

DOT/FAA/AR-11/18

Air Traffic Organization
NextGen & Operations Planning
Office of Research and
Technology Development
Washington, DC 20591

Freighter Airplane Cargo Fire Risk Model

September 2011

Final Report

This document is available to the U.S. public through the National Technical Information Services (NTIS), Springfield, Virginia 22161.

This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.



U.S. Department of Transportation
Federal Aviation Administration



Transport
Canada

Transports
Canada



NOTICE

This research was commissioned by the Federal Aviation Administration and Transport Canada by means of their respective Memorandums of Cooperation regarding Civil Aviation Research and Development with the Civil Aviation Authority of the United Kingdom. This activity has been carried out in cooperation between the Federal Aviation Administration, Transport Canada, and the UK Civil Aviation Authority under the auspices of the International Cabin Safety Research Technical Group whose goal is to enhance the effectiveness and timeliness of cabin safety research.

This document is disseminated under the sponsorship of the U.S. Department of Transportation in the interest of information exchange. The United States Government assumes no liability for the contents or use thereof. The United States Government does not endorse products or manufacturers. Trade or manufacturer's names appear herein solely because they are considered essential to the objective of this report. The findings and conclusions in this report are those of the author(s) and do not necessarily represent the views of the funding agency. This document does not constitute FAA policy. Consult the FAA sponsoring organization listed on the Technical Documentation page as to its use.

This report is available at the Federal Aviation Administration William J. Hughes Technical Center's Full-Text Technical Reports page: actlibrary.tc.faa.gov in Adobe Acrobat portable document format (PDF).

Technical Report Documentation Page

1. Report No. DOT/FAA/AR-11/18		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle FREIGHTER AIRPLANE CARGO FIRE RISK MODEL				5. Report Date September 2011	
				6. Performing Organization Code	
7. Author(s) RGW Cherry & Associates Limited				8. Performing Organization Report No.	
9. Performing Organization Name and Address RGW Cherry & Associates Limited The Lord Wake Suite The Priory, High Street Ware, Hertfordshire SG12 9AL United Kingdom				10. Work Unit No. (TRAIS)	
				11. Contract or Grant No.	
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Air Traffic Organization NextGen & Operations Planning Office of Research and Technology Development Washington, DC 20591				13. Type of Report and Period Covered Final Report	
				14. Sponsoring Agency Code ADG-200	
15. Supplementary Notes Jointly funded by the Federal Aviation Administration and Transport Canada. The Federal Aviation Administration Airport and Aircraft Safety R&D Division Technical Monitor was Richard Hill.					
16. Abstract Following the Boeing 747 freighter airplane accident on September 3, 2010, at Dubai International Airport in the United Arab Emirates, the Federal Aviation Administration, Transport Canada, and the United Kingdom Civil Aviation Authority initiated a study to assess the magnitude of the potential threat to freighter airplanes from onboard cargo fires. As part of this study, a risk model was developed to assess the likely number of U.S.-registered freighter fire accidents through the year 2020 and the average annual cost due to their occurrence. The study focused on the potential fire threat from the bulk shipment of lithium batteries (primary and secondary) because they were likely contributors to two of the freighter fire accidents that occurred on U.S.-registered airplanes. For this reason, the risk model considered the potential threat from lithium batteries separately from other cargo. This report summarizes the risk model, explains the data and algorithms used, and explains how the model may be used. Subsequent phases of this study will address cost benefit ratios for various mitigation strategies.					
17. Key Words Cargo fire, Risk model, Lithium battery, Accident characteristics, Airplane damage			18. Distribution Statement This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161. This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov .		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 37	22. Price

TABLE OF CONTENTS

	Page
EXECUTIVE SUMMARY	ix
1. INTRODUCTION	1
2. RISK MODEL	1
3. FREIGHTER CARGO FIRE ACCIDENTS	2
4. FREIGHTER CARGO FIRE ACCIDENT RATES	5
4.1 Revenue Ton-Miles	5
4.1.1 Total RTM 1958 Through 2010	5
4.1.2 Division of RTM—Lithium Battery and Other Cargo	7
4.2 Accident Rates, Accident Rate Distributions, and Number of Accidents	10
5. ACCIDENT COSTS	13
5.1 Accident Characteristics	14
5.1.1 Probability of Controlled or Uncontrolled Accidents	14
5.1.2 Probability of an Accident Resulting in Collateral Damage	16
5.1.3 Assessment of Accident Characteristics	16
5.2 Crew Injuries	17
5.2.1 Proportion of the Crew Sustaining Fatal, Serious, and Minor/No Injuries	17
5.2.2 The Number of Crew Onboard	17
5.2.3 The Monetary Value Associated With Injuries	19
5.3 Airplane Damage	20
5.3.1 Airplane Value	20
5.3.2 The Monetary Value Associated With Airplane Damage	21
5.4 Cargo Damage	21
5.5 Collateral Damage	22
5.6 Total Damage Cost	23

6.	CONCLUSIONS	25
7.	REFERENCES	25

APPENDIX A—TITLE 14 CODE OF FEDERAL REGULATIONS 25.857 CARGO
COMPARTMENT CLASSIFICATION

LIST OF FIGURES

Figure		Page
1	Philadelphia Accident Switch	5
2	Assessment of the Annual Number of RTM Carried in Non-Class C Cargo Compartments per Annum for the U.S.-Registered Freighter Fleet—1958 Through 2010	6
3	Estimated Annual Number of Secondary Lithium Battery Cells Produced Worldwide	7
4	Assessment of the Annual Number of RTM Carried in Non-Class C Cargo Compartments per Annum for the U.S.-Registered Freighter Fleet—1958 Through 2020	10
5	χ^2 Distribution Switch	11
6	Predicted Number of U.S.-Registered Freighter Airplane Cargo Fire Accidents Through 2020	12
7	Confidence Range Switch	12
8	Predicted Average and 95 Percentile Range of the Number of Cargo Fire Accidents Through 2020	13
9	Cumulative Probability Distribution of the Probability That an Accident is Controlled	15
10	Example Determination of the Probability of an Accident Being Controlled	15
11	Weibull Distribution for Number of Crew in Each Weight Category	18
12	Relationship Between the 2010 List Price and the MTOW	21
13	Probability Distribution of the Monetary Value of Collateral Damage	23
14	Confidence Range in the Predicted Average Annual Accident Cost	24
15	Confidence Range in Annual Prediction of Average Accident Cost	24
16	Accident Cost Elements	25

LIST OF TABLES

Table		Page
1	Airplane Types in the 2010 U.S.-Registered Freighter Fleet	2
2	The RTM (2010) in Non-Class C Cargo Compartments by Airplane Type— All Cargo	7
3	The RTM in Non-Class C Compartments by Airplane Type—Battery and Non-Battery Cargo for 2010	8
4	Assessed Cumulative RTM in Non-Class C Compartments for the U.S.-Registered Freighter Fleet Through 2010—Battery and Non-Battery	9
5	Assessed Annual RTM in Non-Class C Cargo Compartments for the U.S.-Registered Freighter Fleet 2011 Through 2020—Battery and Non-Battery	9
6	Division of Fire-Related Accidents to U.S. Freighter Airplanes Over the Period 1958 Through 2010—Controlled vs Uncontrolled	14
7	Categorization of Accidents With Collateral or No Collateral Damage	16
8	Data Used to Determine Primary Damage for the Uncontrolled With No Collateral Damage Data Set (Example Only)	17
9	Airplane Weight Categories	18
10	Airplane Weight Categories by Airplane Type	19
11	Monetary Value of Injuries	19
12	Average Cargo Value per Flight	22
13	Monetary Value Used in the Assessment of Collateral Damage	22

LIST OF ACRONYMS

CAA	Civil Aviation Authority
CFR	Code of Federal Regulations
CSRTG	Cabin Safety Research Technical Group
DXB	Dubai International Airport
FAA	Federal Aviation Administration
FedEx	Federal Express
MAIS	Maximum abbreviated injury scale
MTOW	Maximum takeoff weight
NTSB	National Transportation Safety Board (USA)
RTM	Revenue ton-miles
UAE	United Arab Emirates
UK	United Kingdom
UPS	United Parcel Service
USD	United States Dollars

EXECUTIVE SUMMARY

Following the Boeing 747 freighter airplane accident on September 3, 2010, at Dubai International Airport in the United Arab Emirates, the Federal Aviation Administration, Transport Canada, and the United Kingdom Civil Aviation Authority initiated a study to assess the magnitude of the potential threat to freighter airplanes from onboard cargo fires.

As part of this study, a risk model was developed to assess the likely number of U.S.-registered freighter fire accidents through the year 2020 and the average annual cost due to their occurrence.

Five cargo fire accidents to U.S.-registered freighter airplanes were identified from the Cabin Safety Research Technical Group Accident Database over the period 1958 through 2010. These accidents were used as a basis for the determination of accident occurrence rates used by the risk model.

Particular attention was directed toward the potential fire threat from the bulk shipment of lithium batteries (primary and secondary), since it was considered that they likely contributed to two of the freighter fire accidents that occurred on U.S.-registered airplanes. For this reason, the risk model considered the potential threat from lithium batteries (primary and secondary) and other cargo separately.

