Comparing the Relative Risk of Spaceflight to Terrestrial Modes of Transportation and Adventure Sport Activities

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ABSTRACT

The safety records of crewed spacecraft (Space Shuttle, Soyuz) are compared with the safety records of various common terrestrial transportation modalities (automotive, rail, boating, general aviation, commercial aviation) and select adventure sport activities (skydiving, mountaineering, SCUBA diving). Raw fatality and exposure data for each activity are reviewed and then amalgamated as six different rate metrics (fatal accidents per vehicle-trip, fatal accidents per vehicle-mile, fatal accidents per vehicle-hour, fatalities per person-trip, fatalities per person-mile, and fatalities per person-hour). The results indicate that, for the periods reviewed, spaceflight was the riskiest activity (or one of the riskiest activities) in four of the six metrics (fatal accidents per vehicle-trip, fatal accidents per vehicle-hour, fatalities per person-trip, and fatalities per person-hour). However, spaceflight was calculated to be less risky than automobiles, general aviation, and rail transportation on a fatal accidents per vehicle-mile basis, and it was roughly comparable to climbing Mt. Everest on a fatalities per person-trip basis. These conflicting results suggest that relative safety records alone are ambiguous, and they may not be a wholly representative means of communicating risk to prospective spaceflight participants.

INTRODUCTION

Spaceflight participants (SFPs) traveling to orbital and suborbital space will be exposed to a non-negligible level of risk,[1–4] which must be conveyed to each SFP before he or she can legally consent to fly.[4] Specifically, operators of commercial spacecraft will be required to inform prospective SFPs of the safety record of their launch and entry vehicles before receiving compensation or entering into an agreement to fly an SFP.[4]

How an SFP interprets this quantitative safety record, however, will likely be influenced by external factors. Studies of risk perception have shown that recent and/or emotionally salient events can affect an uninformed individual's perception of actuarial data (such as safety records).[5] The perceived risk of nuclear power, for example, grew significantly after the Fukushima disaster,[6] despite the fact that the disaster did not substantially alter the safety record of nuclear power plants (the rate of major accidents grew only slightly after Fukushima, from 0.14 major accidents per thousand reactor-years to 0.21 major accidents per thousand reactor-years[7]).

These observations suggest that SFP perception of spaceflight risk may differ from what is demonstrated by actual safety records. The recent losses of the Cygnus (October 28, 2014) and Dragon (June 28, 2015) cargo spacecraft and the in-flight death of a Virgin Galactic SpaceShipTwo test pilot (October 31, 2014)—three nearly coinciding events that, though rare, were highly salient to the industry—may lead prospective SFPs to perceive spaceflight as riskier than what is measured by actual spacecraft safety records. This potential divergence between perception and data can, in turn, lead prospective SFPs to make decisions regarding spaceflight that are not entirely informed.

This article attempts to reduce any potentially biased interpretation of risk by presenting spacecraft safety records in conjunction with the safety records of other more familiar activities for context. Such relative comparisons have been shown to be an effective means of conveying risk to uninformed individuals,[8,*] and they may prove to be particularly useful to SFPs, who will have little (if any) spaceflight experience on which to base their decisions.

Federal regulations already require commercial operators to present prospective SFPs with a limited number of relative risk comparisons. As specified by 14 CFR 460.45c, all commercial operators must provide prospective SFPs with the safety

*It is important to note that not all risk perception researchers agree on the efficacy of such relative risk comparisons.[8–11] However, the primary shortcomings identified with relative risk comparisons, namely, the absence of *quantitative* (*e.g.*, absolute) numeric labels[12] and *qualitative* descriptors,[9,10] are mitigated by current federal regulations, which require spacecraft operators to present SFPs with their vehicle's safety records (which allow for absolute risk comparisons) and to present a complete list of known (qualitative) hazards.[4]

