The Risk of Groundling Fatalities from Unintentional Airplane Crashes

Kimberly M. Thompson, R. Frank Rabouw, and Roger M. Cooke

The crashes of four hijacked commercial planes on September 11, 2001, and the repeated televised images of the consequent collapse of the World Trade Center and one side of the Pentagon will inevitably change people's perceptions of the mortality risks to people on the ground from crashing airplanes. Goldstein and colleagues were the first to quantify the risk for Americans of being killed on the ground from a crashing airplane for unintentional events, providing average point estimates of 6 in a hundred million for annual risk and 4.2 in a million for lifetime risk. They noted that the lifetime risk result exceeded the commonly used risk management threshold of 1 in a million, and suggested that the risk to “groundlings” could be a useful risk communication tool because (a) it is a man-made risk (b) arising from economic activities (c) from which the victims derive no benefit and (d) exposure to which the victims cannot control. Their results have been used in risk communication. This analysis provides updated estimates of groundling fatality risks from unintentional crashes using more recent data and a geographical information system approach to modeling the population around airports. The results suggest that the average annual risk is now 1.2 in a hundred million and the lifetime risk is now 9 in ten million (below the risk management threshold). Analysis of the variability and uncertainty of this estimate, however, suggests that the exposure to grounding fatality risk varies by about a factor of approximately 100 in the spatial dimension of distance to an airport, with the risk declining rapidly outside the first 2 miles around an airport. We believe that the risk to groundlings from crashing airplanes is more useful in the context of risk communication when information about variability and uncertainty in the risk estimates is characterized, but we suspect that recent events will alter its utility in risk communication.

KEY WORDS: risk assessment, risk communication, airplane accidents, ground fatalities

1. INTRODUCTION

Every few months, news media remind us that airplane accidents may kill people on the ground. For example, on October 4th, 1992, a freight carrier crashed into an apartment building in Amsterdam, The Netherlands, killing 43 people on the ground. On July 25th, 2000, a few minutes after taking off, a Concorde heading from Paris, France to New York City crashed into a hotel killing all 109 on board and 4 people on the ground. In 1986, an air carrier and a small general aviation aircraft collided in Cerritos, California and went crashing into several houses killing all the people on board both planes and 15 people on the ground.

At the time this article was accepted for publication the impact of intentional plane crashes to people...
on the ground in America was limited to a few suicidal cases, distant memories associated with Pearl Harbor, and popular fiction such as Tom Clancy’s *Debt of Honor*. However, the events of September 11, 2001 provide an important reminder that sometimes the worst-case scenario does occur, no matter how unlikely, and people’s perceptions of the risks of dying on the ground from a crashing airplane have inevitably changed along with perceptions of the risks of flying. Whereas previous studies have simply talked about the risk to groundlings from crashing airplanes, all studies post-September 11, 2001 will need to clearly differentiate between intentional and unintentional crashes in characterizing ground fatality risks.

In 1992, Goldstein et al. quantitatively estimated the fatality risks to people on the ground from crashing airplanes associated with crashes that occurred between 1975 and 1985, and thus focused on accidents or unintentional events. They used data provided by the National Transportation Safety Board (NTSB) and reported that 150 groundling fatalities occurred due to aviation accidents during that 11-year period. Using the 1980 U.S. residence population as a base, Goldstein et al. estimated the fatality risk of being hit by a crashing airplane while on the ground as 0.06 per million per year or a 70-year lifetime risk of 4.2 per million. They noted that the risk was above the 1 in a million threshold enshrined in many regulatory approaches and suggested that the risk of being killed by a crashing airplane could be a useful risk communication tool, especially for comparisons with chemical and physical hazards in the environment. Subsequently, their estimate has been used for risk communication purposes.

Since the period of 1975 to 1985, the accident and fatality rates have decreased significantly, due to the introduction of new technologies. However, increases in air traffic and greater congestion of airspace, especially around airports, could lead to offsetting effects. Given these important changes, we decided to perform an analysis of recent data to update the estimate of the risk to groundlings specifically from accidental airplane crashes. Our preliminary review of crash data suggested that the majority of aviation crashes occurred in the vicinity of an airport, which implies that people who live near an airport are at higher risk. Although Goldstein et al. mentioned the issue of variability, they did not quantify it. We performed a study to simultaneously update the estimates of risks to people on the ground from unintentional crashes and to quantify spatial variability in the dimension of distance to the airport.

This analysis also distinguished the three different aviation categories: air carriers, air taxis and commuters, and general aviation. We used definitions from the Terminal Area Forecast System, which defines air carriers as commercial aircraft with seating capacity of more than 60 seats, air taxis and commuters as commercial aircraft that have a maximum of 60 seats (including both scheduled commuter flights and nonscheduled or for-hire flights), and general aviation aircraft as all civil (nonmilitary) aircraft not classified as air carrier or air taxi/commuter. In the present study, a groundling accident or grounding crash was defined as an aviation accident (unintentional) that killed at least one groundling. A distinction was also made between those fatalities of people who were involuntarily exposed (consistent with the context discussed by Goldstein et al.) and those who were exposed voluntarily either by being on the airstrip or by otherwise having a connection with the plane that killed them. We included among the people exposed involuntarily those who live on private property near airports, because no policies exist to prevent them from doing so or to warn them about the risk, even though some might reasonably suspect that living near an airport leads to heightened exposure. We generally reserved the use of the term “groundling fatality” to imply the death of someone on the ground involuntarily exposed to the risk from the crashing non-military airplane as discussed by Goldstein et al.

### 2. UPDATE OF THE AVERAGE RISK OF GROUNDLING FATALITIES

#### 2.1. Grounding Fatality Data

A review of the accident database of the NTSB provided a list of civil aviation accidents in which fatalities to people on the ground occurred. However, not all the offboard fatalities in this database qualify as “groundling fatalities” in the sense used here to refer generally to people killed by planes falling out of the sky in accidents. For example, we do not classify a ground crewmember who died because he walked into a propeller as an involuntarily exposed groundling fatality, but rather as an occupational fatality. Similarly, a bystander who is hit by a landing airplane while taking pictures on the runway has voluntarily exposed himself to higher risk and does not contribute to involuntary grounding risk.