This report supplements the risk model, which is constructed in Microsoft® Excel®. The report is structured to explain the data used by the risk model, its algorithms, and the way in which the model may be used.

Subsequent phases of this study will develop a model to predict likely cost benefit ratios for various mitigation strategies identified by the FAA and develop a risk and cost benefit model appropriate to the Canadian fleet.

1. INTRODUCTION.

Following the Boeing 747 freighter airplane accident on September 3, 2010, at Dubai International Airport in the United Arab Emirates¹, the Federal Aviation Administration (FAA) and Transport Canada initiated a study to assess the magnitude of the potential threat to freighter airplanes from onboard cargo fires.

The FAA, Transport Canada, and the United Kingdom (UK) Civil Aviation Authority (CAA), as part of this study, developed a risk model to assess the likely number of U.S.-registered freighter fire accidents through the year 2020 and the average annual cost due to their occurrence. Particular attention was directed toward the potential fire threat from the bulk shipment of lithium batteries (primary and secondary), since it was considered that they likely contributed to two of the freighter fire accidents that occurred on U.S.-registered airplanes. For this reason, the risk model considered the potential threat from primary lithium batteries, secondary lithium batteries, and other cargo separately.

This report is structured to explain the data² used by the risk model, its algorithms, and the way in which the risk model may be used.

Subsequent phases of this study will address the fire risk to the Canadian fleet and assess likely cost benefit ratios for various mitigation strategies.

2. RISK MODEL.

The risk model is based on the Monte Carlo simulation methodology, which uses statistical distributions derived from data on in-service airplanes and accidents.

In a Monte Carlo simulation, variables are randomly chosen based on their probability of occurrence. The variables are then combined to determine the required output—in this case, the number of U.S.-registered freighter cargo fire accidents likely to occur during the foreseeable future and the annual cost of such accidents.

The risk model was developed to allow user selection of certain criteria via the risk model control panel. For example, the user can select whether the risk model should consider the Philadelphia accident to be “Battery Related” or “Non-Battery Related.” The user is also able to select whether the χ^2 or the modified χ^2 distribution is used by the risk model and the confidence range displayed for the prediction of the future number of accidents.

By running the risk model many thousands of times, a distribution of the predicted number of accidents and the resultant annual cost can be generated.

¹See accident reference 20100903A in section 3 of this report.

²It should be noted that the number of significant figures contained within any data presented in this report is not indicative of the accuracy of the data. The number of figures contained within the data sets used are retained for ease of cross reference and to prevent rounding errors.

The data in the risk model are appropriate to the U.S.-registered freighter fleet in 2010. The airplane types are shown in table 1. Small turboprops were excluded from this study because they constitute an extremely small proportion of the revenue ton-miles (RTM) carried by the U.S.-registered freighter fleet.

Table 1. Airplane Types in the 2010 U.S.-Registered Freightier Fleet

Airplane Type
A-300
A-310
ATR42 and 72
B-727
B-737
B-747-100, 200, and 300
B-747-400
B-757
B-767-200
B-767-300
B-777
CV-580
DC-8
DC-9
DC-10
L-100
MD-11

3. FREIGHTER CARGO FIRE ACCIDENTS.

The Cabin Safety Research Technical Group (CSRTG) Accident Database [1] was searched to identify all cargo fire-related accidents on U.S.-registered cargo operations over the period 1967³ through 2010. The following criteria were used for the selection of accidents:

- U.S.-registered airplane (N registration)
- Cargo-only operation
- Fire-related accidents involving fire or smoke from the cargo compartment

Only airplane accidents conforming to the ICAO Annex 13 [2] definition were included in the analysis. The prevention of occurrences in which there were no serious or fatal injuries to personnel or any substantial damage to the airframe is unlikely to incur significant costs.

³Although the study period was from 1958 to 2010, reference 1 does not contain data prior to 1967.

The National Transportation Safety Board (NTSB) Database [3] and The Boeing Company also supplied a list of accidents involving cargo fires, including the following five cargo fire accidents to U.S.-registered airplanes from 1958 through 2010:

- Accident Reference: 20100903A
Date: September 03, 2010
Operator: United Parcel Service (UPS)
Airplane: B-747-44AF (Registration N571UP)
Location: Dubai, United Arab Emirates
Airplane Damage: Destroyed
Crew Injuries: All Fatal—Two Crew Members

“At about 7:45 pm local time (1545 UTC), United Parcel Service (UPS) Flight 6, a Boeing 747-400F (N571UP), crashed while attempting to land at Dubai International Airport (DXB), Dubai, United Arab Emirates (UAE). Approximately 45 minutes after takeoff, the crew declared an emergency due to smoke in the cockpit and requested a return to DXB. The two flight crew members were fatally injured. The airplane was being operated as a scheduled cargo flight from Dubai, UAE to Cologne, Germany.” (Source: NTSB DCA10RA092)

- Accident Reference: 20060207A
Date: February 7, 2006
Operator: UPS
Airplane: DC8 (Registration N748UP)
Location: Philadelphia, Pennsylvania, USA
Airplane Damage: Substantial
Crew Injuries: None

“Although the cause of the in-flight fire could not be determined in the UPS accident, the presence of a significant quantity of electronic equipment in the containers where the fire most likely originated led the Safety Board to closely examine safety issues involving the transportation of rechargeable lithium batteries on commercial aircraft, including batteries in airline passengers’ laptop computers and other personal electronic devices.” (NTSB Safety Recommendation January 7, 2008)

- Accident Reference: 20040427A
Date: April 27, 2004
Operator: Mountain Air Cargo
Airplane: F27-500 (Registration N715FE)
Location: Melo, Uruguay
Airplane Damage: Destroyed
Crew Injuries: None

“A FedEx flight operated by Mountain Air Cargo. The flight diverted after discovery of a fire in the cargo bay. The cause of the fire was unknown.”

- Accident Reference: 19960905B
Date: September 5, 1996
Operator: Federal Express Corporation (FedEx)
Airplane: DC10-10CF (Registration N68055)
Location: Newburgh/Stewart, New York, USA
Airplane Damage: Destroyed
Crew Injuries: None

“The National Transportation Safety Board determines that the probable cause of this accident was an in-flight cargo fire of undetermined origin.”

- Accident Reference: 19731103B
Date: November 3, 1973
Operator: Pan American World Airways
Airplane: B-707 (Registration N458PA)
Location: Boston, Massachusetts, USA
Airplane Damage: Destroyed
Crew Injuries: All Fatal—Three Crew Members

“About 30 minutes after the aircraft departed from JFK, the flight crew reported smoke in the cockpit. The flight was diverted to Logan International Airport where it crashed just short of runway 33 during final approach. Although the source of the smoke could not be established conclusively, the NTSB believes that the spontaneous chemical reaction between leaking nitric acid, improperly packaged and stowed and the improper sawdust packing surrounding the acid’s package initiated the accident sequence.”

For the majority of these accidents, the precise cause of the fire was not determined. However, it is known that for both the Dubai accident (accident reference 20100903A) and the Philadelphia accident (accident reference 20060207A), lithium batteries were being transported and could have contributed to the onboard fires that resulted in catastrophic events.

The risk model is based on these five accidents, which are categorized as either battery- or non-battery-related. For the Philadelphia accident, the risk model allows the user to select either the battery- or non-battery-related options. To identify this in the risk model, the user may select these options by clicking on the appropriate button on the Philadelphia Accident Switch on the model control panel, as shown in figure 1.

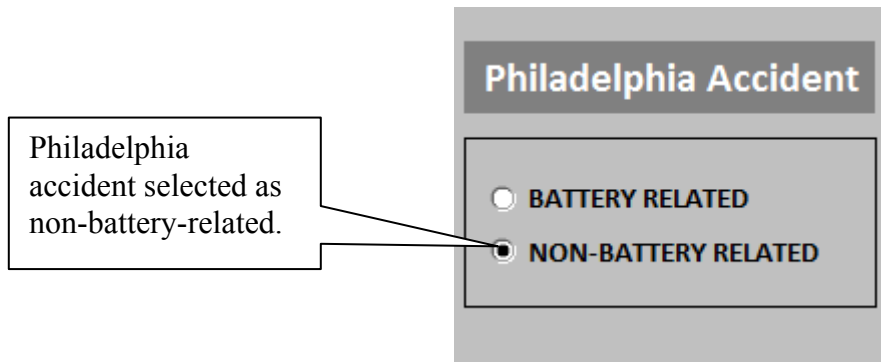


Figure 1. Philadelphia Accident Switch

4. FREIGHTER CARGO FIRE ACCIDENT RATES.

4.1 REVENUE TON-MILES.

The risk model is based on the assumption that the risk of a cargo fire accident occurring is a function of the RTM of the cargo. RTM was chosen over hours flown or number of flights because it is reasonable to assume that the probability of a cargo fire occurring should be related to the quantity of the cargo. RTM gives a representation of the quantity of cargo carried and is a usage value that is routinely recorded and used by the air transport industry.

