The Journal of Space Safety Engineering 5 (2018) 135–139

Contents lists available at ScienceDirect

The Journal of Space Safety Engineering

journal homepage: www.elsevier.com/locate/jsse

Applying regression analysis to model the risk of space flight and terrestrial activities

Robert P. Ocampo*, David M. Klaus

Department of Aerospace Engineering Sciences, University of Colorado Boulder, 429 UCB, Boulder, CO 80309, USA

A R T I C L E I N F O

Keywords:
Spaceflight
Risk
Safety

A B S T R A C T

This article presents a novel method for coarsely modeling space flight risk in the absence of vehicle-specific data. Risk and usage rates for several different modes of transportation (including space flight) and adventure sports activities (mountaineering, skydiving, and SCUBA diving) were correlated, and a line of best fit equation was derived. The strong, inverse correlation between number of fatal accidents per trip (i.e. risk) and number of trips per year (i.e. usage) ($r = -0.90$, $p < 0.01$), and the strong correlation between number of fatalities per participant and number of participants per year ($r = -0.93$), suggest that risk and usage may be inherently correlative, even across distinct modalities. As such, this quantitative relationship can be used to supplement traditional analysis techniques and serve as a sanity check for expert opinion—particularly during the early stages of vehicle development, when quantitative data is limited and cannot readily support alternative risk prediction techniques. In addition, this general relationship can provide an additional benchmark for tracking performance throughout the operational lifetime of a program, and offers a unique perspective for comparing the relative risk of spaceflight to more commonly experienced terrestrial activities.

1. Introduction

Commercial human space flight can be thought of as a unique combination of adventure and travel. While the purpose of such a trip is for the experience itself and not for point-to-point transportation (at least initially), crewmembers and paying passengers are nevertheless “traveling” on a space vehicle and consequently exposing themselves to risk. As such, this work examines the safety records of various adventure sports and transportation modes in order to determine whether risk exhibits any trends across these activities, and if so, whether such trends can be used to supplement current space flight risk modeling techniques.

2. Background

Space flight will never be perfectly safe [1–4]. Therefore, engineers must strive to design, develop, and operate spacecraft that are safe *enough*—defined here and in previous work [1,5,6] as a state in which the measured risk of the system and its operations is less than or equal to an established risk threshold.

The specific value assigned to this threshold must balance what is maximally *acceptable* from a personal or policy standpoint with what is minimally *achievable* given technical, budget, and schedule constraints [1,7] (see Fig. 1). This approach ensures spacecraft are as “safe as modern technology can and should provide” [8]. For NASA's Commercial Crew Program (CCP), the overall risk threshold for missions to the International Space Station is currently set as a probability of Loss of Crew (LOC) value less than or equal to 1 in 200 [9].

Determining whether this (or any) value is appropriate (i.e. acceptable *and* achievable) can be a difficult and protracted task [7]. Risk threshold targets must be established during the initial stages of a program's lifecycle, when they can most effectively guide the development of operational and design requirements. Yet determining whether a risk threshold is achievable requires a thorough risk analysis—*which cannot be performed without firm operational and design requirements in place* [10,11]. This feedback loop (see dashed red line in Fig. 2) presents engineers with something of a “chicken or egg dilemma”: Risk thresholds cannot be established without a firm understanding of achievable risk, but achievable risk cannot be calculated without first defining and establishing a risk threshold.

To resolve this dilemma, crewed space programs tend to rely on expert opinion to guide the development of an initial risk threshold [7]. This initial threshold then sets a target value that engineers can design towards during the early stages of program development. As detailed design knowledge and operational experience with the system are acquired, risk analysis products can then be iteratively integrated with

---

* Corresponding author.
E-mail address: robert.ocampo@colorado.edu (R.P. Ocampo).

https://doi.org/10.1016/j.jsse.2018.08.001
Received 22 May 2018; Received in revised form 22 July 2018; Accepted 3 August 2018