DOI: 10.1089/space.2016.0012

record of all launch or reentry vehicles that have carried one or more people aboard.[4] This article takes the presentation of relative risk a step further by contrasting spacecraft safety records against the safety records of other, more familiar (*e.g.*, terrestrial) modes of transportation, such as automobiles, rail, boating, general aviation, and commercial aviation. In addition, spacecraft safety records are compared against the safety records of several adventure sport activities, including skydiving, mountaineering (Everest, Denali, Rainier), and SCUBA diving. These thrill-seeking activities are specifically included in the analysis, because they also take place in extreme environments (such as spaceflight) and are expected to be reasonably familiar to most prospective SFPs.[13]

Given the limited number of commercial crewed spacecraft that have flown to date, only Space Shuttle and Soyuz safety records are used in this analysis. As the number of commercial spaceflights increases, however, these commercial spacecraft safety records can augment the Shuttle/Soyuz data in future analyses.

Although this article highlights the relative risks of spaceflight, the results are not intended to define commercial spaceflight (or any specific spacecraft) as being safe or unsafe,[1] but rather to provide prospective SFPs with additional data from which they can make informed decisions.

DEFINITIONS AND CONCEPTS

Before the safety records of these varying activities can be effectively compared, several terms and concepts must first be defined. Without clear and consistent definitions, both within and across activities, relative risk comparisons may not be appropriately commensurate (*i.e.*, "apples to apples"). These definitions and concepts are described next.

Exposure and Fatality Characteristics (Unprocessed Data)

Fatality. A death that directly results from performing or engaging in an activity.†

Fatal accident. An accident in which one or more fatalities occur. No qualification is given to the total number of fatalities that occur during the accident.

Vehicle-trip. A single, uninterrupted trip on board a single vehicle, regardless of exposure length or number of people on board. For example, a scheduled train trip from New York to Washington DC would be considered a single vehicle-trip, even if the number of passengers changes from station to station.

Vehicle-miles. A single vehicle-mile is the movement of one vehicle for 1 mile, regardless of the number of people on board.[14] A train that travels 100 miles on Saturday and 100 miles on Sunday has traveled a total of 200 vehicle-miles during the 2-day period.

Vehicle-hours. A single vehicle-hour is the movement of one vehicle for 1 h, independent of the number of people on board the vehicle. If *Bus A* is driven for 3 h and *Bus B* is driven for 4 h, the total number of vehicle-hours for the two buses is 7 h.

Person-trip. A single person-trip is the exposure of one person to one trip (or activity). An individual who dives the same reef four times accounts for four person-trips (1 person $\times$ 4 trips = 4 person-trips); three people who take two sailing trips result in six person-trips (3 persons $\times$ 2 trips = 6 person-trips).‡

Person-mile. A single person-mile is the movement of one person for 1 mile. A 10-mile car trip with three passengers on board would accumulate 30 person-miles (3 people $\times$ 10 miles).

Person-hour. A single person-hour is the movement of one person for 1 h. An aircraft that flies 200 people for 5 h results in 1,000 person-hours (200 people $\times$ 5 h).

Fatality Rates (Processed Data)

Unprocessed fatality data, by itself, cannot effectively communicate risk, as such data do not provide a sufficient temporal perspective. Ten fatalities over the course of an hour would likely be perceived as high risk, but 10 fatalities over the course of a century would likely be perceived as low risk. Safety records are, therefore, more appropriately represented as a rate, for example, a fatality characteristic divided by an exposure characteristic, typically based on event, time, or distance as described next. This article collectively refers to these rates as "risk metrics."

Six different risk metrics are established for this analysis: (1) fatal accidents per vehicle-trip, (2) fatal accidents per vehicle-hour, (3) fatal-accidents per vehicle-mile, (4) fatalities

†The period in which death must occur to be considered an activity-related fatality (*e.g.*, within *x* days of the activity) is not specified here, as fatality data sources do not consistently define this period. However, it may broadly be interpreted as occurring within 30 days of the activity, as this is the time frame specified by both the National Highway Traffic Safety Association (NHTSA)[14] and the Federal Aviation Administration (FAA).[15]

‡With regards to transportation data, person-trips are equivalent to the number of non-unique passengers who have participated in an activity during a given period; however, the term *person-trip* is retained here to account for the fact that participants in adventure sport activities are generally not referred to as "passengers."

per person-trip, (5) fatalities per person-hour, and (6) fatalities per person-mile. These six metrics can be categorized as either vehicle centric or person centric:

Vehicle centric. Vehicle-centric risk metrics (fatal accidents per vehicle-trip, fatal accidents per vehicle-hour, fatal accidents per vehicle-mile) emphasize the risk associated with a given vehicle, and they are, therefore, not amenable to presenting the safety records of adventure sport activities. Vehicle-centric risk metrics are not affected by the number of passengers on board the vehicle. Historically, the National Aeronautics and Space Administration (NASA) has used vehicle-centric risk metrics to present the actuarial safety records and predicted risk of its spacecraft (*e.g.*, Loss of Crew).

Person centric. Person-centric risk metrics (fatalities per person-trip, fatalities per person-hour, fatalities per person-mile) emphasize the individual risk associated with a given activity, specifically accounting for the fact that risk may vary from individual to individual within the same activity. For example, evidence suggests that passengers near the rear of an aircraft are more likely to survive a plane crash than passengers near the front.[16] With regards to commercial spaceflight, older, less healthy SFPs may be less likely to survive off-nominal events than their younger, healthier counterparts.

Person-centric risk metrics can be used to present the safety records of both adventure sports and modes of transportation. In cases where only a subset of participants on board a vehicle are lost, such as the 2014 SpaceShipTwo accident, it may be preferable to measure safety records using person-centric metrics, rather than vehicle-centric metrics, as the former serves to emphasize the varying internal levels of risk that can exist on a vehicle.

In addition, raw fatality and exposure data are also presented, thereby allowing for the ready calculation of additional risk metrics, as desired.[§]

METHODOLOGY

Fatality and exposure data for eight of the activities reviewed here—mountaineering on Denali (Alaska), mountaineering on Mt. Rainier (Washington), driving a personal automobile on U.S. roads, travel aboard Amtrak passenger trains, boating within U.S. waters, flights aboard U.S. part 91 (general) aviation, flights aboard U.S. part 121 (scheduled airline) aviation, and flights aboard the Space Shuttle—were aggregated from several different U.S. government sources, including the National Park Service (NPS), the National Highway Traffic Safety Administration (NHTSA), the Federal Highway Administration (FHWA), the Federal Railroad Administration (FRA), the U.S. Coast Guard (USCG), the Federal Aviation Administration (FAA), the Bureau of Transportation Statistics (BTS), and the NASA. The anticipated risk associated with NASA's Commercial Crew Program—derived specifically from NASA requirements—was also included in the analysis.

For those activities that were not directly regulated by the U.S. government during the periods reviewed here (*e.g.*, climbing Mt. Everest, skydiving, SCUBA diving, and flights aboard Soyuz), statistics were gathered either from the activity's governing body or from other non-U.S. government agencies. Concerted efforts were made to ensure that fatality and exposure data sources were consistent within each activity so as to best maintain the precision of each calculated risk metric.

Wherever possible, fatality and exposure data for each activity were aggregated over a 5-year period to help minimize the effects of outlier years. With very few exceptions, these periods represent the most recent years for which data were available so as to help ensure the currency of risk comparisons. The specific periods that were assessed for this article are listed in *Table 1*.

RESULTS

Exposure and Fatality Data

Fatality and exposure data for the different activities are summarized in *Table 1*.

A full, uniform set of exposure data could not be identified in the literature, as not all activities maintain records for each exposure type. Certain combinations of activities and exposure types are simply not amenable to record keeping, because either the measurements are unrealistic to collect (*e.g.*, Mt. Everest person-miles) or they are of little relevance to the activity's governing body (*e.g.*, skydiving person-hours). Other combinations of activity and exposure measurements are nonsensical; for example, there are generally no vehicles involved in SCUBA diving, so SCUBA diving vehicle-hours are not reviewed in this analysis.

In some cases, however, exposure data could be readily estimated from previously identified exposure characteristics. For example, vehicle-miles can be approximated from vehicle-hours if an average speed of the vehicle is assumed

[§]Risk is presented here as the number of fatalities (or fatal accidents) per given exposure period. However, risk does not always have to be associated with a fatal event. Commercial spacecraft operators will also likely be concerned with the risk of injury (both serious and non-serious), the risk of an abort or early termination, and other comparable statistics. However, since such data tend to be poorly characterized for non-space activities, they are not presented here.