Because the threat from cargo fires is limited to Class E⁴ and D⁵ cargo compartments (on the assumption that fire threats in Class C compartments are adequately accommodated by the current protection means), the proportion of the total RTM carried in these compartments must be determined.

4.1.1 Total RTM 1958 Through 2010.

Assessments of non-Class C RTM (i.e., Class E and D) were made for each airplane type in the U.S.-registered freighter fleet in 2008, 2009, and 2010 based, in part, on data contained in reference 4.

Using data contained in references 4 through 6, the annual total RTM for the U.S.-registered freighter fleet prior to 2008 was assessed. These totals were factored to determine the non-Class C RTM based on the proportions of the total derived from the 2010 data. For reference, the proportion of total RTM carried in non-Class C compartments was 80%. Based on these data sources, the best estimate of the annual non-Class C RTM accumulated by the U.S.-registered freighter fleet is shown in figure 2.

⁴See appendix A for cargo compartment classifications.

⁵There are a limited number of Class D cargo compartments on U.S.-registered airplanes. They are no longer accepted as adequate for newly certificated airplanes and, as such, are no longer specified in Title 14 Code of Federal Regulations 25.857. On this basis, it is conservatively assumed that the protection afforded by Class D compartments is to a similar level for Class E compartments.

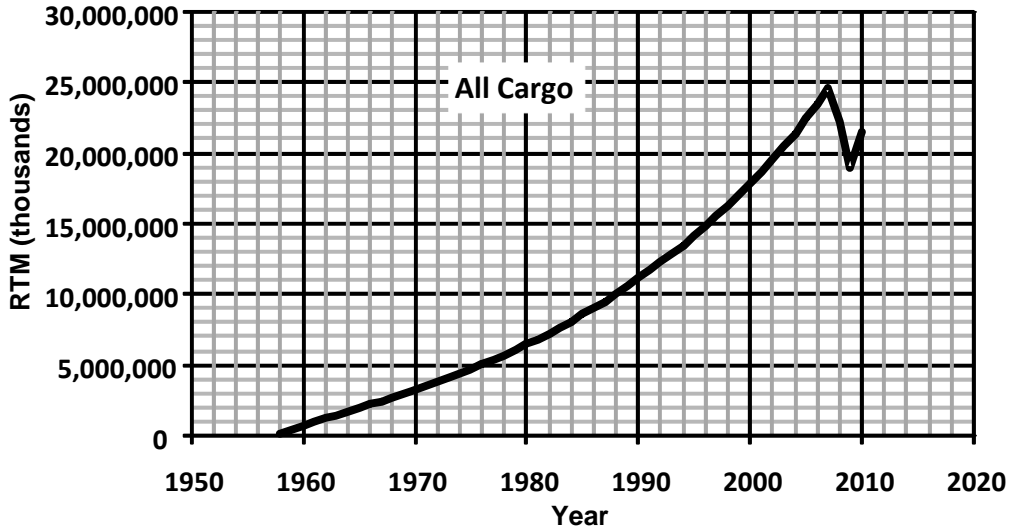


Figure 2. Assessment of the Annual Number of RTM Carried in Non-Class C Cargo Compartments per Annum for the U.S.-Registered Freighter Fleet—1958 Through 2010

Using the data illustrated in figure 2, the RTM carried by U.S.-registered freighter airplanes in non-Class C cargo compartments was assessed as follows:

- 518,716,612,124 RTM for the period 1958 through 2010
- 21,450,562,411 RTM for 2010

This total RTM, carried by U.S.-registered freighter airplanes in non-Class C cargo compartments, is divided into airplane types, as shown in table 2.

Table 2. The RTM (2010) in Non-Class C Cargo Compartments by Airplane Type—All Cargo

Airplane Type	RTM (2010)
A-300	1,576,654,045
A-310	284,581,190
ATR42 and 72	2,757,465
B-727	386,148,133
B-737	16,356,450
B-747-100, 200, and 300	2,084,601,533
B-747-400	4,330,981,395
B-757	824,387,992

Table 2. The RTM (2010) in Non-Class C Cargo Compartments by Airplane Type—All Cargo
(Continued)

Airplane Type	RTM (2010)
B-767-200	409,623,487
B-767-300	1,979,964,159
B-777	566,721,213
CV-580	6,932,577
DC-8	183,618,371
DC-9	6,631,049
DC-10	2,398,854,543
L-100	7,877,889
MD-11	6,383,870,922
Total	21,450,562,411

4.1.2 Division of RTM—Lithium Battery and Other Cargo.

Because accident rates had to be derived for both lithium battery fire-related accidents and those attributable to other cargo, the RTM in non-Class C cargo compartments was divided into these two cargo categories. All assessments relate to the bulk shipment of lithium batteries and may be conservative since the potential threat from the secondary shipment of batteries contained in electronic devices (laptops, cell phones, etc.) was not included.

Based on data contained in reference 7, the growth in production of secondary lithium battery cells was assessed. Figure 3 shows the estimated annual number of secondary lithium battery cells produced worldwide from 1995 to 2010, with a future extrapolation through 2020.

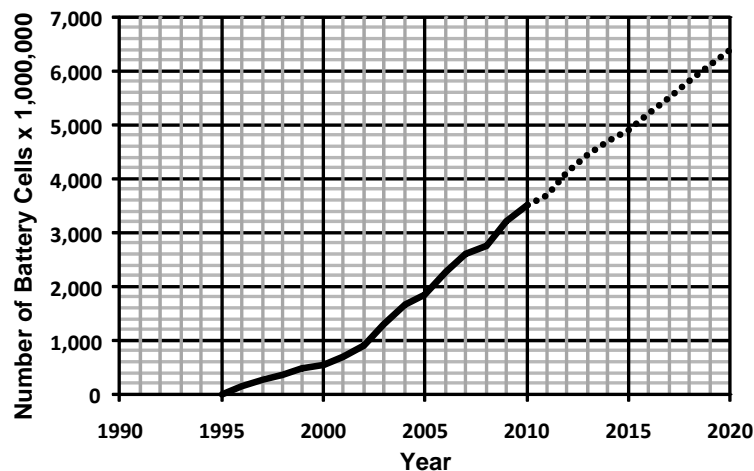


Figure 3. Estimated Annual Number of Secondary Lithium Battery Cells Produced Worldwide

The data shown in figure 3 is not currently available for primary lithium batteries. However, based on information contained in reference 8, it was estimated that primary lithium battery production was approximately 25% of the secondary lithium batteries. Therefore, the annual number of secondary lithium batteries produced worldwide, as indicated in figure 3, may be multiplied by 1.25 to obtain an estimate of the total number of lithium batteries (primary and secondary) produced annually.

It was further assumed that 50% of the world's lithium battery cell production is carried by the U.S.-registered freighter fleet. The annual lithium battery RTM carried on U.S.-registered freighter airplanes was estimated by multiplying the number of cells carried, by the weight of a typical cell¹ and the average stage length of a flight². Based on this assessment, in 2010, battery RTM accounted for 0.77% of the total RTM. On the assumption that battery RTM accounts for 0.77% of the total RTM for all airplane types, the battery and non-battery cargo assessed for each airplane type would be as shown in table 3.

Table 3. The RTM in Non-Class C Compartments by Airplane Type—Battery and Non-Battery Cargo for 2010

Airplane Type	Battery Cargo	Non-Battery Cargo	All Cargo
A-300	12,092,623	1,564,561,422	1,576,654,045
A-310	2,182,681	282,398,508	284,581,190
ATR42 and 72	21,149	2,736,316	2,757,465
B-727	2,961,679	383,186,454	386,148,133
B-737	125,451	16,230,999	16,356,450
B-747-100, 200, and 300	15,988,479	2,068,613,055	2,084,601,533
B-747-400	33,217,765	4,297,763,630	4,330,981,395
B-757	6,322,892	818,065,100	824,387,992
B-767-200	3,141,731	406,481,757	409,623,487
B-767-300	15,185,931	1,964,778,228	1,979,964,159
B-777	4,346,639	562,374,574	566,721,213
CV-580	53,171	6,879,405	6,932,577
DC-8	1,408,316	182,210,054	183,618,371
DC-9	50,859	6,580,190	6,631,049
DC-10	18,398,737	2,380,455,806	2,398,854,543
L-100	60,422	7,817,467	7,877,889
MD-11	48,963,019	6,334,907,902	6,383,870,922
Total	164,521,543	21,286,040,868	21,450,562,411

¹The common, cylindrical 18650 lithium battery cell, weighing 0.1 lb, was considered typical for the purpose of this assessment. This battery cell is widely used in laptop battery packs and other consumer items.

²The average stage length for U.S.-registered freighter airplanes in 2010 was assessed to be 2116 miles.

the years 1958 through 2010. The battery RTM was subtracted from the total RTM to determine the non-battery RTM, appropriate to non-Class C cargo compartments, for each year from 1958 through 2020. The cumulative RTM for both battery and non-battery cargo through 2010 was derived by summing the results for each preceding year, as shown in table 4. Table 5 shows the predicted RTM in non-Class C cargo compartments for both battery and non-battery cargo for each year from 2011 through 2020.