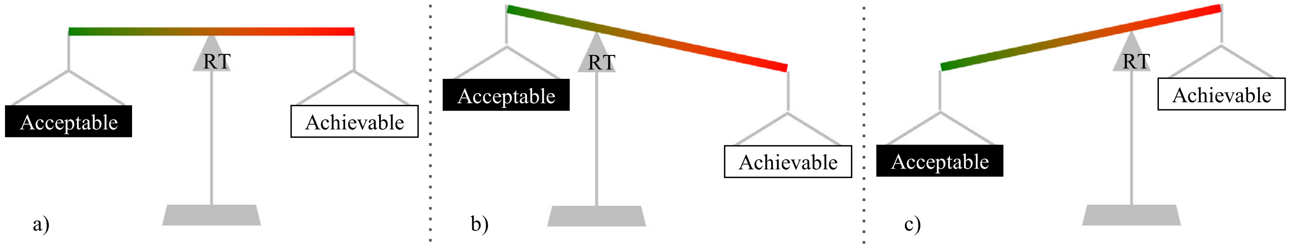

Fig. 1. Risk thresholds can (a) balance acceptable with achievable, (b) have high acceptability and low achievability, or (c) have high achievability and low acceptability.

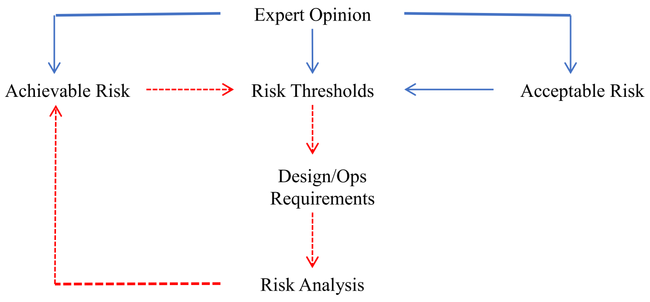

Fig. 2. Process for determining spacecraft risk thresholds.

expert opinion to form increasingly accurate predictions of achievable risk (see Fig. 2).

These improving predictions can in turn be used as rationale for refining the risk threshold, as necessary. The Constellation Program, for example, was originally required to meet a risk threshold of 1/1000 for its mission to the International Space Station (ISS), but this value was increased to 1/270 when NASA realized the Orion and Ares spacecraft could not meet the more demanding requirement [12]. In a similar fashion, NASA's Commercial Crew Program (CCP) increased its risk threshold from 1/270 to 1/200 when analysis indicated the risk associated with micrometeoroid and orbital debris (MMOD) would preclude CCP spacecraft from meeting the original risk requirement [13].

This tendency to incrementally “relax” risk thresholds over the course of program development can lead to spacecraft design requirements that are technically achievable. However, this approach can also inadvertently lead to spacecraft designs that are *programmatically unacceptable* from a risk perspective [14]. In such instances, acceptability is gradually traded for achievability until the conceptual scale depicted in Fig. 1c reaches its tipping point.

3. Rationale

Early *and* accurate models of achievable risk are therefore critical to a program's ultimate viability. If risk is predicted to be acceptably low, the program can continue forward; conversely, if risk is predicted to be unacceptably high, the program can be restructured (or cancelled) before significant resources are committed to a specific design or operational paradigm.

Risk progression trends may prove useful in developing and improving these models. While space flight risk has a tendency to *increase* during program development [12,13], it also has a tendency to *decrease,* in a quasi-predictable fashion, over the course of a program's operational lifetime. This reduction in space flight risk can be seen in both probabilistic and actuarial measures. Space Shuttle mean probability of Loss of Crew (LOC) values declined logarithmically over the course of the program, from 1 in 12 at STS-1 to 1 in 90 at STS-133 [15]. Cumulative failure rates for expendable launch vehicles show a comparable decrease with usage, typically in a manner that can be fitted to a logarithmic decay function (as depicted in Fig. 3).[1]

These risk progression trends do not appear to be limited to space systems. The total number of fatal automobile accidents (per billion miles of vehicle travel) also declined logarithmically from 1994 to 2013, decreasing 34% (Fig. 4a) [16]. The total number of fatal general and commercial aviation accidents (per thousand hours) also exhibited a similar logarithmic decline (from 1970 to 2010), decreasing 57% and 95%, respectively [17,18] (Fig. 4b).

This inverse relationship between risk and usage can be seen in non-transportation modalities as well. Mountaineering fatality rates (e.g. fatalities per total number of participants) on Mt. Everest, Denali, and Mt. Rainier, for example, each exhibited a logarithmic decline over the last 50 years [19–31] (see Fig. 5).

4. Method

Together, these findings suggest that risk (as characterized by number of fatalities) and usage may be inversely related. Given its seeming independence from any specific vehicle or mode of operation, this relationship may prove useful as a tool for coarsely modeling space flight risk in the absence of vehicle-specific data.