We reviewed all civil aviation accidents that killed people on the ground in the United States in the period 1964 to 1999 and classified the fatalities as...
resulting from voluntary or involuntary exposure. Voluntarily exposed groundling fatalities and all occupational casualties were removed from the database. Although several sources were consulted to confirm the “voluntary” nature of the ground fatalities, including accident-related newspaper articles and NTSB accident abstracts and accident reports, the nature of some of the groundling fatalities remained unknown (and are referred to as unconfirmed involuntary groundling fatalities). Figure 1 shows the annual number of groundling fatalities due to aviation accidents since 1964.

2.2. Approach

The following formula is used to estimate the average groundling risk for the year 2000:

\[
\text{average groundling risk} = \frac{\text{expected number of groundling fatalities in U.S. in 2000}}{\text{U.S. resident population in 2000}}. \tag{1}
\]

The U.S. Census Bureau estimated that the U.S. resident population in the year 2000 was approximately 275 million people. Applying Equation (1) requires an estimate of the expected number of groundling fatalities in 2000. The easiest approach to estimate this expected number is to divide the number of groundling fatalities in 1964 to 1999 (205) by the duration of the period (26 years). This simple model results in an estimate of 7.9 groundling fatalities per year in 2000. However, Fig. 1 shows that the annual number of groundling fatalities has followed a decreasing trend since 1964, and thus using groundling fatality data from 1964 to 1999 to estimate the expected number of groundling fatalities in 2000 is likely to overestimate the true number. Therefore, we adopted the following approach.

Consider the stochastic process where \( N_{\text{ground fatalities}}(t) \) is the number of groundling fatalities in year \( t \) and we are interested in estimating \( E\left[N_{\text{ground fatalities}}(2000)\right] \), the expected number of groundling fatalities in the year 2000 to apply Equation (1). The number of groundling fatalities in year \( t \), \( N_{\text{ground fatalities}}(t) \), depends on the number of groundling accidents in year \( t \), \( N_{\text{ground accidents}}(t) \), and the number of groundling fatalities occurring in one grounding accident, \( F/A \), where a grounding accident means that at least one person on the ground is killed. When we assume independence between these two stochastic variables, then \( E[N_{\text{ground fatalities}}(t)] \) can be estimated as:

\[
E[N_{\text{ground fatalities}}(t)] = E[F/A] E[N_{\text{ground accidents}}(t)]. \tag{2}
\]

Accidents and mortality rates can be measured by different units of exposure, depending on the activity and the availability of data. For example, for the grounding accident rate, we could use three potential units of exposure: per year, per million airport operations (takeoff or landing), or per million hours flown. In this analysis, we decided to measure accident rates per airport operation, because about 70% of all aviation accidents involving commercial jets and 60% of the accidents involving general aviation aircraft occur during the landing, final approach, takeoff, or initial climb. Because airport-related operations are the most risky phases of a flight, the aviation industry frequently measures the risk per airport operation, which makes it easier to compare risks at busy and nonbusy airports and to generate forecasts of the grounding fatality risk in the future (using projections of the number of airport operations). Finally, the grounding accident rate per operation has not fluctuated significantly since the late eighties and, therefore, the current rate per operation can be reasonably estimated by using data from the last decade (see discussion below). Thus, Equation (2) is expanded to include the expected number of operations in year \( t \), \( E[O(t)] \), to become:

\[
E[N_{\text{ground fatalities}}(t)] = E[F/A] E[N_{\text{ground accidents}}(t)/O] E[O(t)], \tag{3}
\]

where \( E[N_{\text{ground accidents}}(t)/O] \) is the number of ground accidents per operation in year \( t \).

We estimated the quantities \( E[F/A] \) and \( E[N_{\text{ground accidents}}(t)/O] \) from the data discussed above and used the data on the number of airport operations at U.S. airports for 1978 to 1999 and forecasts for 2000 to 2015 provided by the Terminal Area Forecast system of the Federal Aviation Administration (FAA).
Figure 2 shows that the grounding accident rate per operation decreased significantly between 1964 and the late 1980s, but that the rate has remained relatively constant since the late 1980s. Based on these data, we believe that the current grounding accident rate per operation can be estimated reasonably by using grounding accident data since 1987. Large differences exist in grounding accident rates and crash consequences among aviation categories, so this analysis distinguishes among them. Table I shows the grounding accident rates per operation.

The data provided no indication that the number of grounding fatalities per grounding accident changed for any of the aviation categories since 1964. Consequently, the expected number of grounding fatalities per grounding accident was estimated using data from 1964 to 1999. Table II presents the calculations and results, and Fig. 3 graphs the number of fatalities per grounding accident for the whole set of accidents. Collisions between aircraft of different categories that caused grounding fatalities are modeled as two separate accidents with only half of the fatalities.

### Table I. Estimates of the Current Grounding Accident Rates per Operation for Air Carriers, Air Taxis/Commuters, and General Aviation

<table>
<thead>
<tr>
<th>Category</th>
<th>Air carrier</th>
<th>Air taxi/commuter</th>
<th>General aviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of grounding accidents in 1987–1999&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2</td>
<td>4</td>
<td>14</td>
</tr>
<tr>
<td>Number of airport operations in millions 1987–1999&lt;sup&gt;b&lt;/sup&gt;</td>
<td>174.5</td>
<td>174.3</td>
<td>1,413.4</td>
</tr>
<tr>
<td>Grounding accident rate per million operations&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.011</td>
<td>0.023</td>
<td>0.0099</td>
</tr>
</tbody>
</table>

<sup>a</sup> Counting collisions between aircraft of different categories in each category because two planes were involved in the accident (total number of grounding accidents is 19, which includes one collision between an air carrier and general aviation and one collision between an air taxi/commuter and general aviation).

<sup>b</sup> Numbers are provided by the Terminal Area Forecasting system of the Federal Aviation Administration.<sup>9</sup>

<sup>c</sup> Grounding accident is an accident that causes at least one grounding fatality.