Table 4. Assessed Cumulative RTM in Non-Class C Compartments for the U.S.-Registered Freighter Fleet Through 2010—Battery and Non-Battery

Cumulative Battery RTM Through 2010	Cumulative Non-Battery RTM Through 2010
1,056,698,370	517,659,913,754

Table 5. Assessed Annual RTM in Non-Class C Cargo Compartments for the U.S.-Registered Freighter Fleet 2011 Through 2020—Battery and Non-Battery

Date	Annual Battery RTM	Annual Non-Battery RTM
2011	173,922,774	23,274,071,439
2012	192,725,236	24,347,631,463
2013	209,177,391	25,476,375,423
2014	220,928,930	26,666,047,153
2015	230,330,161	27,917,914,908
2016	244,432,007	29,228,755,059
2017	258,533,854	30,607,323,816
2018	272,635,700	32,057,932,799
2019	286,737,547	33,585,118,665
2020	300,839,394	35,193,674,092
Totals	2,390,262,994	288,354,844,818

The assessed annual number of RTM carried in non-Class C cargo compartments over the period 1958 through 2020 is shown in figure 4.

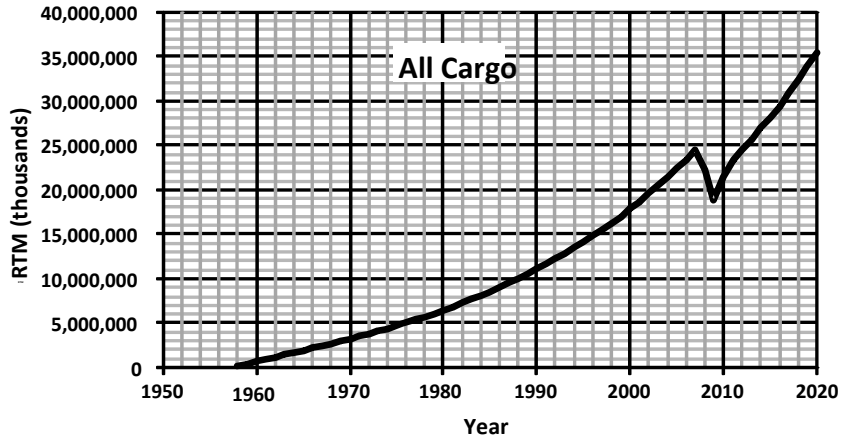


Figure 4. Assessment of the Annual Number of RTM Carried in Non-Class C Cargo Compartments per Annum for the U.S.-Registered Freighter Fleet—1958 Through 2020

4.2 ACCIDENT RATES, ACCIDENT RATE DISTRIBUTIONS, AND NUMBER OF ACCIDENTS.

The average accident rate attributable to cargo fires may be determined using the following formula.

$$Accident\ Rate = \frac{Number\ of\ Cargo\ Fire\ Accidents}{Cumulative\ RTM}$$

This formula may be used to determine the average accident rates attributable to battery or non-battery cargo by dividing the number of accidents attributable to each cause by the associated cumulative RTM given in table 4.

Therefore, assuming that the Philadelphia accident was related to lithium batteries, the associated accident rates may be derived by dividing the applicable number of accidents by the associated cumulative RTM up to and including 2010.

$$Battery\ Accident\ Rate = 2 \div 1,056,698,370 = 1.89 \times 10^{-9} \text{ per RTM}$$

$$Non-Battery\ Accident\ Rate = 3 \div 517,659,913,754 = 5.80 \times 10^{-12} \text{ per RTM}$$

However, with such small data sets, it is more realistic to develop distributions that indicate a confidence level in a range of accident rates rather than determining an average value.

The χ^2 distribution may be used to derive the confidence level in any given accident rate based on the number of accidents experienced over a given time period. Two accident rate distributions are derived using the χ^2 distribution; one for battery fire accidents and the other for non-battery fire accidents. Using the RTM values given in table 4 and the number of battery- and non-battery-related fire accidents, probability distributions may be derived for the associated accident rates.

Although the χ^2 distribution has a sound mathematical basis, it tends to give answers that are more pessimistic than may be expected. Therefore, the risk model provides an option that allows the user to select a designated switch (shown in figure 5) that modifies the χ^2 distribution to provide confidence ranges closer to what may be expected. This modifier multiplies the accident rate derived from the χ^2 distribution by $x/(x+1)$; where x is the number of occurrences experienced (in this case, the number of accidents).

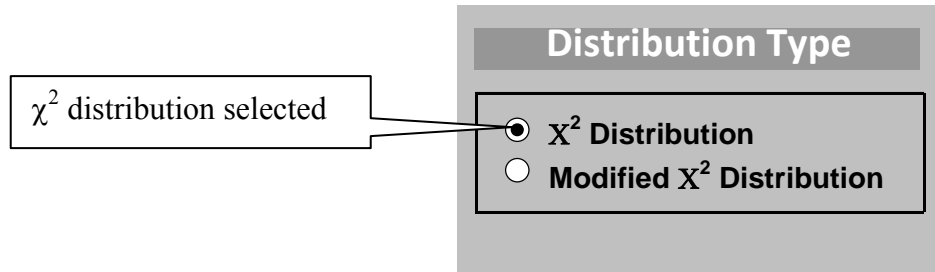


Figure 5. χ^2 Distribution Switch

At each iteration of the risk model, random selections are made on the χ^2 distribution (or the modified χ^2 distribution, if selected) to derive an accident rate. This process is performed for both the battery fire and the non-battery fire accident rates. The number of battery fire accidents per year and the number of non-battery fire accidents per year are derived by simply multiplying the derived accident rates by the appropriate RTM. The RTM for battery and non-battery cargo is shown in table 5 for 2011 through 2020.

The average number of accidents that can be expected over a given period may be assessed by multiplying the RTM for the period by the associated accident rate.

For example, the expected number of battery fire accidents over the period 2011 through 2020 would be

$$\begin{aligned} &\text{Battery Accident Rate} \times \text{Battery RTM 2011 through 2020} \\ &= 1.89 \times 10^{-9} \times 2,390,262,994 \cong 4.5 \text{ accidents} \end{aligned}$$

The total number of cargo fire accidents in any 1 year, or range of years, is the sum of the predicted number of battery- and non-battery-related accidents over the specified period.

The process of randomly selecting the χ^2 distributions and multiplying by the appropriate RTM is repeated 10,000 times to derive a distribution of the annual predicted number of accidents for each year from 2011 through 2020. The average prediction is derived for each year through 2020. These predicted number of accidents are sequentially added to the five accidents up to year 2010 to derive a prediction of the cumulative number of accidents through 2020, as shown by the bold curve in figure 6.

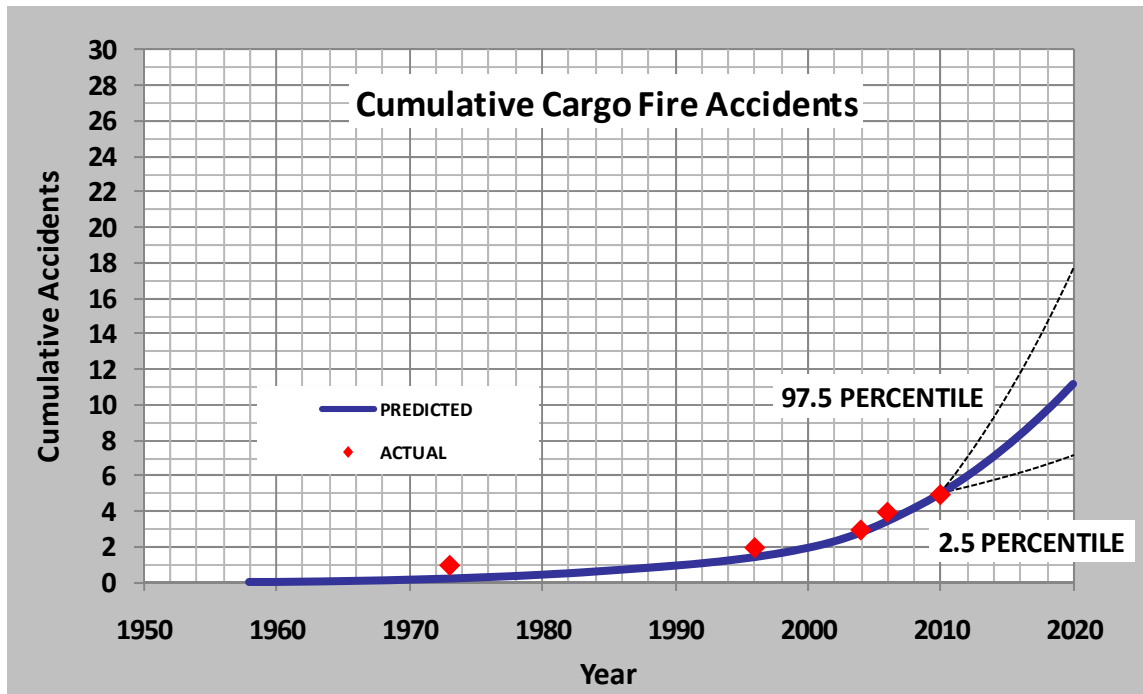


Figure 6. Predicted Number of U.S.-Registered Freighter Airplane Cargo Fire Accidents Through 2020

The risk model prediction of the annual number of accidents for each year from 2011 through 2020 allows a confidence range to be established, as shown in figure 6. Because this confidence range is variable, the user may select a confidence range using a designated switch, as shown in figure 7. (For example, the figure 6 predictions are based on the modified χ^2 distribution assuming that the Philadelphia accident was attributable to a lithium battery fire.)