In order to further investigate this relationship, risk and usage data were collected for several additional modes of transportation and adventure sport activities. In total, data were collected for 12 different activities across a (roughly) 5 year time period. These activities include driving on U.S. roads, boating on U.S. waters, traveling on Amtrak trains, flying on both U.S. general aviation and commercial aviation aircraft, flying on the Space Shuttle and Soyuz, SCUBA diving, skydiving, and climbing on Mt. Everest, Denali, and Mt. Rainier.[2]

Risk was operationalized using two distinct metrics: number of *fatal accidents per vehicle trip* and *number of fatalities per participant*. The first metric (*fatal accidents per vehicle trip*) is a vehicle-centric metric [32]. It emphasizes the risk associated with a given vehicle, not the individual participant. Under such a metric, a single vehicular accident that leads to 1 fatality (out of 100 participants) and a single vehicular accident that leads to 100 fatalities (also out of 100 participants) are both registered as a single fatal accident. Risk in human space flight has historically been measured using vehicle-centric metrics.

Conversely, the second metric (*fatalities per participant*) is categorized as a person-centric metric, as it highlights the varying internal levels of risk that may exist within a system. With this metric, an event that leads to 1 fatality out of 100 participants is evaluated differently than an event that leads to 100 fatalities out of 100 participants. Such a

---

[1] Cumulative failure rate is a running summary of total failures divided by total launches. Thus, the cumulative failure rate of a launch vehicle that has suffered an initial failure followed by two successes is 1/1 after the first flight, 1/2 after the second flight, and 1/3 after the third flight.

[2] Other transportation and adventure sport activities, such as bicycling and skiing, and other human space programs, such as Mercury, Gemini, Apollo, Vostok, and Voskhod, were originally considered for inclusion in this analysis; however, they were ultimately excluded from further study either because their usage data did not exist outside of rudimentary estimates, or because sample size precluded an appropriate statistical analysis. For a more detailed description of how risk and usage values were measured or estimated, see [32].

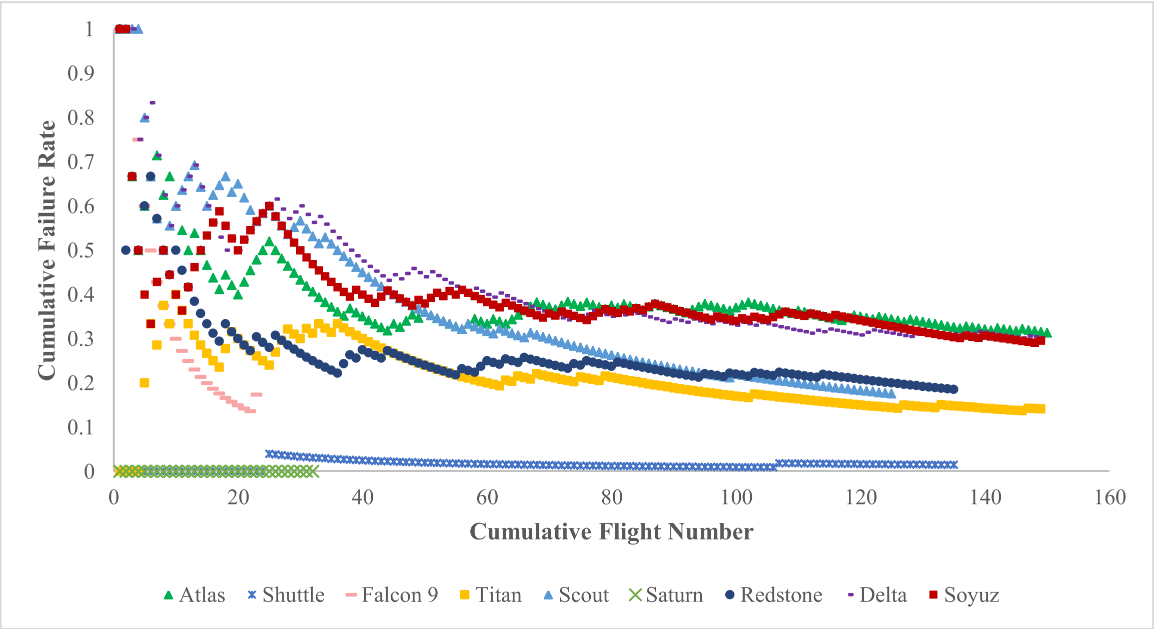

Fig. 3. Cumulative launch vehicle failure rate vs. Flight number for first 150 flights.