Table 1. Fatality and Exposure Data for Spaceflight, Terrestrial Transportation, and Adventure Sport Activities

Activity	Fatalities	Fatal accidents	Vehicle-trips	Vehicle-hours	Vehicle-miles	Person-trips	Person-hours	Person-miles
U.S./Canada SCUBA (Insured Divers)[17] *2000–2006*	187	187	N/A	N/A	N/A	2.67×10^{7}	N/A	N/A
Skydiving[18] *2010–2014*	113	113	N/A	N/A	N/A	1.56×10^{7}	N/A	N/A
Mt. Everest[19] *2005–2009*	23	23	N/A	N/A	N/A	2.28×10^{3}	N/A	N/A
Denali[20–24] *2010–2014*	16	16	N/A	N/A	N/A	6.03×10^{3}	N/A	N/A
Mt. Rainier[25,26] *2006–2010*	3	3	N/A	N/A	N/A	4.96×10^{4}	N/A	N/A
Automobiles[14,27,28] *2009*	33,883	30,862	2.34×10^{11}	*7.48×10^{10}*	2.25×10^{12}	3.27×10^{11}	N/A	3.30×10^{12}
Amtrak Rail[29–42] *2010–2014*	19	1	5.66×10^{5}	3.92×10^{6}	2.04×10^{8}	1.47×10^{8}	N/A	3.37×10^{10}
Boating[43–44] *2012*	651	578	2.44×10^{8}	1.39×10^{9}	N/A	5.86×10^{8}	3.58×10^{9}	N/A
U.S. Part 91 (General) Aviation[45–50] *2003–2007*	2,957	1,583	1.91×10^{8}	1.22×10^{8}	*1.22×10^{10}*	*3.82×10^{8}*	N/A	N/A
U.S. Part 121 (Scheduled Airline) Aviation[51–53] *2008–2012*	57	5	4.88×10^{7}	9.02×10^{7}	3.85×10^{10}	3.65×10^{9}	*5.71×10^{9}*	2.86×10^{12}
Soyuz[54–55] *1967–March 2015*	4	2	125	3.44×10^{5}	5.92×10^{9}	3.18×10^{2}	9.51×10^{5}	1.64×10^{10}
Space Shuttle[56] *1981–2011*	14	2	135	3.19×10^{4}	5.43×10^{8}	8.17×10^{2}	2.00×10^{5}	3.40×10^{9}
NASA Com. Crew[57] *Anticipated*	N/A	1	200	N/A	N/A	N/A	N/A	N/A

Estimated exposure data are listed in italics.

based on general knowledge of the activity. For this study, the following four exposure characteristics were estimated:

Automobile vehicle-hours. Automobile vehicle-hours were estimated by dividing vehicle-miles by 30 mph—the assumed average speed of an automobile for all trips. A sensitivity analysis of this estimate, using assumed values ranging from 10 to 60 mph, did not affect the automobile's relative risk ranking in terms of fatal accidents per vehicle-hour.

General aviation vehicle-miles. General aviation vehicle-miles were estimated by multiplying vehicle-hours by 100 mph—the assumed average speed of a general aviation aircraft. A sensitivity analysis of this estimate, using values ranging from 50 to 200 mph, did not affect the general aviation's relative risk ranking in terms of fatal accidents per vehicle-mile.

General aviation person-trips. General aviation person-trips were estimated by multiplying the total number of trips by 2—the assumed average number of people on board each general aviation aircraft during each trip. A sensitivity analysis of this estimate, using values ranging from 1 to 6 passengers, did not affect the general aviation's relative risk ranking in terms of fatalities per person-trip.

Part 121 aviation person-hours. Part 121 (scheduled airliner) commercial aviation person-hours were estimated by dividing the number of person-miles by 500 mph—the assumed average speed of a scheduled commercial airliner. A sensitivity analysis of this estimate, using values ranging from 100 to 600 mph, did not affect part 121's relative risk ranking in terms of fatalities per person-hour.