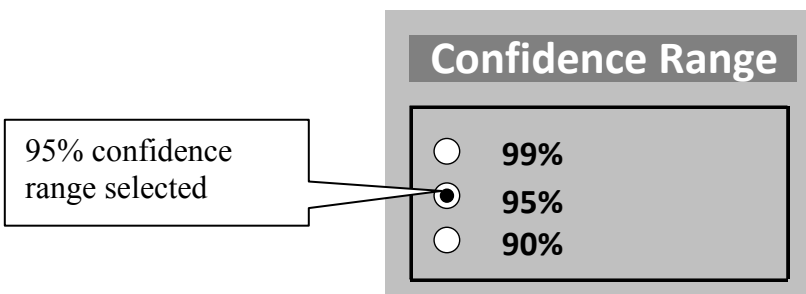


Figure 7. Confidence Range Switch

Figure 8 shows the average prediction of the number of cargo fire accidents from 2011 through 2020 divided into those accidents caused by battery and non-battery cargo. Also shown in figure 8 is the 95 percentile range (from the 2.5 percentile to the 97.5 percentile) of the predicted total number of accidents from 2011 through 2020.

ACCIDENTS PREDICTED OVER 10 YEARS (2011 - 2020)			
	2.5	Average	97.5
Battery Fire Accidents		4.5	
Non-Battery Fire Accidents		<u>1.7</u>	
Total Accidents	2.2	6.2	12.8

Figure 8. Predicted Average and 95 Percentile Range of the Number of Cargo Fire Accidents Through 2020

The predictions shown in figure 8 are based on the modified χ^2 distribution, assuming that the Philadelphia accident was attributable to a lithium battery fire.

These predictions do not account for suppression systems that may have been fitted to the main cargo decks of U.S.-registered freighter airplanes or any other means that may have been adopted to mitigate fires. They are also very dependent on the future extrapolation of RTM.

5. ACCIDENT COSTS.

The annual cost of cargo fire accidents on U.S.-registered freighter airplanes is the predicted number of accidents per year multiplied by the cost per accident.

$$\frac{Cost}{Year} = \frac{Accidents}{RTM} \times \frac{RTM}{Year} \times \frac{Cost}{Accident} \quad (1)$$

These annual costs are derived separately for battery and non-battery cargo for each airplane type over the period 2011 through 2020. The accident rates for battery and non-battery cargo are distributions and are derived as described in section 4.2. The RTM per year for battery and non-battery cargo is a fixed value for each airplane type, as specified in table 5.

The costs per accident are determined separately for each airplane type based on the assessed costs associated with the following areas:

- Crew injuries
- Airplane damage
- Cargo damage
- Collateral damage (damage to persons and property on the ground)

These costs per accident will be a separate distribution for each airplane type.

The extent of the damage and injuries incurred is a function of the nature or characteristics of the accident. Section 5.1 describes the manner in which the risk model assesses the likely characteristics of accidents.

5.1 ACCIDENT CHARACTERISTICS.

Freighter fire accidents are categorized as controlled or uncontrolled accidents. Controlled accidents are those in which after the fire event, the flight crew had some degree of control to land the airplane. Uncontrolled accidents are those in which after the fire event, the flight crew lost control in flight and the airplane impacted with the ground. In instances where control is lost on final approach and the airplane is stopped within the airport perimeter, the accident is considered controlled.

A distinction between these two categories is required since uncontrolled accidents are more likely to incur collateral damage and to result in more severe consequences to the airplane and occupants than controlled accidents.

Furthermore, accidents involving ground collateral damage are also likely to affect the extent of the primary damage (crew injuries, airplane damage, and cargo damage).

5.1.1 Probability of Controlled or Uncontrolled Accidents.

Data for the cargo fire accidents of the U.S.-registered freighter fleet over the period 1958 through 2010, as described in section 3, were assessed to determine whether the accidents were controlled or uncontrolled. All were assessed to be controlled except for the B-747 accident on September 3, 2010, which was considered an uncontrolled accident.

For future accidents, the proportion that are likely to be controlled (or uncontrolled) may be assessed, from the division of accidents shown in table 6, for any particular confidence level, by using the binomial distribution.

Table 6. Division of Fire-Related Accidents to U.S. Freighter Airplanes Over the Period 1958 Through 2010—Controlled vs Uncontrolled

Controlled	Uncontrolled
4	1

Using the binomial distribution, figure 9 shows the cumulative probability distribution for the probability of an accident being controlled.

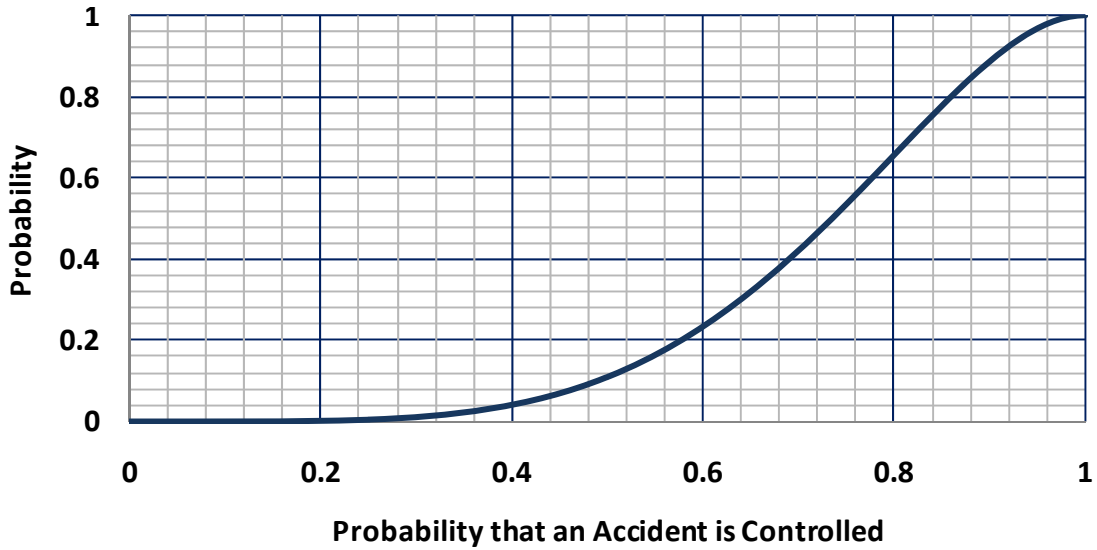


Figure 9. Cumulative Probability Distribution of the Probability That an Accident is Controlled

The risk model randomly selects a number from the vertical axis of the distribution shown in figure 9 and derives a probability that the accident is controlled.

An example of this determination is shown in figure 10. In this example, a random number generates a value of 0.4. This value equates to a probability of 0.69 that the accident is controlled. The risk model then selects a second random number. If its value is less than 0.69, the accident is deemed controlled. If it is greater than 0.69, the accident is deemed uncontrolled at this iteration of the risk model.

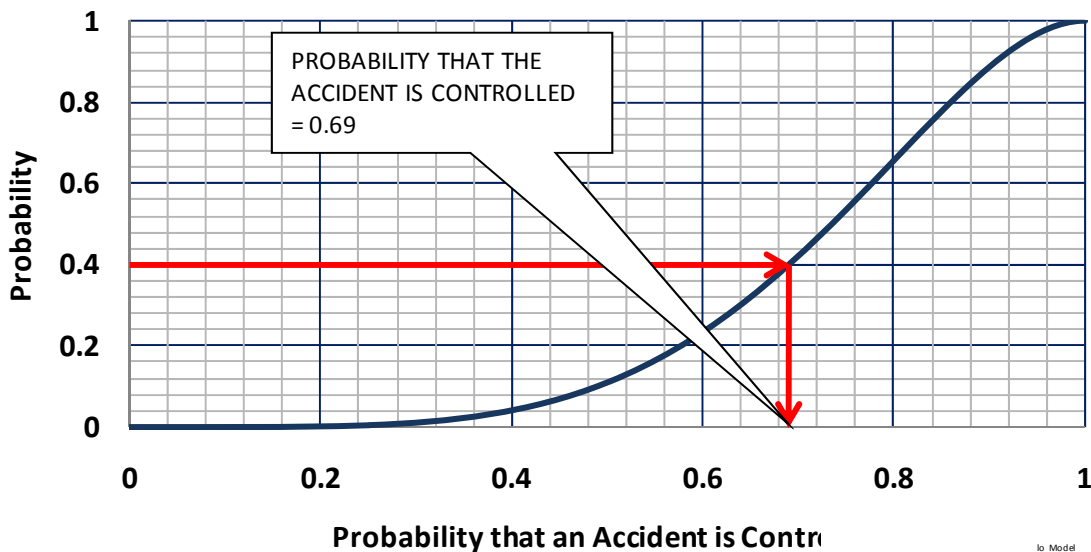


Figure 10. Example Determination of the Probability of an Accident Being Controlled

5.1.2 Probability of an Accident Resulting in Collateral Damage.

The probability of the accident resulting in collateral damage is expected to be different for controlled and uncontrolled accidents. The CSRTG Accident Database [1] was searched for accidents to passenger- and cargo-carrying airplanes that had similar in-flight events and impact sequences to what may be expected from an in-flight cargo fire. One hundred and seventy-eight accidents to passenger- and cargo-carrying airplanes were identified and categorized as controlled or uncontrolled.