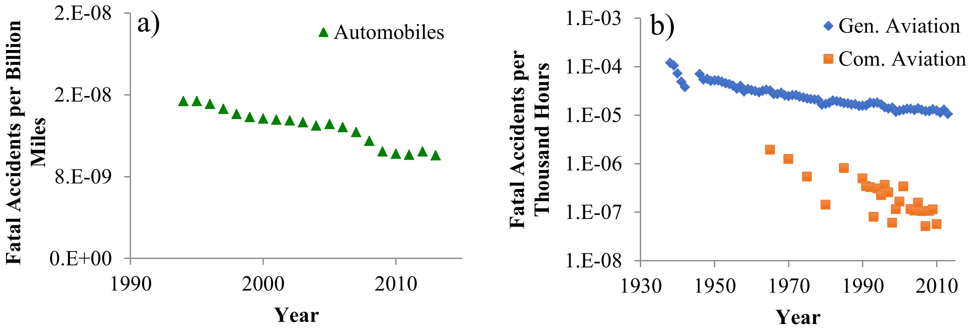

Fig. 4. Risk reduction rates for (a) automobiles and (b) general and commercial aviation.

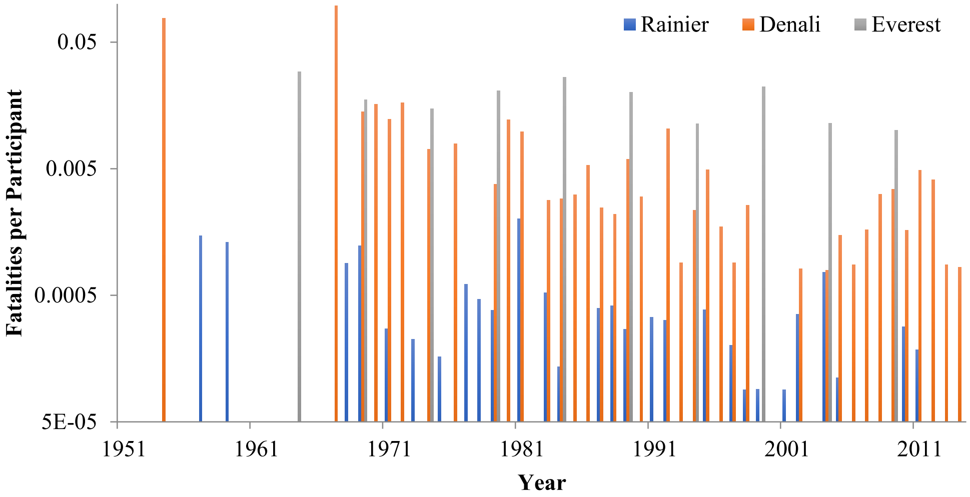

Fig. 5. Mountaineering fatality rates vs. year for Mt. Everest, Denali, and Mt. Rainier.

metric more precisely measures risk in instances where one or more crewmembers survive a catastrophic event (as was the case during the SpaceShipTwo accident).

The second variable, usage, was also measured from both vehicle-centric and person-centric perspectives. Specifically, usage was characterized as the number of *participants per year* (person-centric metric) and the number of *vehicle-trips per year* (vehicle-centric metric) (see Table 1).

Once the data was collected and aggregated, risk and usage were correlated, then fitted to a comprehensive equation using logarithmic regression analysis. Specifically, person-centric risk was correlated with person-centric usage, and vehicle-centric risk was correlated with

Table 1
Methods for operationalizing risk and usage.

	Risk	Usage
Vehicle-centric	*fatal accidents per vehicle trip*	*vehicle-trips per year*
Person-centric	*fatalities per participant*	*participants per year*

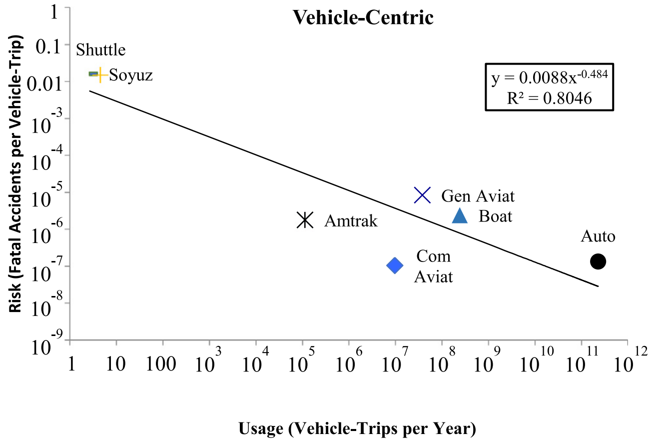

Fig. 6. Log-log plots of risk (fatal accidents per vehicle-trip) and usage (vehicle-trips per year) from a vehicle-centric perspective.

vehicle-centric usage.