### Table II. Estimates of the Expected Number of Grounding Fatalities per Grounding Accident for Air Carriers, Air Taxis/Commuters, and General Aviation

<table>
<thead>
<tr>
<th>Category</th>
<th>Air carrier</th>
<th>Air taxi/commuter</th>
<th>General aviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of grounding accidents in 1964–1999&lt;sup&gt;a&lt;/sup&gt;</td>
<td>14</td>
<td>11</td>
<td>66</td>
</tr>
<tr>
<td>Number of grounding fatalities in 1964–1999&lt;sup&gt;b&lt;/sup&gt;</td>
<td>60</td>
<td>25</td>
<td>120</td>
</tr>
<tr>
<td>Expected number of grounding fatalities per grounding accident</td>
<td>4.3</td>
<td>2.3</td>
<td>1.8</td>
</tr>
</tbody>
</table>

<sup>a</sup> Counting collisions between aircraft of different categories in each category because two planes were involved in the accident (88 accidents total includes two collisions between general aviation and air carriers and one accident between general aviation and an air taxi/commuter).

<sup>b</sup> Grounding fatalities that resulted from a collision between aircraft of different categories were evenly divided.

#### Fig. 2. The grounding accident rate for the period 1970–1999.

#### Fig. 3. The number of grounding fatalities per grounding accident.

#### 2.3. Grounding Fatality Risk in 2000

The FAA Terminal Area Forecasting system provided projections of the airport activity at U.S. airports in 2000: 15.5 million air carrier operations, 14.6 million air taxi/commuter operations, and 113.1 million general aviation operations. The expected number of grounding fatalities in 2000 caused by crashing aircraft can be estimated by applying Equation (3) to each aviation category.
Grounding Fatalities from Airplane Crashes

Table III. Projections of the Number of Airport Operations at U.S. Airports for Three Categories

<table>
<thead>
<tr>
<th>Year</th>
<th>Air carrier</th>
<th>Air taxi/commuter</th>
<th>General aviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>15.48</td>
<td>14.58</td>
<td>113.12</td>
</tr>
<tr>
<td>2005</td>
<td>17.45</td>
<td>15.84</td>
<td>117.48</td>
</tr>
<tr>
<td>2010</td>
<td>19.66</td>
<td>17.07</td>
<td>121.99</td>
</tr>
<tr>
<td>2015</td>
<td>22.00</td>
<td>18.31</td>
<td>126.69</td>
</tr>
</tbody>
</table>

Source: Terminal Area Forecasting system of the Federal Aviation Administration.  

Air carrier:  
\[0.011 \times 4.3 \times 15.5 = 0.7 \text{ groundling fatalities}\]

Air taxi/commuter:  
\[0.023 \times 2.3 \times 14.6 = 0.8 \text{ groundling fatalities}\]

General aviation:  
\[0.0099 \times 1.8 \times 113.1 = 2.0 \text{ groundling fatalities}\]

Total: 3.5 groundling fatalities

These results show that general aviation accounts for 60% of the expected groundling fatalities in 2000, and that air carriers and air taxis/commuters each account for 20%. Using a U.S. resident population in 2000 of 275 million, the annual risk of dying due to a crashing aircraft for a random U.S. resident, \(X\), can then be estimated by applying Equation (1):

\[P(X \text{ dies due to crashing aircraft in 2000}) = \frac{3.5}{275 \text{ million}} = 1.3 \times 10^{-8}. \quad (4)\]

The corresponding 70-year lifetime risk is equal to \(9 \times 10^{-7}\) (or the 75-year lifetime risk rounds up to \(1 \times 10^{-6}\)), which is just under (or right at) the one in a million de minimis risk management threshold.


Based on this approach and available forecasts, we consider the impact of current projections on estimates of grounding risks for the years 2005, 2010, and 2015 according to the same procedure used above. Table III presents the estimates provided by the FAA for future airport activity; all other quantities of interest, including the grounding accident rate, are assumed to remain unchanged in the next 15 years. Table IV presents the results and shows that the average individual risk of grounding fatalities in the United States is expected to remain relatively even, although the population risk increases from 3.5 fatalities in 2000 to 4.3 fatalities in 2015. The individual risk remains constant because the U.S. resident population is expected to grow from 275 million in 2000 to 312 million in 2015.  

These projections assume that the estimates provided by the FAA for future airport activity are correct (Table III) and simply show the consequences of changes in projected airport activity for the risk of grounding fatalities, given that all other quantities remain unchanged. The FAA bases its projections of airport activity on a scenario analysis that assumes a strong relation between the economic climate and the aviation activity, and, unfortunately, it does not provide any uncertainty analysis. Annual percent changes of activity are derived for each aviation category making fundamental economic assumptions concerning future economic growth, fuel prices, and interest rates. We note that given the recent hijackings and their repercussions on the economy, these estimates might be significantly different than what will occur if Americans significantly and permanently reduce the amount they travel by air, and we expect that future projections might revise these estimates downward.

Table IV. Projections of the Risk of Groundling Fatalities due to Uncontrollable Aviation Accidents 2000–2015

<table>
<thead>
<tr>
<th>Year</th>
<th>Population risk(^a)</th>
<th>Projection of U.S. population (in thousands)(^b)</th>
<th>Annual individual risk</th>
<th>Corresponding 75-year lifetime risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>3.5</td>
<td>275,306</td>
<td>(1.3 \times 10^{-8})</td>
<td>(9.5 \times 10^{-7})</td>
</tr>
<tr>
<td>2005</td>
<td>3.8</td>
<td>287,716</td>
<td>(1.3 \times 10^{-8})</td>
<td>(9.9 \times 10^{-7})</td>
</tr>
<tr>
<td>2010</td>
<td>4.0</td>
<td>299,862</td>
<td>(1.3 \times 10^{-8})</td>
<td>(1.0 \times 10^{-6})</td>
</tr>
<tr>
<td>2015</td>
<td>4.3</td>
<td>312,268</td>
<td>(1.3 \times 10^{-8})</td>
<td>(1.0 \times 10^{-6})</td>
</tr>
</tbody>
</table>

\(^a\) Expected annual number of groundling fatalities.  
\(^b\) Population projections from U.S. Census Bureau.  