Exposure data that were estimated by the authors are italicized in *Table 1*; exposure data that could not be estimated (or identified in the literature) are listed as N/A.

Relative Fatality Rates

The relative fatality rates for each activity are described next and pictorially depicted in *Figures 1* and *2*. A Chi-squared test was performed within each metric to identify cases of statistical significance. If the riskiest activity was found to be significantly greater than the second riskiest activity, it was inferred to be significantly greater than all activities.

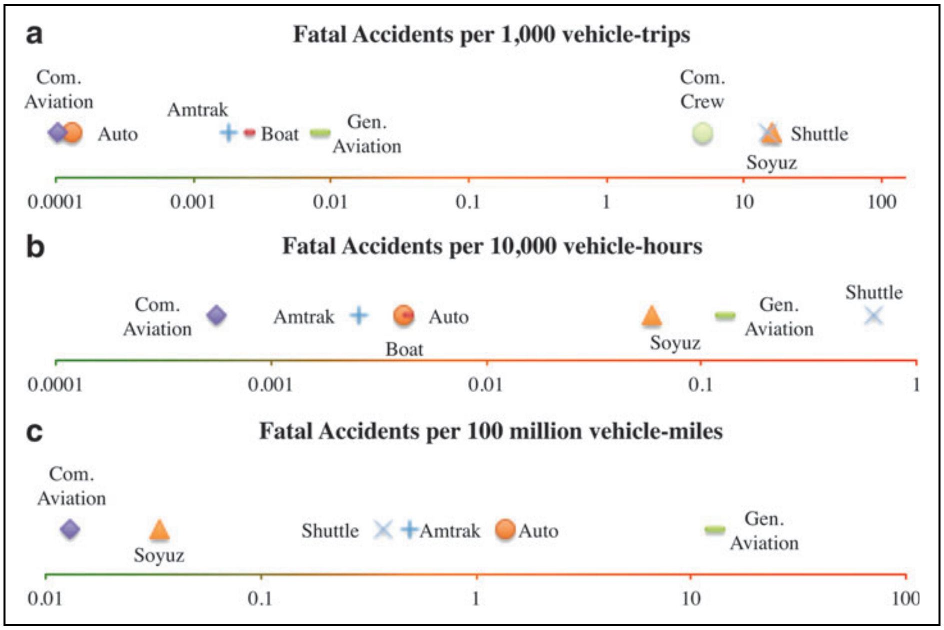

Fig. 1. Number of fatal accidents on a **(a)** per 1,000 vehicle-trip basis, **(b)** per 10,000 vehicle-hour basis, and **(c)** per 100 million vehicle-mile basis.

Fatal accidents per 1,000 vehicle-trips. Spaceflight was measured to be riskier than all other terrestrial activities by several orders of magnitude on a fatal accidents per vehicle-trip basis (*Fig. 1a*). Space Shuttle and Soyuz data, when extrapolated to 1,000 vehicle-trips, suffered 14.8 and 16.0 fatal accidents per 1,000 vehicle-trips, respectively. In comparison, general aviation, the riskiest non-space activity on a fatal accident per vehicle-trip basis, experienced only 0.008 fatalities per 1,000 vehicle-trips between 2003 and 2007—a rate that is statistically less (and six orders of magnitude lower) than that experienced by the Space Shuttle and Soyuz (Chi-squared test, $P < 0.01$).

Fatal accidents per 10,000 vehicle-hours. Human spaceflight (as characterized by the Space Shuttle and Soyuz) was also identified as one of the riskiest activities when measured on a fatal accidents per vehicle-hour basis (*Fig. 1b*). Of the seven activities whose fatal accidents per vehicle-hour rates could be calculated, flights aboard the Space Shuttle were the riskiest (0.63 fatal accidents per 10,000 vehicle-hours). However, flights aboard the general aviation aircraft (0.13 fatal accidents per 10,000 h) were measured to be riskier than flights aboard the Soyuz spacecraft (0.06 fatal accidents per 10,000 vehicle-hours).