5. Results

Log-log plots of risk and usage from both a vehicle-centric (Fig. 6) and person-centric (Fig. 7) perspective are presented below. Risk and usage exhibited a strong correlation when assessed on both a *vehicle-centric* basis ($r = -0.90$) and *person-centric* basis ($r = -0.93$). Despite fewer vehicle-centric data points, both correlations were statistically significant, with p-values less than 0.01.

A regression analysis was performed on both sets of data and the resulting logarithmic equations are plotted and listed in their respective figures. These functions exhibited high goodness of fit, with R^2 values equal to 0.8046 and 0.8676 for vehicle-centric and person-centric data, respectively.

6. Discussion

The quantitative relationship between risk and usage identified above can be described as highly correlative, but not *necessarily* causal. There is, however, strong *qualitative* evidence to suggest the two variables may share a cause and effect relationship, as described below. Notably, this relationship can credibly be described as bi-directional, with both risk affecting usage and usage affecting risk.

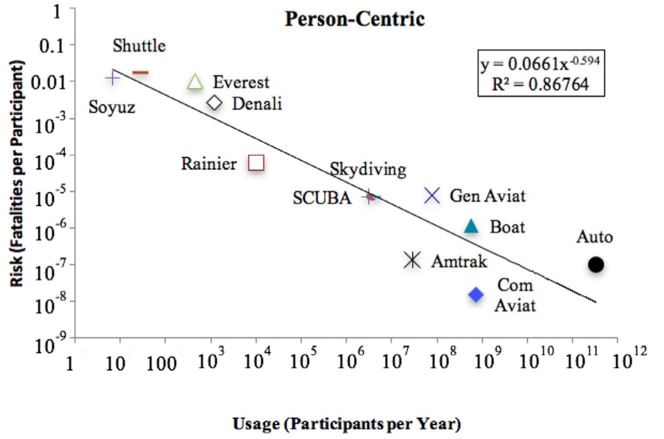

Fig. 7. Log-log plots of risk (fatalities per participants) and usage (participants per year) from a person-centric perspective.

6.1. *Increasing usage leads to decreasing risk*

An increase in usage can provide an environment where lessons can be rapidly learned and assimilated, both at the hardware and operations level. This in turn can lead to an overall reduction in risk as hazards are identified and mitigated. Project Gemini's overall success, for example, can be partially attributed to the rapid progression of ground tests and space flights (and attendant increases in resources) that occurred between 1965 and 1966 (10 crewed flights in a 21 month time period) [33] .[3]

An increase in usage can also serve as an impetus and means for infrastructure improvements, ranging from the addition of traffic lights at busy intersections (as a result of increased tax revenue from an increasing number of registered vehicles), to the construction of air traffic control towers at congested airports, to the use of fixed lines on heavily climbed mountains, such as Mt. Everest. These improvements in turn can lead to commensurate decreases in risk.

6.2. *Decreasing usage leads to increasing risk*

Conversely, a decrease in usage can lead to an atrophy of technical skills and expertise; which in turn can lead to an overall increase in risk. In their 2009 review of United States Human Space Flight Plans, the Augustine Committee stated that one of the benefits to flying the Space Shuttle beyond its scheduled retirement date, at a "minimum safe flight rate", was the preservation of workforce and skills that "enable the U.S. to enjoy a robust human spaceflight program" [35]. In a similar vein, the Aerospace Safety Advisory Panel (ASAP) has expressed concerns regarding the infrequent flight rate of the Space Launch System (SLS), stating that the proposed flight manifest may lead to an overall increase in risk due to "personnel loss and fading memories" [13].

6.3. *Increasing risk leading to decreasing usage*

For certain modalities, the relationship between risk and usage may also be bidirectional. In other words, usage may affect risk (as noted above), but *risk may also affect usage*. For instance, participants may be less inclined to perform an activity or use a mode of transportation if there is an increase to the real or perceived risk of the system. After the 9/11 terrorist attacks, for example, commercial airlines experienced a 30% reduction in passengers in the months which followed [36,37]. Following a surge in fatalities on Mt. Everest in 2014 and 2015, the number of climbers decreased by 50% during the 2016 season [38].