Collateral damage to buildings, airplanes, or persons on the ground was determined for each accident. The accidents were then categorized as shown in table 7.

Table 7. Categorization of Accidents With Collateral or No Collateral Damage

	Controlled	Uncontrolled	Total
Collateral damage	1	9	10
No collateral damage	71	97	168
Total	72	106	178

Based on these data, there is typically a 1 in 72 chance of a controlled accident resulting in collateral damage, i.e., a probability of approximately 0.014. Similarly, for an uncontrolled accident, the probability of sustaining collateral damage may be expected 9 in 106, or approximately 0.085. However, the Monte Carlo simulation uses an assessment of the likely variation in these probabilities based on the binomial distribution using a similar process to that described in section 5.1.1 for the determination of an accident being controlled or uncontrolled.

5.1.3 Assessment of Accident Characteristics.

At each iteration of the risk model, and separately for each airplane type, two random numbers are generated. These random numbers determine whether the accident is controllable or uncontrollable, as described in section 5.1.1.

The risk model then determines whether the accident results in collateral damage. This determination is made by randomly selecting binomial distributions of the probability of collateral damage, as described in section 5.1.2.

The 178 accidents discussed in section 5.1.2, which had accident sequences similar to what would be expected in an in-flight cargo fire, were placed into four data sets:

- Controlled with no collateral damage
- Controlled with collateral damage
- Uncontrolled with no collateral damage
- Uncontrolled with collateral damage

In each data set, the accidents were ranked in order of severity in terms of the proportion of injuries sustained by the crew (Fatal and Serious) and the damage sustained by the airplane and cargo. Table 8 illustrates the nature of the data used to determine primary damage (i.e., crew injuries, airplane damage, and cargo damage).

Table 8. Data Used to Determine Primary Damage for the Uncontrolled With No Collateral Damage Data Set (Example Only)

Accident Number	Proportion of Crew			Airplane Damage	Assessed Proportion of Cargo Damage
	Fatal Injuries	Serious Injuries	Minor/No Injuries		
1	1	0	0	Destroyed	1
2	0.8	0.2	0	Destroyed	1
3	0.6	0.3	0.1	Destroyed	1
4	0.5	0.5	0	Substantial	1
⋮	⋮	⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮	⋮	⋮
98	0	0	1.0	Minor	0.5

5.2 CREW INJURIES.

The cost per accident incurred from crew injuries is calculated from the product of:

- The proportion of the crew sustaining Fatal, Serious, and Minor/No injuries
- The number of crew onboard
- The monetary value associated with the injuries

5.2.1 Proportion of the Crew Sustaining Fatal, Serious, and Minor/No Injuries.

The proportion of the crew sustaining Fatal, Serious, and Minor/No injuries is determined by randomly selecting the appropriate accident data set allocated by the risk model, as described in section 5.1.3.

5.2.2 The Number of Crew Onboard.

Data relating to the distribution of the number of crew⁸ by airplane type are not currently available; however, data are available for freighter airplanes by airplane weight category. The freighter airplanes considered in this study have been assigned a weight category based on the subdivisions of maximum takeoff weights (MTOW), as shown in table 9.

⁸ The number of crew includes all personnel onboard.

Table 9. Airplane Weight Categories

Weight Category	Airplane MTOW (lb)
B	12,500 to 100,000
C	100,000 to 250,000
D	250,000 to 400,000
E	Greater than 400,000

The distribution of the number of crew onboard for each airplane weight category was based on data for freighter airplanes contained in reference 1. Only U.S.-registered freighter airplanes, type-certificated to Title 14 Code of Federal Regulations (CFR) Part 25 and operating under 14 CFR Part 121, were selected from the database. The extracted data were assumed to follow Weibull distributions, which are shown in figure 11.

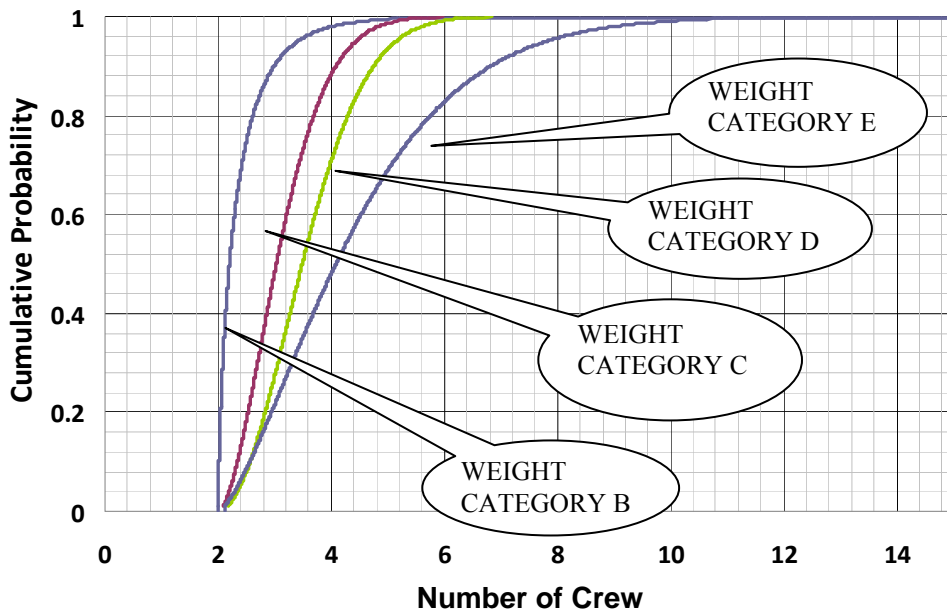


Figure 11. Weibull Distribution for Number of Crew in Each Weight Category

The weight categories of each freighter airplane type considered in this study are shown in table 10.

Table 10. Airplane Weight Categories by Airplane Type

Airplane Type	Weight Category
A-300	D
A-310	D
ATR42 and 72	B
B-727	C
B-737	C
B-747-100, 200, and 300	E
B-747-400	E
B-757	C
B-767-200	D
B-767-300	E
B-777	E
CV-580	B
DC-8	D
DC-9	C
DC-10	E
L-100	C
MD-11	E

5.2.3 The Monetary Value Associated With Injuries.

Table 11 shows the monetary value associated with the predicted injuries to crewmembers, which is based on data obtained from the FAA [9]. Serious injuries are assigned a monetary value of 2.76 million U.S. dollars (USD). This is the average value for injuries classified as Severe (maximum abbreviated injury scale (MAIS) 4) and Critical (MAIS 5), based on the reference 9 data.

Table 11. Monetary Value of Injuries

Injury Severity	Monetary Value (Millions USD)
Fatal	5.8
Serious	2.76

At each iteration of the model and for each airplane type, the number of crew onboard the airplane is determined by randomly selecting the distribution of crew numbers appropriate to the airplane weight category. How the proportion of the crew sustaining Fatal, Serious, and

Minor/No injuries is determined is described in section 5.1.3, and the cost of these injuries is determined using the values shown in table 11.

For example, to determine the crew injury costs for accident number 4 in table 8 for a freighter airplane with four crewmembers would be calculated as follows:

$$\begin{aligned} &0.5 \times 4 \times 5.8 + 0.5 \times 4 \times 2.76 \text{ million USD} \\ &= 11.6 + 5.52 \text{ million USD} \\ &= 17.12 \text{ million USD} \end{aligned}$$

5.3 AIRPLANE DAMAGE.

Airplane damage is a function of the value of the airplane and the extent of the damage sustained during the accident.

5.3.1 Airplane Value.

Official valuations for the freighter airplanes in the U.S.-registered freighter fleet were unavailable. Individual airplane valuations were, therefore, estimated based on airplane type and age. All U.S.-registered freighter airplanes in this study were identified, and their age was determined based on the date of first delivery.

For airplane types still in production, the residual value of each airplane was based on its 2010 list price and reduced using a compound rate of 8% per year of age.

For airplane types that are no longer in production, an artificial 2010 list price was estimated based on the MTOW. The relationship between the 2010 list price and the MTOW was derived from the manufacturer's data and is shown in figure 12. The residual value of each airplane was based on its artificial 2010 list price, as determined from the trend line in figure 12. Again, depreciation was applied at a compound rate of 8% per year of age.

Distributions of estimated residual values were, thus, obtained for all U.S.-registered freighter airplane types considered in this study.