Fatal accidents per 100 million vehicle-miles. On a fatal accidents per vehicle-mile basis, human spaceflight was actually one of the least risky activities, experiencing only 0.03 (Soyuz) and 0.37 (Space Shuttle) fatal accidents per 100 million vehicle-miles (*Fig. 1a*). In contrast, automobiles (1.37), Amtrak passenger rail (0.49), and general aviation (12.99) experienced significantly more fatal accidents per 100 million vehicle-miles than both the Space Shuttle and Soyuz ($P < 0.01$).

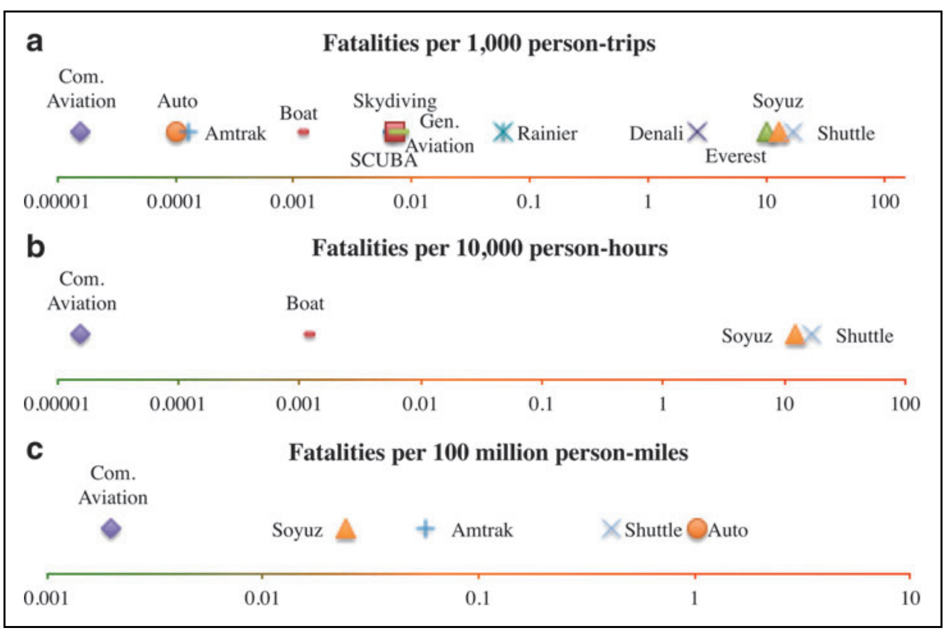

Fig. 2. Number of fatalities on a **(a)** per 1,000 person-trip basis, **(b)** per 10,000 person-hour basis, and **(c)** per 100 million person-mile basis.

Fatalities per 1,000 person-trips. As shown in *Figure 2a*, both the Space Shuttle and Soyuz exhibited a higher number of fatalities per 1,000 person-trips (17.1 and 12.6 per 1,000 person-trips, respectively) than any of the other reviewed activities (*Fig. 2a*). However, the number of fatalities per 1,000 person-trips for Mt. Everest (10.1 fatalities per 1,000 person-trips) was roughly comparable on an order-of-magnitude basis. In fact, statistical analysis indicates the fatalities per 1,000 person-trip rates for Mt. Everest, and Soyuz and Shuttle were not significantly different (Chi-squared test, $P < 0.05$).

Fatalities per 10,000 person-hours. When measured on a fatalities per person-hour basis, human spaceflight (0.70 fatalities per 10,000 person-hours for Space Shuttle, 0.04 fatalities per 10,000 person-hours for Soyuz) was significantly riskier than either boating (0.0018 fatalities per 10,000 person-hours, Chi-squared test, $P < 0.01$) or part 121 (scheduled airline) aviation (0.0001 fatalities per 10,000 person-hours, Chi-squared test, $P < 0.01$)—the only two other activities with comparable data reviewed in this article (*Fig. 2b*).

Fatalities per person-mile. Human spaceflight was calculated to be one of the riskiest activities when measured on a fatalities per person-mile basis (*Fig. 2c*). However, it is worth noting that spaceflight was not the riskiest of all activities reviewed here, as the rate of automobile fatalities per 100 million person-miles (1.03 fatalities per 100 million person-miles) exceeded that of either the Space Shuttle (0.41 fatalities per 100 million person-miles) or the Soyuz (0.02 fatalities per 100 million person-miles).