2000

Air carrier:
0.011
3
4.3
3
15.5
5
0.7 groundling fatalities

Air taxi/commuter:
0.023
3
2.3
3
14.6
5
0.8 groundling fatalities

General aviation:
0.0099
3
1.8
3
113.1
5
2.0 groundling fatalities

Total: 3.5 groundling fatalities

These results show that general aviation accounts for 60% of the expected groundling fatalities in 2000, and that air carriers and air taxis/commuters each account for 20%. Using a U.S. resident population in 2000 of 275 million, the annual risk of dying due to a crashing aircraft for a random U.S. resident, \(X\), can then be estimated by applying Equation (1):

\[P(X \text{ dies due to crashing aircraft in 2000}) = \frac{3.5}{275 \text{ million}} = 1.3 \times 10^{-8}. \quad (4)\]

The corresponding 70-year lifetime risk is equal to \(9 \times 10^{-7}\) (or the 75-year lifetime risk rounds up to \(1 \times 10^{-6}\)), which is just under (or right at) the one in a million de minimis risk management threshold.
The projections also assume that all the other quantities of interest for the grounding fatality risk, including the grounding accident rate per operation, will remain unchanged in the next 15 years. In the last 50 years, accident and fatality rates in aviation have significantly decreased due to technological developments.\textsuperscript{(11)} However, the decrease has leveled off in the last decade,\textsuperscript{(12)} and the grounding accident rate per airport operation seems to have followed the same trend (Fig. 2), although it is more difficult to observe because grounding accidents are rare events. The baseline scenario assumes that grounding accident rates per operation remain constant until 2015 for each aviation category, even though the population is expected to grow from 275 million to 312 million in 2015. An increase in the population might increase the grounding fatality rate, because a crashing aircraft is more likely to hit a grounding. On the other hand, new technologies and better information sharing between airlines, NTSB, and FAA\textsuperscript{(12)} may decrease the accident and fatality rates in general. In the last 13 years, the grounding accident rate per operation remained relatively constant despite an increase in population from 242 million in 1987 to 275 million in 1999 and introductions of several new technologies. Presumably, both effects canceled each other, resulting in an approximately constant grounding accident per operation in the last decade. We expect that this trend will continue, and consequently assume that the grounding accident rates per operation will remain relatively constant in the near future.

All of these point estimates ignore the data that suggests that people near an airport experience a higher grounding fatality risk than those who are farther away because most aviation accidents occur during landing or takeoff. To account for this factor, a method was applied to quantify the spatial variability of the risk in the dimension of distance to an airport.

3. VARIABILITY OF THE GROUNDLING FATALITY RISK

3.1. Mathematical Representation of the Variability of the Grounding Fatality Risk

To consider variability we must begin by mathematically defining what we mean by the variability of the risk. Consider a random U.S. resident, \( X \), and define the following event:

\[ B_{[t, t + \Delta t]}(X) : \{ X \text{ becomes a grounding fatality in } [t, t + \Delta t] \} \]

The probability \( P[B_{[t, t + \Delta t]}(X)] \) represents the involuntary risk of death for individual \( X \) due to a crashing aircraft in the time interval \([t, t + \Delta t]\). As mentioned above, airplanes are more likely to crash in the vicinity of an airport, and consequently, individuals who spend most of their time close to an airport are at higher risk. This analysis quantifies the variability of the risk associated with the dimension of distance to an airport. The following stochastic quantity defines the behavior of individual \( X \) with respect to this dimension:

\[ D(X, t) : \text{Distance between individual } X \text{ and the nearest airport at time } t. \]

\( D(X, t) \) is a stochastic process parameterized by time. Consider a time interval \( \Delta t \) and distance interval \( \Delta d \) and define the following event:

\[ A_{[t, t + \Delta t]}^{(d, d + \Delta d)}(X) = \{ D(X, \tilde{t}) \in [d, d + \Delta d] : \tilde{t} \in [t, t + \Delta t] \} \]

Then, \( P[B_{[t, t + \Delta t]}(X) | A_{[t, t + \Delta t]}^{(d, d + \Delta d)}(X)] \) is the probability \( X \) becomes a grounding fatality in \([t, t + \Delta t]\), given that \( X \) stays within \([d, d + \Delta d]\) for that time interval. Applying Bayes’ theorem to this conditional probability results in:

\[
P[B_{[t, t + \Delta t]}(X) | A_{[t, t + \Delta t]}^{(d, d + \Delta d)}(X)] = \frac{P[A_{[t, t + \Delta t]}^{(d, d + \Delta d)}(X) | B_{[t, t + \Delta t]}(X)] P[B_{[t, t + \Delta t]}(X)]}{P[A_{[t, t + \Delta t]}^{(d, d + \Delta d)}(X)]}.
\] (5)

The left-hand side of Equation (5) represents the quantity of interest with respect to the spatial variability of the risk in the dimensions time and distance to an airport. The distance conditional grounding mortality rate is:

\[
h_{X,d}(t) = \lim_{\Delta t \to 0} \left( \frac{P[B_{[t, t + \Delta t]}(X) | A_{[t, t + \Delta t]}^{(d, d + \Delta d)}(X)]}{\Delta t} \right),
\] (6)

and the general grounding mortality rate is:

\[
\lambda_{X}(t) = \lim_{\Delta t \to 0} \frac{P[B_{[t, t + \Delta t]}(X)]}{\Delta t}.
\] (7)

Define the following distribution functions:

\[
G_{X,d}(d) = \lim_{\Delta t \to 0} P[D(X, \tilde{t}) \leq d : \tilde{t} \in [t, t + \Delta t] | B_{[t, t + \Delta t]}(X)]
\] (8)

\[
F_{X,d}(d) = \lim_{\Delta t \to 0} P[D(X, \tilde{t}) \leq d : \tilde{t} \in [t, t + \Delta t] \}
\] (9)

\( G_{X,d}(d) \) and \( F_{X,d}(d) \) are cumulative distribution functions in \( \Delta t \) and \( d \) are defined for all \( t \). Further, the related
density functions (assuming that $G_X(d)$ and $F_X(d)$ are differentiable, are defined as:

$$g_X(d) = \frac{\partial}{\partial d} G_X(d),$$  
(10)

$$f_X(d) = \frac{\partial}{\partial d} F_X(d).$$  
(11)

Although these functions are defined as a limit, the interpretations of the distributions are clear:

$G_X(d)$: The probability that $X$ is within distance $d$ of an airport at time $t$, given that $X$ becomes a groundling fatality at time $t$.