6.4. *Decreasing risk leading to increasing usage*

Lastly, a decrease in risk can lead to an increase in usage. The use of improved weather forecasts, better technical equipment, and superior navigational tools, for example, is thought to have contributed to an increase in usage in activities ranging from commercial aviation to mountaineering [39,40].

---

[3] This relationship between increased usage and decreased risk appears to hold true only when there are sufficient resources available to incorporate applicable lessons learned. Prior to the *Challenger* accident, the Space Shuttle Program was "approaching a state of saturation in which no more flights could be accommodated" [4]; in this environment (unlike the one in which Gemini was developed), lessons learned from one mission could not adequately be incorporated into the next [34].

7. Conclusion

The statistical analysis presented here, coupled with the supporting qualitative evidence detailed above, suggests that the relationship between risk and usage may be inherently correlative. Such a relationship, though not necessarily causal, may prove useful as a tool for coarsely modeling risk, providing a sanity check for expert opinion, and supplementing standard prediction techniques—particularly during the early stages of vehicle development when quantitative data may be limited or immature. This general relationship can also serve as an additional tool for benchmarking performance throughout the operational lifetime of a program (e.g. is the program's risk maturing as predicted at its given stage of operations) and offers a unique perspective for comparing the relative risk of spaceflight to more commonly experienced terrestrial activities.

Acknowledgments

The FAA has sponsored this project in part through the Center of Excellence for Commercial Space Transportation. However, the agency neither endorses nor rejects the findings of this research. The presentation of this information is in the interest of invoking technical community comment on the results and conclusions of the research.