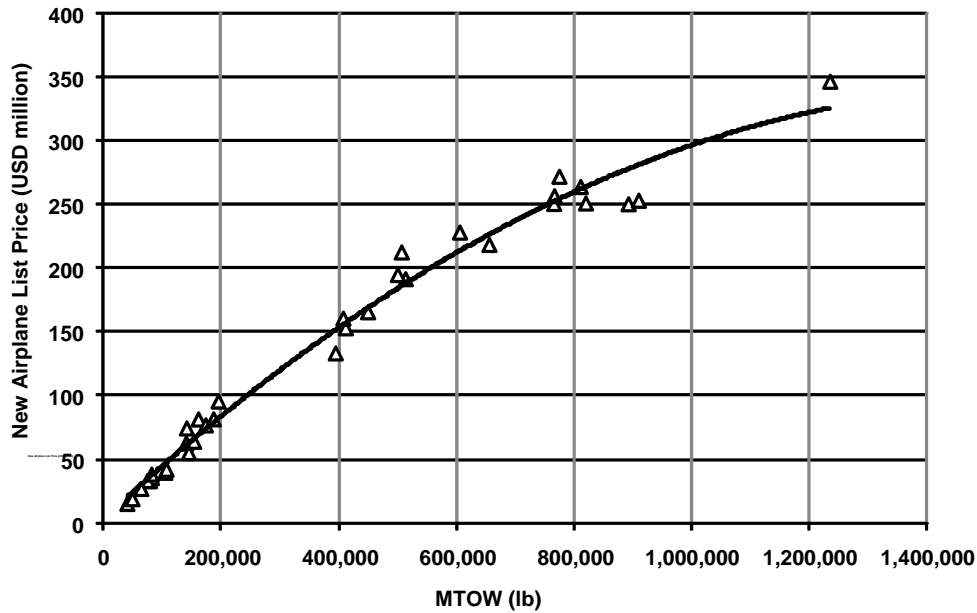


Figure 12. Relationship Between the 2010 List Price and the MTOW

5.3.2 The Monetary Value Associated With Airplane Damage.

The airplane damage is determined by randomly selecting the appropriate accident data set allocated by the model, as described in section 5.1.3.

5.4 CARGO DAMAGE.

Based on reference 3, the average cargo value per ton was determined to be \$63,104⁹. The average number of tons of cargo carried per flight in 2010 was assessed for each airplane type based on data contained in reference 3. Using these data, the average cargo value per flight for each airplane type is shown in table 12.

Cargo damage is assessed in a similar manner to airplane damage. The cargo value appropriate to the airplane type is simply multiplied by the assessed proportion of cargo damage, determined by randomly selecting the appropriate accident data set allocated by the risk model (see section 5.1.3) to obtain a monetary value.

For example, the cargo damage costs for accident number 98 in table 8 for a DC-8 airplane would be calculated as follows:

$$0.5 \times 1.1 \text{ million USD} = 0.55 \text{ million USD}$$

⁹ 2007 data escalated at 2% per annum to 2010 levels.

Table 12. Average Cargo Value per Flight

Airplane Type	Average Cargo Value Per Flight (Millions USD 2010)
A-300	1.8
A-310	0.8
ATR 42 and 72	0.2
B-727	0.7
B-737	0.4
B-747-100, 200, and 300	2.1
B-747-400	2.9
B-757	0.9
B-767-200	0.9
B-767-300	1.4
B-777	2.1
CV-580	0.1
DC-8	1.1
DC-9	0.1
DC-10	2.6
L-100	0.4
MD-11	2.3

5.5 COLLATERAL DAMAGE.

It is assumed that the values of collateral damage resulting from an accident to a freighter airplane are similar to those for a passenger airplane. The collateral damage value was assessed from passenger and freighter airplane accidents that had similar in-flight events and impact sequences to what would be expected from an in-flight cargo fire. The total monetary value for each accident was determined based on the data contained in table 13. These values were based on those contained in reference 9 and advice from the FAA Office of Aviation Policy and Plans.

Table 13. Monetary Value Used in the Assessment of Collateral Damage

Damage	Monetary Value (Millions USD)
Fatal injury	5.8
Serious injury	2.76
Large buildings	5.0
Small buildings	0.3

The assessed collateral damage values for each accident were arranged in increasing level of monetary value and plotted as a cumulative Weibull distribution, as shown in figure 13.

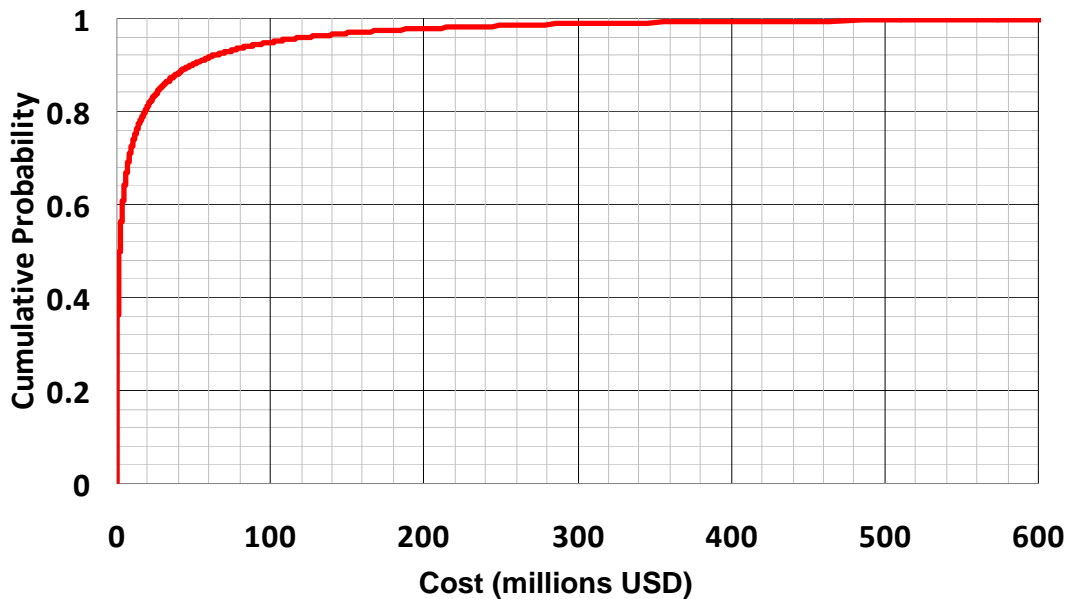


Figure 13. Probability Distribution of the Monetary Value of Collateral Damage

For accidents deemed to result in collateral damage, as determined by the process described in section 5.1.3, the risk model selects a random number for each iteration and for each airplane type. This number is used to select the probability distributions of monetary values of collateral damage shown in figure 13.

For accidents deemed not to result in collateral damage, the risk model returns a zero value for collateral damage.

5.6 TOTAL DAMAGE COST.

The total damage cost per accident is the sum of the following costs:

- Crew injuries
- Airplane damage
- Cargo damage
- Collateral damage

The resultant value is derived for each iteration of the risk model and for each airplane type to determine a distribution of the cost per accident. The distribution of the annual cost is then derived for each airplane type using equation 1 shown in section 5. At each iteration of the risk model, the annual cost is summed for all airplane types to derive the distribution of the total damage cost per annum for the entire U.S.-registered freighter fleet.

All costs are derived at 2010 values. However, due to changes in the RTM for both battery cargo and non-battery cargo, the predicted annual cost distributions will change. The risk model assesses these costs, at 2010 values, for the years 2011 through 2020, as well as any range of years in between. Figure 14 shows the annual prediction of accident cost over the period 2011 through 2020 (39.5 million USD) together with its confidence range. For the example shown in figure 14, there is a 95% rate of confidence that the accident costs will not exceed 65 million USD. The date range for the average prediction of annual cost and its associated confidence range may be varied by using the year range drop-down tool shown in figure 14.

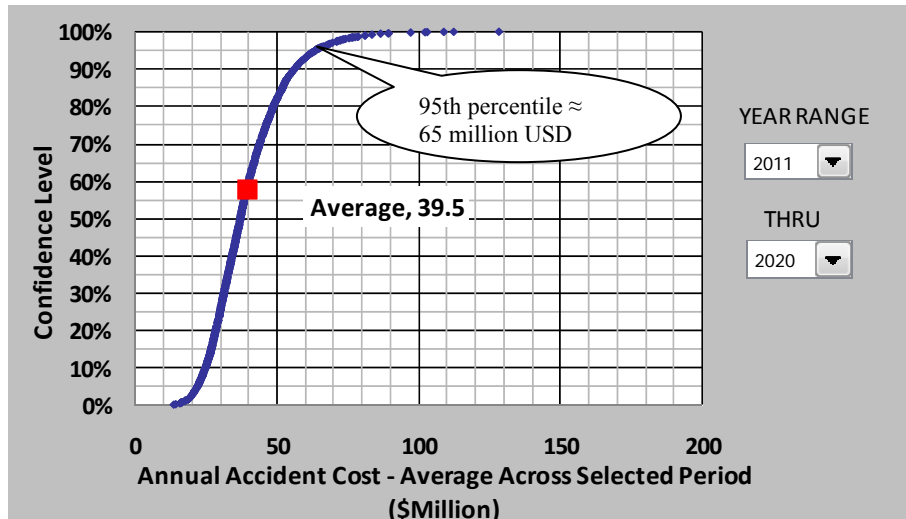


Figure 14. Confidence Range in the Predicted Average Annual Accident Cost

The risk model also displays the predicted average annual accident cost for each year from 2011 through 2020, as shown in figure 15.