$F_X(d)$: The probability that $X$ is within distance $d$ of an airport at time $t$.

In fact, $G_X(d)$ represents a groundling fatality distribution function, and $F_X(d)$ is the distribution function of the population, both parameterized by the distance to an airport. The functions $G_X(d)$, $F_X(d)$, $g_X(d)$, and $f_X(d)$ can, under appropriate assumptions, be estimated from data. The following expression can be derived by first applying Bayes’ Theorem according to Equation (5) and then calculating the limit in Equation (6):

$$h_{X,d}(t) = \frac{g_{X}(d)}{f_{X}(d)} \Lambda_X(t)$$  
(12)

This analysis focuses on the spatial variability of the risk associated with the dimension distance to an airport and the risks are measured per year. Therefore, the following hypothetical risk is considered:

The risk that an individual becomes a groundling fatality in 2000, given that this individual stays at distance $d$ away from the nearest airport for the whole year. Notation: $P[B_{2000}(X)\mid A^d_{2000} (X)]$.

The risk is hypothetical because nobody stays at exactly distance $d$ of the nearest airport for a year, but it is the most reasonable measure to quantify the current spatial variability of the risk. Assuming that each of the quantities on the right-hand side of Equation (12) are constant within the year 2000, then the hypothetical risk for groundling fatality in 2000 can be calculated as:

$$P[B_{2000}(X)\mid A^d_{2000}(X)] = \int_{2000}^{2001} h_{X,d}(t) dt$$  
(13)

$$= \frac{g_{X,2000}(d)}{f_{X,2000}(d)} P[B_{2000}(X)].$$

The risk for a random individual $X$ to become a groundling fatality in 2000, $P[B_{2000}(X)]$, is estimated in the previous subsection as $1.3 \times 10^{-8}$ [see Equation (4)]. Equation (13) formed the basis of the method that was used to quantify the spatial variability of the groundling fatality risk. However, a close examination of the available groundling fatality data showed that some adjustments were needed to better quantify the variability of the risk.

3.2. Grounding Risk Model

A close analysis of the data showed that directly applying Equation (13) would not result in properly estimating the variability of the grounding risk. Further distinction is required for airport-related and airport-unrelated accidents, and to aggregate by aviation category.

An analysis of the grounding accident data showed that most accidents occurred during take-off or landing, but that sometimes aircraft lose control during the cruising phase, and crash and cause grounding fatalities in areas other than airport regions. Because of the format of the data, we do not always know in which phase of flight an aircraft was when it crashed. Thus, the following definition of an airport-related accident was used:

An accident is related to an airport if the airport is registered with the FAA, is the origin or the final destination of the flight, and the accident occurred within 10 miles of the airport.

Consider the following events:

$B_{2000,\text{related}}(X)$: $\{X$ becomes a groundling fatality due to an airport-related accident in 2000\}$

$B_{2000,\text{unrelated}}(X)$: $\{X$ becomes a groundling fatality due to an airport-unrelated accident in 2000\}$

Note that $B_{2000,\text{unrelated}}(X)$ and $B_{2000,\text{related}}(X)$ are disjunct and that

$$B_{2000}(X) = B_{2000,\text{related}}(X) \cup B_{2000,\text{unrelated}}(X),$$

and consequently,

$$P[B_{2000}(X)\mid A^d_{2000} (X)] = P[B_{2000,\text{related}}(X)\mid A^d_{2000} (X)]$$

$$+ P[B_{2000,\text{unrelated}}(X)\mid A^d_{2000} (X)].$$  
(14)

Although airport-unrelated grounding fatalities are more likely to occur on flight paths, it is reasonable to assume that the airport-unrelated grounding risk is location independent [variability of the airport-unrelated
risk can be neglected to the variability of the airport-related risk in Equation (14):

\[ P[B_{2000}(X) | A_{2000}^d(X)] = P[B_{2000,unrelated}(X)]. \]  

(15)

Because the airport-related grounding risk strongly depends on the distance to the airport, the second term on the right-hand side of Equation (14) is rewritten by applying the same approach as presented in Section 3.1 [compare with equation (13)]:

\[ P[B_{2000}(X) | A_{2000}^d(X)] = \frac{g_{X,2000,related}(d)}{f_{X,2000}(d)} P[B_{2000,related}(X)] + P[B_{2000,unrelated}(X)]. \]  

(16)

with

\[ g_{X,2000,related}(d) = \frac{\partial}{\partial d} G_{X,2000,related}(d). \]  

(17)

\[ G_{X,2000,related}(d): \text{The probability that } X \text{ is within distance } d \text{ of the related airport at time } t \text{ given that } X \text{ becomes an airport-related grounding fatality at time } t, t \in (2000, 2001). \]

The difference between \( g_{X,2000}(d) \) and \( g_{X,2000,related}(d) \) is that the last grounding density function only applies to airport-related grounding fatalities. The second conclusion of the data analysis addressed the need to aggregate by aviation category in order to properly model the variability of the grounding risk. Therefore, the following events were defined:

\[ B_{AC,2000,unrelated}(X): \{ X \text{ becomes a grounding fatality due to an airport-unrelated air carrier accident in 2000} \} \]

\[ B_{2000,unrelated}(X): \{ X \text{ becomes a grounding fatality due to an airport-unrelated air taxi or commuter accident in 2000} \} \]

\[ B_{GA,2000,unrelated}(X): \{ X \text{ becomes a grounding fatality due to an airport-unrelated general aviation accident in 2000} \} \]