DISCUSSION

By most metrics, human spaceflight was riskier than all other activities reviewed here. Flights on the Space Shuttle and Soyuz were significantly riskier than all other activities on a fatal accidents per vehicle-trip and a fatalities per person-hour basis, and they were one of the riskiest activities on a fatal accidents per vehicle-hour basis. Additionally, Space Shuttle and Soyuz flights were riskier than all other activities on a fatalities per person-trip basis (though not to a statistically significant degree).

However, when assessed on a per-mile basis (both fatal accidents per vehicle-mile and fatalities per person-mile), spaceflight was actually less risky than a number of other activities. For example, automobiles were identified to be significantly riskier than the Space Shuttle on both a fatal accidents per vehicle-mile and a fatalities per person-mile basis. Although these comparisons may seem irrelevant given the current state of the commercial spaceflight, they are, nonetheless, legitimate comparisons and may prove more meaningful if point-to-point suborbital transportation comes to fruition.

These seemingly contradictory findings serve to demonstrate the limitations that are inherent in communicating risk with any single metric. However, the converse approach—characterizing risk with a multitude of metrics—may prove confusing to prospective SFPs, particularly when the different approaches appear to present contradictory information. Such confusion from "too much information" may, in fact, diminish the ability of SFPs to make sound, informed decisions.

One potential workaround is to present SFPs with only those metrics that directly relate to the activity's primary motive. Given that commercial spaceflight is currently being promoted as an experience, rather than a means of transportation, per-trip metrics (*e.g.*, fatal accidents per vehicle-trip, fatalities per person-trip) are more relevant and applicable to SFPs than per-hour or per-mile metrics at this stage of operations. NASA already measured crewed spacecraft risk as a per-trip metric (and only as a per-trip metric), so there is precedence to reporting risk in this manner.

However, even focused metrics such as these have the potential to mischaracterize risk. Soyuz suffered two fatal accidents and four fatalities over the course of its first 125 flights (dating to March, 2015). However, both accidents (and all four fatalities) occurred early in the program's history (in 1967 and 1971). Given that the hazards that led to these fatal accidents appear to have been mitigated (as evidenced by the fact that no parachute or equalization valve has catastrophically failed on a Soyuz spacecraft in the past 40 years), the cumulative Soyuz safety record may not accurately reflect current Soyuz risk. However, if only safety records from the past 5 years of operations are included in this analysis (as was the protocol for all other activities reviewed here), then both Soyuz and Space Shuttle safety records would be perfect (0 fatal accidents and 0 fatalities over the course of 21 flights for both Soyuz and Shuttle), which is an equally misleading description of spaceflight risk.

In a similar vein, Soyuz and Space Shuttle may not accurately represent the risk of nascent commercial spacecraft, which should (ideally) benefit from past Soyuz and Shuttle "lessons learned." However, simply listing the safety records of nascent commercial spacecraft may also prove misleading, as these safety records are unlikely to characterize the true, mature risk of the vehicle. This is best exemplified by the fact that a spacecraft that has been successfully launched one time (and only one time) would have a mathematically perfect safety record, but could not, in good conscience, be described as "zero risk" for subsequent launches. This attribute of safety records is a general concern for any low-frequency activities (such as spaceflight), and as such, the concept of comparing actual and predicted safety records should be carefully explained to SFPs when communicating risk.

CONCLUSION

These findings suggest that even relative quantitative risk comparisons may not be a wholly sufficient means of communicating risk to SFPs. As such, commercial operators must continue to provide qualitative descriptors of spacecraft hazards (as already required by federal regulations[4]), in addition to quantitative, relative safety records. Although adequate communication of the technical and medical aspects of qualitative hazards to SFPs presents its own set of challenges, presenting both qualitative and quantitative relative risk data may help SFPs to make better, more suitably informed, decisions regarding personal risk acceptance.

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 comments on the results and conclusions of the research.

AUTHOR DISCLOSURE STATEMENT

No competing financial interests exist.

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