References

[1] R.P. Ocampo, D.M. Klaus, A quantitative framework for defining how safe is safe enough? In crewed spacecraft, New Space 4 (2) (2016) 75–82, https://doi.org/10.1089/space.2015.0040.
[2] Aerospace Safety Advisory Panel, Aerospace Safety Advisory Panel Annual Report for 2012, Aerospace Safety Advisory Panel Washington, DC, 2013.
[3] Slay, A., Post-challenger evaluation of space shuttle risk assessment and management, 1988.
[4] U.S. House of Representatives, Investigation of the Challenger Accident, U.S. House of Representatives Washington DC, 1986.
[5] H Dezfuli, NASA's risk management approach, Proceedings of the Workshop on Risk Assessment and Safety Decision Making Under Uncertainty, , Bethesda, MD, 2010September.
[6] M. Stamatelatos, Safety Goals at NASA or How Safe is Safe Enough and How to Get There, HQ-STI-10-148, (October 2010), pp. 1–11.
[7] Aerospace Safety Advisory Panel. Aerospace Safety Advisory Panel Annual Report for 2013. Aerospace Safety Advisory Panel, Washington, DC, (2014).
[8] Aerospace Safety Advisory Panel, Aerospace Safety Advisory Panel Annual Report for 2010, Aerospace Safety Advisory Panel, Washington, DC, 2011.
[9] NASA, ISS Crew Transportation and Services Requirements Document, NASA CCT-REQ-1130 Rev D-1, NASA March 2015.
[10] Tumer, I., Barrientos, F., and Mehr, A.F., Towards Risk Based Design (RBD) of Space Exploration Missions: A Review of RBD Practice and Research Trends at NASA, American Society of Mechanical Engineers, Paper No. DETC2005-85100, September 2005.
[11] NASA, NASA Risk Management Handbook, NASA, 2011 NASA/SP-2011-3422 November.
[12] Aerospace Safety Advisory Panel, Aerospace Safety Advisory Panel Annual Report for 2011, Aerospace Safety Advisory Panel Washington, DC, 2012.
[13] Aerospace Safety Advisory Panel, Aerospace Safety Advisory Panel Annual Report for 2015, Aerospace Safety Advisory Panel, Washington, DC, 2016.
[14] Aerospace Safety Advisory Panel, Aerospace Safety Advisory Panel Annual Report for 2014, Aerospace Safety Advisory Panel Washington, DC, 2015.
[15] Hamlin, T.L., Thigpen, E., Kahn, J., and Lo, Y., Shuttle Risk Progression: Use of the Shuttle Probabilistic Risk Assessment (PRA) to Show Reliability Growth, AIAA Paper 2011-7353, AIAA January 2011.
[16] National Highway Traffic Safety Administration, Fatality Analysis Reporting System (FARS) Encyclopedia, National Highway Traffic Safety Administration [online database], http://www-fars.nhtsa.dot.gov/Main/index.aspx [retrieved 1 May 2016].
[17] Bureau of Transportation Statistics, Table 2–14: U.S. General Aviation(a) Safety Data, Bureau of Transportation Statistics [online table], http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_02_14.html [retrieved May 1, 2016].
[18] Bureau of Transportation Statistics, Table 2–9: U.S. Air Carrier(a) Safety Data, Bureau of Transportation Statistics [online table], http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_02_09.html [retrieved May 1, 2016].
[19] R. Salisbury, E. Hawley, The Himalaya by the Numbers: A Statistical Analysis of Mountaineering in the Nepal Himalaya, Vajra Publications, Florida, 2011.
[20] J. Waterman, Surviving Denali: A Study of Accidents on Mount McKinley, 1903–1990, The Mountaineers Books, Seattle, 1991.
[21] S.E. McIntosh, A.D. Campbell, J. Dow, C.K. Grissom, Mountaineering fatalities on Denali, High Alt. Med. Biol. 9 (1) (2008) 89–95, https://doi.org/10.1089/ham.2008.1047.
[22] National Parks Service, Denali National Park and Preserve Annual Mountaineering Summary – 2007, National Parks Service 2008.
[23] National Parks Service, Denali National Park and Preserve Annual Mountaineering Summary – 2008, National Parks Service 2009.
[24] National Parks Service, Denali National Park and Preserve Annual Mountaineering Summary – 2009, National Parks Service 2010.
[25] National Parks Service, Denali National Park and Preserve Annual Mountaineering Summary – 2010, National Parks Service 2011.
[26] National Parks Service, Denali National Park and Preserve Annual Mountaineering Summary – 2011, National Parks Service 2012.
[27] National Parks Service, Denali National Park and Preserve Annual Mountaineering Summary – 2012, National Parks Service 2013.
[28] National Parks Service, Denali National Park and Preserve Annual Mountaineering Summary – 2013, National Parks Service 2014.
[29] National Parks Service, Mount McKinley South Peak (20,320 feet) Attempts and Summits, National Parks Service 2015.
[30] National Parks Service, Fatalities at Mt. Rainier National Park, National Parks Service [online database], http://www.mountrainierclimbing.us/sar/fatalities.php [retrieved 1 May 2016].
[31] National Parks Service, Mount Rainier Annual Climbing Statistics, National Parks Service 2010.
[32] R.P. Ocampo, D.M. Klaus, Comparing the relative risk of space flight to terrestrial modes of transportation and adventure sport activities, New Space 4 (3) (2016) 190–197.
[33] Hacker, B.C., and Grimwood, J.M., On the Shoulders of Titans: A History of Project Gemini: 'Spirit of'76. NASA SP-4203, 1970, pp. 1–261.
[34] Presidential Commission On Space Shuttle Challenger, Report of the Presidential Commission on the Space Shuttle Challenger Accident, Presidential Commission On Space Shuttle Challenger Washington DC, 1986.
[35] Augustine, N., Austin, C.D.W., Bejmuk, M.B., Chyba, C., Crawley, E., Greason, M.J., and Kennel, C, Review of US Human Space Flight Plans Committee. Seeking a Human Spaceflight Program Worthy of a Great Nation, Washington, DC, 2009, pp. 1–4.
[36] Logan, G., The Effects of 9/11 on the Airline Industry, USA Today [online], http://traveltips.usatoday.com/effects-911-airline-industry-63890.html [retrieved 1 May 2016].
[37] Bureau of Transportation Statistics, Airline travel since 9/11, Issue Brief 13 (2005) 1–2.
[38] O'Neil, D., What to Expect on Everest for the 2016 Season, Outside Online, 2016, http://www.outsideonline.com/2066566/what-expect-everest-2016-season [retrieved 1 May 2016].
[39] T.A. Heppenheimer, Turbulent Skies: The History of Commercial Aviation, J. Wiley & Sons, San Francisco, 1995.
[40] M. Jenkins, Maxed out on Everest, Natl. Geogr. 32 (6) (2013) 94–113 online http://ngm.nationalgeographic.com/2013/06/125-everest-maxed-out/jenkins-text retrieved 1 May 2016.