These events are disjunct and

\[ B_{2000,unrelated}(X) = B_{AC,2000,unrelated}(X) \cup B_{AT,2000,unrelated}(X) \cup B_{GA,2000,unrelated}(X). \]

Applying the same method as in Section 3.1 to each aviation category results in the following equation:

\[ P[B_{2000}(X) | A_{2000}^d(X)] = P[B_{2000,unrelated}(X)] \]

\[ + \frac{g_{X,2000,AC}(d)}{f_{X,2000}(d)} P[B_{2000,AC,unrelated}(X)] + \frac{g_{X,2000,AT}(d)}{f_{X,2000}(d)} P[B_{2000,AT,unrelated}(X)] \]

\[ + \frac{g_{X,2000,GA}(d)}{f_{X,2000}(d)} P[B_{2000,GA,unrelated}(X)]. \]  

(18)

The distance to the nearest Top100 airport is denoted as \( d_{Top100} \), and \( B_{AC,2000,related}(X) \) represents the grounding risk due to Top100-related air carrier accidents in the year 2000. Given our assumptions, this equation applies for \( d_{Top100} < 10 \) miles. The airport-unrelated risk in this formula corresponds to all remaining grounding risk due to aircraft flying overhead. The variability of the grounding risk associated with the Top100 airports is derived by separately estimating the quantities on the right-hand side of Equation (19).

3.3. Variability Associated with Different Airport Groups

Great diversity exists among the airports in activity and facilities. Approximately 650 airports have a certification that allows air carriers to use these airports (certification is under Federal Activation Regulation part 139), and the 30 largest airports account for 70% of all enplanements.\(^{(13)}\) Consequently, it is expected that the risk of grounding fatalities is higher in the vicinity of busy airports than around less busy airports. As a result, in this study three different airport groups were separately analyzed, to account for the differences in the types of airports: the busiest 100, 250, and 2,250 airports, denoted as the Top100, Top250, and Top2250 airport lists. Our analysis for the Top100 airport list is described, and only the results for the Top250 and Top2250 lists are presented. The method is described qualitatively; for details see Rabouw.\(^{(14)}\)

Consider the 100 busiest airports (highest airport activity) in the United States and ignore the airport-related risk of all other airports. For this case, the variability of the grounding risk associated with the Top100 airports can be written as [see Equation (18)]:

\[ P[B_{2000}(X) | A_{2000}^d(X)] = P[B_{2000,unrelated}(X)] \]

\[ + \frac{g_{X,2000,AC}(d_{Top100})}{f_{X,2000}(d_{Top100})} P[B_{AC,2000,related}(X)] \]

\[ + \frac{g_{X,2000,AT}(d_{Top100})}{f_{X,2000}(d_{Top100})} P[B_{AT,2000,related}(X)] \]

\[ + \frac{g_{X,2000,GA}(d_{Top100})}{f_{X,2000}(d_{Top100})} P[B_{GA,2000,related}(X)]. \]  

(19)
3.4. Top100-Airport Related and Unrelated Grounding Risk

Each grounding accident was classified as airport-related or airport-unrelated according to the definition in Section 3.2. General aviation accidents tend to be more often airport-unrelated than commercial aviation (air carrier or air taxi/commuter) accidents. Reasons for this difference might be that general aviation aircraft can land on and take off from lakes, rivers, non-registered airfields, and highways (emergency landing when the aircraft runs out of fuel), whereas commercial flights must follow a predetermined flight plan that minimally defines an FAA-registered destination, and commercial aircraft normally do not run out of fuel.

A review of the grounding accident data from the period 1978 to 1999 showed that 13 of the 35 accidents in which general aviation aircraft were involved were airport unrelated. Only 2 of the 15 accidents with grounding fatalities that involved commercial aircraft were airport unrelated. The results are presented in Table V.

In Section 2.3 we estimated 2.0 expected groundling fatalities due to general aviation accidents. Using the percentage in Table V results in an estimate of the expected number of groundling fatalities due to airport-unrelated general aviation accidents of 2.0.

The FAA forecasts of airport activity at Top100 airports in 2000 were 13.3 million air carrier operations, 6.9 million air taxi/commuter operations, and 11.4 million general aviation operations. The 13.3 million air carrier operations imply an expected number of 13.3 \times 0.011 = 0.15 grounding accidents in 2000 (see Table I for the grounding accident rate per air carrier operation of 0.011). We assumed that 87% (Table V) of these accidents would be airport related (to Top100 airports), corresponding to 0.15 \times 0.87 = 0.13 Top100-related grounding accidents. Each accident was expected to cause 4.3 grounding fatalities (Table II), and the expected number of Top100-related general aviation accidents in 2000 can then be estimated as 0.13 \times 4.3 = 0.55 for air carriers. For air taxis/commuters we estimated 0.32 grounding fatalities in 2000 and 0.13 for general aviation, implying a total of 1 grounding fatality for Top100 airports in 2000. Considering a U.S. residence population in 2000 \((X)\) is a random U.S. resident) results in the estimates of the following average Top100-related risks:

\[
P[B_{2000,\text{related}}(X)] = 0.55 \frac{275\text{ million}}{275\text{ million}} = 0.20 \times 10^{-9}, (21)
\]

\[
P[B_{2000,\text{not-related}}(X)] = 0.32 \frac{275\text{ million}}{275\text{ million}} = 1.2 \times 10^{-9}, (22)
\]

\[
P[B_{2000,\text{GA,related}}(X)] = 0.13 \frac{275\text{ million}}{275\text{ million}} = 4.7 \times 10^{-10}. (23)
\]

Note that these are average risks and that Top100-related grounding fatalities only occur within 10 miles of a Top100 airport.

