
Columbia	\$71.3 million

The threshold of the investing cost can be calculated by substituting \$6.2 million into C_{1life} in Eq. (6) and solving for C_{inv}. The thresholds for the Challenger and Columbia cases are obtained as \$316 million and \$101 million respectively. It can be said that the accident investigations and the implementation of the safety recommendations for the Space Shuttle accidents were worth spending more than \$100 million from the point of view of maintaining secure access to the low earth orbit.

IV. Conclusions

Cost effectiveness of accident investigation for the Space Shuttle disasters is examined. We first defined the cost effectiveness of accident investigations based on system level safety improvement, and compared it to the effectiveness based on safety improvement of direct causes. It is found that for airliners we can ignore risks that were not involved in the accident, but for spacecraft this approximation is not accurate enough, and the effect of the corrective actions on the system failure probability must be accounted for.

The study shows that the accident investigations of the Space Shuttle were not cost effective according to the guideline for public transportation by the Department of Transportation (DOT), $6.2 million for saving a life. Unlike commercial airplanes which have a large number of passengers (a high monetary value of lives to be saved), the Space Shuttle has a small crew size, resulting in less effective. However, once the contribution of the accident investigations to the sustainability of the program (the reconstruction cost of the vehicle which is much higher than monetary values of lives) is considered, the accident investigations for the Challenger becomes very effective, and the investigations and following corrective actions of the Space Shuttle disasters are worth more than $100 million apiece.

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Appendix A: Top 10 risks before/after accidents

Tables A.1 and A.2 show the top 10 risks of the Space Shuttle and their progression before and after the accidents, and Table A.3 describes the overall risk of the Space Shuttle [16].

Table A.1. Top 10 risks before/after Challenger accident

Risk items	Before	After	
	STS-51L (25th mission)	Only direct cause corrected	STS-26 (26th mission)
Ascent debris strikes Orbiter Thermal Protection System (TPS) leading to LOCV on orbit or entry	1 in 22	←	←
Solid Rocket Motor (SRM)-induced SRM catastrophic failure	1 in 25	1 in 1500	←
Micrometeoroid and Orbital Debris (MMOD) strikes Orbiter on orbit leading to LOCV on orbit or entry	1 in 190	←	←
Space Shuttle Main Engine (SSME)-induced SSME catastrophic failure	1 in 190	←	1 in 290
Orbiter flight software error results in catastrophic failure during ascent	1 in 950	←	1 in 1300
Crew error during entry	1 in 1200	←	←
SSME-induced benign shutdown of the SSME	1 in 1800	←	1 in 3800
Fuel supply failure to the OMS during orbit	1 in 2100	←	←
Debonding of TPS during ascent	1 in 2700	←	←
Orbiter APU Shaft Seal Fracture Entry	1 in 2900	←	←
System *	**1 in 10.4**	**1 in 16.8**	**1 in 17.5**

* calculated based on top 10 risks

Table A.2. Top 10 risks before/after Columbia accident

Risk items	Before	After	
	STS-110 (109th mission)	Only direct cause corrected	STS-114 (114th mission)
Ascent debris strikes Orbiter Thermal Protection System (TPS) leading to LOCV on orbit or entry	1 in 130	1 in 600	←
Micrometeoroid and Orbital Debris (MMOD) strikes Orbiter on orbit leading to LOCV on orbit or entry	1 in 190	←	1 in 200
Space Shuttle Main Engine (SSME)-induced SSME catastrophic failure	1 in 610	←	←
Crew error during entry	1 in 1200	←	←
Reusable Solid Rocket Motor (RSRM)-induced SRM catastrophic failure	1 in 1500	←	←
Solid Rocket Booster (SRB) APU shaft seal fracture	1 in 2200	←	←
SRB booster separation motor debris strikes Orbiter windows	1 in 2700	←	←
Orbiter flight software error results in catastrophic failure during ascent	1 in 3800	←	1 in 4400
Flow Control Valve (FCV) poppet failure causes rupture in the GH2 re-pressurization line	1 in 5500	←	←
Ammonia Boiler System (ABS) isolation valve leaks on Orbit overcooling the H20 loops and crew is unable to prevent rupture of the interchanger resulting in Loss of All Cooling	1 in 5600	←	←
System *	**1 in 57.4**	**1 in 87.1**	**1 in 94.1**

* calculated based on top 10 risks

Table A.3. Summary of Overall Shuttle Risk

STS-No.	Mission No.	Risk
STS-1	1	1:12
STS-5	5	1:10
STS-41B	10	1:10
STS-51L	25	1:10
STS-26	26	1:17
STS-29	28	1:36
STS-49	47	1:37
STS-77	77	1:38
STS-86	87	1:21
STS-89	89	1:21
STS-96	96	1:47
STS-109	109	1:47
STS-114	114	1:73
STS-133	133	1:90

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