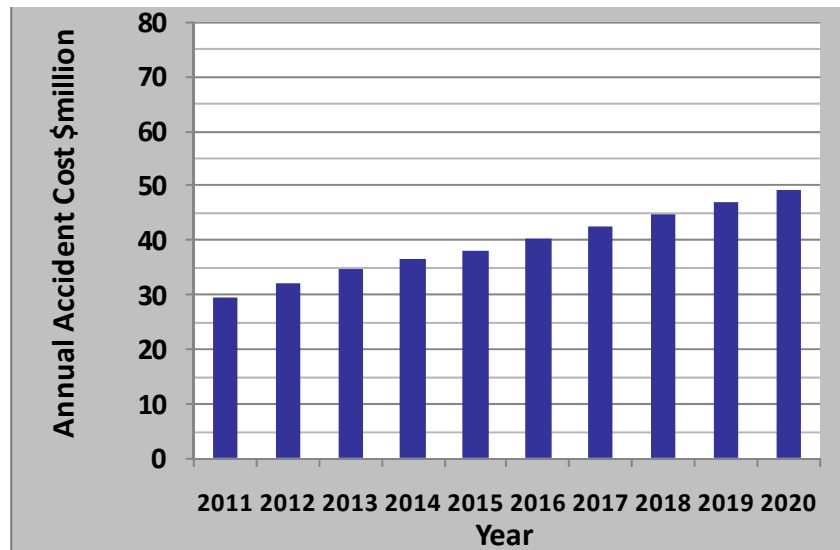


Figure 15. Confidence Range in Annual Prediction of Average Accident Cost

The risk model also determines the average accident cost elements (e.g., airplane damage costs, crew injury costs, cargo damage costs, and collateral damage costs) and presents them as a pie chart, as shown in figure 16.

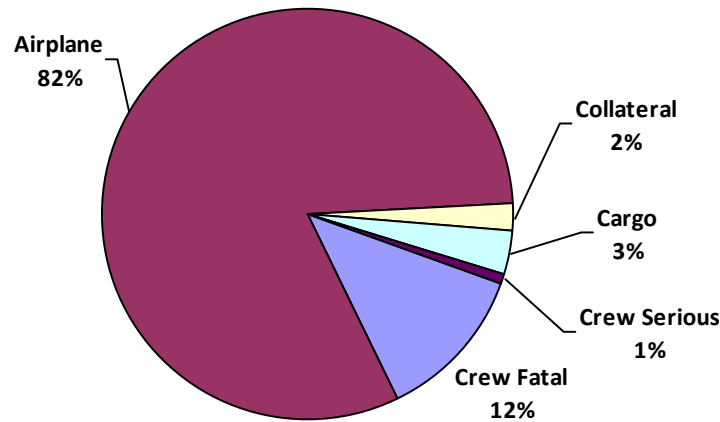


Figure 16. Accident Cost Elements

6. CONCLUSIONS.

The objective of this phase of the project was to develop a risk model prediction of future cargo fire accidents and accident costs pertinent to U.S.-registered freighter airplanes. It is considered that this has been achieved and that the risk model predictions are reasonable, although the limited number of accidents contained in the data set results in a large range in the prediction of future accidents. The risk model predictions are highly influenced by the future prediction of revenue ton-miles (RTM), which are, by necessity, based on extrapolations from past data. Any significant changes in the RTM accumulated by the U.S.-registered freighter fleet, in subsequent years, should be evaluated to consider whether the longer-term predictions of RTM used in the risk model need to be changed. Furthermore, the Federal Aviation Administration (FAA) has suggested that RTMs may not be the best basis for the prediction of cargo fire accidents and a measure of utilization related to number of flights and quantity of cargo might produce more accurate predictions.

Subsequent phases of this project will involve the development of a model aimed at estimating the cost and benefit that might be afforded by certain mitigation strategies identified by the FAA. Models will be developed for both the U.S. and Canadian fleet. Further consideration may also need to be given to the sensitivity of the model outputs to variations in the input data.

7. REFERENCES.

1. RGW Cherry & Associates Limited, *The Cabin Safety Research Technical Group Accident Database*, prepared for Transport Canada, the Federal Aviation Administration, and the UK Civil Aviation Authority, United Kingdom, January 2011, <http://www.rgwcherry-adb.co.uk/> (last visited July 21, 2011).

2. ICAO Annex 13, "Aircraft Accident and Incident Investigations," tenth edition, July 2010.
3. The National Transportation Safety Board Accident Database, <http://www.ntsb.gov/> (last visited July 21, 2011).
4. The U.S. Department of Transportation, Research and Innovative Technology Administration, Bureau of Transportation Statistics, <http://www.bts.gov> (last visited July 21, 2011).
5. RGW Cherry & Associates Limited, "A Cost-Benefit Analysis for the Installation of Fire Suppression Systems in Cargo Compartments of Cargo Airplanes," FAA report DOT/FAA/AR-09/17, April 2009.
6. Federal Aviation Administration, FAA Aerospace Forecast 2008-2025, 2008, http://www.faa.gov/data_research/aviation_forecasts/2009-2025/ (last visited July 21, 2011).
7. Hideo, T., "Safety and Transportation Issues—Lithium Batteries," *Proceedings of the ICAO Working Group on Lithium Batteries*, October 4-5, 2007, Montreal, Canada, International Civil Aviation Organization, Folio 9, Cited in: Klein, V.
8. Saxman, D., "Lithium Batteries: Markets & Materials," BCC Research Market Forecasting, United States, July 2007, <http://www.bccresearch.com/report/lithium-batteries-markets-materials-fcb028e.html> (last visited July 21, 2011).
9. Federal Aviation Administration, "Revised Departmental Guidance: Treatment of the Value of Preventing Fatalities and Injuries in Preparing Economic Analyses," February 2008, http://www.faa.gov/regulations_policies/policy_guidance/benefit_cost (last visited July 21, 2011).

APPENDIX A—TITLE 14 CODE OF FEDERAL REGULATIONS 25.857 CARGO
COMPARTMENT CLASSIFICATION

- Title 14 Code of Federal Regulations (CFR) 25.857 Regulation – Current Standard

“(a) *Class A*. A Class A cargo or baggage compartment is one in which—

(1) The presence of a fire would be easily discovered by a crewmember while at his station; and

(2) Each part of the compartment is easily accessible in flight.

(b) *Class B*. A Class B cargo or baggage compartment is one in which—

(1) There is sufficient access in flight to enable a crewmember to effectively reach any part of the compartment with the contents of a hand fire extinguisher;

(2) When the access provisions are being used, no hazardous quantity of smoke, flames, or extinguishing agent, will enter any compartment occupied by the crew or passengers;

(3) There is a separate approved smoke detector or fire detector system to give warning at the pilot or flight engineer station.

(c) *Class C*. A Class C cargo or baggage compartment is one not meeting the requirements for either a Class A or B compartment but in which—

(1) There is a separate approved smoke detector or fire detector system to give warning at the pilot or flight engineer station;

(2) There is an approved built-in fire extinguishing or suppression system controllable from the cockpit.

(3) There are means to exclude hazardous quantities of smoke, flames, or extinguishing agent, from any compartment occupied by the crew or passengers;

(4) There are means to control ventilation and drafts within the compartment so that the extinguishing agent used can control any fire that may start within the compartment.

(d) [Reserved]

(e) *Class E*. A Class E cargo compartment is one on airplanes used only for the carriage of cargo and in which—

(1) [Reserved]

(2) There is a separate approved smoke or fire detector system to give warning at the pilot or flight engineer station;

(3) There are means to shut off the ventilating airflow to, or within, the compartment, and the controls for these means are accessible to the flight crew in the crew compartment;

(4) There are means to exclude hazardous quantities of smoke, flames, or noxious gases, from the flight crew compartment; and

(5) The required crew emergency exits are accessible under any cargo loading condition.”

- 14 CFR 25.857 Regulation—Amendment 60 Standard for Class D Cargo Compartments

“(d) Class D. A Class D cargo or baggage compartment is one in which--

(1) A fire occurring in it will be completely confined without endangering the safety of the airplane or the occupants;

(2) There are means to exclude hazardous quantities of smoke, flames, or other noxious gases, from any compartment occupied by the crew or passengers.

(3) Ventilation and drafts are controlled within each compartment so that any fire likely to occur in the compartment will not progress beyond safe limits;

(4) [Reserved]

(5) Consideration is given to the effect of heat within the compartment on adjacent critical parts of the airplane.

[(6) The compartment volume does not exceed 1,000 cubic feet.]”