3.5. Fatality Density Functions

We used Equation (19) to estimate the variability of the grounding risk and, consequently, we needed estimates of the fatality density functions for each aviation category, \(g_{2000,X}(d), g_{2000,X}(d), \) and \(g_{2000,X}(d).\) Fatality and crash density functions are not expected to significantly change over time and, therefore, we based our estimates on locations of crashes that killed groundlings since 1978. Further, we assumed that the expected number of grounding fatalities per accident, given at least one grounding fatality, does not depend on the distance between the accident and the related airport. Thus, the grounding fatality density function and the grounding crash density function are assumed to be identical. The grounding

<table>
<thead>
<tr>
<th>Table V. Number of Airport-Related and Unrelated Accidents Since 1978</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air taxi/commuter and air carrier</td>
</tr>
<tr>
<td>-----------------------------------------------</td>
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<tr>
<td>Number of airport-related accidents</td>
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<td>Number of airport-unrelated accidents</td>
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fatality density function only applies to airport-related groundling accidents. We determined the accident locations of the 35 airport-related accidents that caused groundling fatalities since 1978. The distances between accident locations and the related airports were measured and used to construct groundling crash density functions parameterized by the distance to the related airport. The groundling fatality density functions for air taxis/commuters and air carriers are similar, and are different from that of general aviation; the data do not support further disaggregation.

The crash density functions (and the corresponding histograms) for general aviation and commercial aviation (air carriers and air taxis/commuters) are presented in Fig. 4 and Fig. 5, respectively. The density functions are of the form $e^{-e^{a d} + b}$, and the parameters are fitted using maximum likelihood estimation. These crash density functions of the same form were used in a study that evaluated the external risk around Schiphol, The Netherlands.\(^{(15)}\) Note that the fatality density functions are parameterized by distance to the related airport.

### 3.6. Geographical Information System Model

Equation (19) also requires a population density function parameterized by the distance to a Top100 airport: $f_{X,2000}(d_{Top100})$. Consider the distribution function $F_{\chi_{d}}(d)$ with distance $d$ to an airport, with the following interpretation (where $X$ is a random U.S. resident):

$$F_{\chi_{d}}(d) = P[X \text{ is within distance } d \text{ of an airport at time } t]$$

Although people are highly mobile and tend to travel, go to work, or go to school, it is impossible to trace a resident at a random time during the year or even a random time during the day. In addition, people in any given region will have diurnal, seasonal, and yearly patterns of spatial variation. The only available data about how Americans are spatially distributed come from the U.S. Census Bureau data, which contains residence locations for all U.S. residents. In this analysis, $F_{\chi_{d}}(d)$ is estimated based on where U.S. residents live using the Census Bureau database as a proxy for where people spend their time relative to the location of the nearest airport. Given these challenges, we determined that characterizing $F_{\chi_{d}}(d)$ on a finer time scale than allowed by the census data was not worthwhile, and considered $F_{\chi_{d}}(d)$ as averaged over 10 years. At the time of this study, the 2000 census data were not available yet and, therefore, 1990 census data were used. We note that “distance to airport” could be replaced by “distance to a runway flight path” so as to obtain a higher resolution of variation of groundling risk. In our judgment, however, this would require a finer temporal resolution of the population variation than is possible at this juncture. The distribution function $F_{X,2000}(d_{Top100})$ is approximated as follows:

$$F_{X,2000}(d_{Top100}) = P(\text{random } 1990 \text{ U.S. resident } X \text{ is living within } d_{Top100} \text{ miles of a Top100 airport})$$

A Geographic Information System (GIS) model was built to estimate these distribution functions. The model was based on the following procedure:

1. Select a relevant list of airports $L$ (in this case, the Top100 airports).
2. Generate a sample of random U.S. residents and the locations of their residences.
3. Determine the distance to the nearest airport that is in $L$ for each resident in the sample.
4. Use these distances to construct an empirical distribution function that approximates $F_{X,2000}(d_{i})$.
The U.S. Census Bureau does not provide addresses of individuals to third parties due to strict privacy regulations, so we could not get a direct sample of random residents. Fortunately, the Census Bureau provides access to census data for census blocks, the smallest geographic units used in tabulating the 1990 census. The census block data are stored in a database called Master Area Block Level Equivalency (MABLE), which is a collection of 51 state-level datasets containing a total of almost 7 million census blocks. Some variability exists in the area and population per census block, but smaller blocks tend to have a higher population and we determined that we could sample census blocks (weighted by their population) instead of U.S. residents with sufficient precision for this analysis. Figure 6 presents a sample of the results of the GIS modeling (e.g., going out to 5 miles, with the remaining approximately 85% of the U.S. population living more than 5 miles from one of the top 100 airports). Note that the 90% confidence bounds for sampling error (d-wise) for \(F_{X,2000}(d_{top100})\) do not take into account uncertainty associated with mobility and the fact that 1990 census data are used.

4. RESULTS
4.1. Variability of the Groundling Fatality Risk

In this analysis, the variability of the groundling fatality risk associated with Top100 airports is represented by the quantity \(P[B_{2000,Top100-related}(X)]\). This quantity is approximated by applying Equation (19) and the required inputs:

- \(P[B_{2000,unrelated}(X)]\) [Equation (20)];
- \(P[B_{2000,Top100-related}(X)]\);
- \(P[B^{AT}_{2000,Top100-related}(X)]\), and
- \(P[B^{GA}_{2000,Top100-related}(X)]\) [Equations (21), (22), and (23)];

\(g_{2000,X}^{AC}(d_{top100})\), \(g_{2000,X}^{AT}(d_{top100})\), and \(g_{2000,X}^{GA}(d_{top100})\) (Figs. 4 and 5);

\(f_{X,2000}(d_{top100})\) [Fig. 6 shows \(F_{X,2000}(d_{top100})\)].

Combining these estimates resulted in the variability of the annual groundling fatality risk in the dimension of distance to a Top100 airport. The same analysis was performed for two other airport groups, the 250 and 2,250 busiest airports (Top250 and Top2250). Figure 7 presents the results for the three airport lists. Based on this analysis, we conclude that:

1. Risks of groundling fatalities are significantly higher in the vicinity of an airport. The spatial variability of the exposure associated with the dimension distance to an airport is approximately a factor of 100. The variability of the exposure to the groundling fatality risk mainly applies to the first 2 miles around an airport.
2. Risks of groundling fatalities associated with busier airports are higher than risks associated with less busy airports. Differences in exposure between busy and less busy airports mainly apply to the first 2 miles around the airport. The estimate of the average annual exposure within 0.2 miles of a Top100 airport exceeds \(10^{-6}\).

We performed an uncertainty analysis to better interpret the results and concluded that although the uncertainty in this analysis of annual risks is not negligible, variability is a more important factor for the risk of groundling fatalities than uncertainty.

4.2. Limitations

We note that several limitations exist to this approach of determining the spatial variability of the groundling fatality risk. First, the variability is only quantified in the dimension of distance to an airport and variability between busy and less busy airports has been evaluated. A higher resolution of variability could be obtained by considering distance to a runway flight path. As noted above, this should be combined with estimates of population variation on a finer time scale than was possible here.

Evaluations of the risks at airports in Europe (Schiphol Airport, The Netherlands and Farnborough Aerodrome, United Kingdom) show that an-
nual individual risks of $10^{-4}$ may exist at the extension of the runway. If these analyses are correct, then the distance to the runway flight path may account for an additional factor of 100 in the variability of the risk. In addition to risks of groundling fatalities differing among airports due to differences in airport activity, risks also differ because of local variables such as safety procedures, local climate, land use around the airport, and so forth.

The groundling fatality risk shown in Fig. 7 is not the annual risk of an individual residing at distance $d$. Rather, the risk in Fig. 7 is the hypothetical risk of someone remaining at distance $d$ during an entire year, and any given individual will exhibit diurnal and seasonal displacements that may heighten or reduce the risk.

5. DISCUSSION

In 1992, Goldstein et al.\(^{(2)}\) estimated the 70-year lifetime risk to groundlings due to a crashing airplane as 4.2 in a million and suggested the use of this estimate as a risk communication tool for uncontrollable, technological risks. Goldstein et al. used data from 1975 to 1985 to estimate the risk and noted that their estimate of the lifetime risk exceeded 1 in a million, a commonly used risk management threshold. However, we updated the estimate and extrapolated the average point estimate over a 75-year lifetime to yield a lifetime risk estimate of groundling fatalities due to aviation accidents of 0.95 in a million (or a 70-year lifetime risk of 0.9 in a million), just at (or below) the common lifetime risk threshold of 1 in a million.

Goldstein et al.\(^{(2)}\) noted that, “our society seems to have achieved a consensus that governmental action to protect public health is appropriate in environmental matters” in the range of “$10^{-5}$ to $10^{-6}$ lifetime risk” (p. 340). The suggestion is that risks below the $10^{-6}$ lifetime risk threshold require no regulation, but higher risks do require regulation. The current lifetime risk of groundling fatalities due to aviation accidents is just outside this range. However, this risk is not evenly distributed; rather it is concentrated near airports. Most people who accept “the technological risk of becoming a groundling fatality” are not accepting a lifetime risk of one in a million, but a risk that is much lower.

The lifetime hypothetical risk to individuals spending most of their time near the perimeter of an airport could be on the order of $10^{-4}$ according to this analysis, assuming consistency of the model and inputs over that many years, and it may be substantially higher if variability with respect to distance to flight path were taken into account. This could raise the question whether responsible authorities ought to alert residents near an airport of their heightened exposure to this risk. Because airport authorities derive economic benefits from activities that impose heightened risks on nearby residents, discussions regarding remedial and/or compensatory measures might not seem inappropriate. However, it is not clear that people who live near airports do not already derive benefits from their proximity, or that they are not already compensated.

Considerable uncertainty exists about how airplane risks will change over the next several decades and any analysis of lifetime risks should also consider the reality that most people do not live in a single location over the course of their entire lives. In addition, events such as the intentional crashing of airplanes into ground targets will impact not only people’s perceptions of the risks from unintentional events, but also the amount that people travel by air. Although we have not quantified the risks of dying from intentional airplane crashes or the associated spatial variability, we should assume that people who happen to be in or around likely targets will be at much greater risk than those who are not. Consequently, variability exists in this risk as well.

Goldstein et al.\(^{(2)}\) remarked that adjusting one’s lifestyle to reduce the risk of dying due to a crashing airplane seems ludicrous considering the
magnitude of the risk. However, the variability of the risk puts this argument in a different perspective. U.S. residents are free to decide where to live (i.e., where to spend most of their time), and if people are aware of the risk but still choose to live near airports then the risks take on more of a voluntary nature. Given the relatively small magnitude of these risks, it is not unreasonable to think that people might reasonably choose to spend most of their time near an airport because they find the benefits of doing so (e.g., living near work) worth the risk.

We emphasize the importance of variability and uncertainty in risk management and appropriate consideration of their impacts on decisions. At first, the risk of grounding fatalities due to a crashing airplane was presented as a “random” risk (i.e., nonvariable) and it has been used for risk communication purposes several times in that context. A closer analysis of the risk shows that it is highly variable and that the criteria formulated for the comparison do not necessary apply to most U.S. residents. Indeed, once we consider the variability in the risk and the fact that for most people the risk is well below the one in a million threshold, it is very reasonable that most people are not concerned about this very small, but nonzero risk. Explicitly considering the variability shows how misleading it can be to use estimates of average risk that ignore important sources of variability, or apply the estimates to an inappropriate population in the context of risk communication. We hope that this analysis will lead to improved discussions of the impacts of variability in risk.

We expect that the tragic outcomes of the four hijacked airplanes that killed thousands of people on the ground on September 11, 2001 will heighten concern and awareness of this risk and may dramatically alter people’s perception of the magnitude of both intentional and unintentional airplane mortality risks to people on the ground. These events alone will impact the use of grounding fatality risks in risk communication.

ACKNOWLEDGMENT

The authors thank Carol Floyd from the National Transportation Safety Board for helping to access the NTSB accident data files.

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