

A PROBABILISTIC APPROACH TO ASSESSING PASSENGER SURVIVAL IN AIRCRAFT ACCIDENTS NEAR AN AIRPORT AREA

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ABSTRACT

This study proposes a probabilistic model to assess the likelihood of passenger survival in fires resulting from aircraft accidents. The model evaluates the risk of passenger death in a fire, considering the type of aircraft and airline. By comparing the time available for passengers to fully evacuate a burning plane with the time required for evacuation using modern means and technologies, onboard rescue equipment, and the qualifications of crew members and rescue personnel, we introduce a comprehensive approach to quantify passenger survival rates. Additionally, the concept of the hazard coefficient is introduced, which accounts for factors such as cabin temperature and toxic components.

Keywords

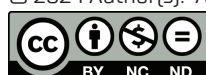
aircraft; aviation incident; statistical model; probability of experiencing an aviation incident; probability of surviving an aviation incident.

1. INTRODUCTION

Global data shows that almost two-thirds of all aviation incidents take place in an airport area during takeoff, approach, and landing, even though these phases constitute only about 4% of total flight time [1,2]. This statistic has remained unchanged since 2001 – as Bill Curtis, airline pilot and leader of the Flight Safety Fund (FSF), notes – and we have been unable to influence this situation in any way [3].

According to Airbus estimates, approximately 4% of landings on any given day do not meet the criteria for a normative (steady state) approach. This corresponds to data from IATA audits of flight safety, which found that 3.4% of approaches are non-normative. In the United States, for example, there are approximately a thousand

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non-normative approaches daily out of 10 million flights annually on local and international routes.

More concerning is that in over 90% of these non-normative approaches, pilots proceed with executing the landing, resulting in aviation incidents near airports. This statistic is similar in Europe and globally. Aviation incidents can generally be categorized into three groups:

- Fatal (Non-Survivable): Incidents where no crew or passengers survive,
- Partially Survivable: Incidents where some crew and passengers survive,
- Non-Fatal (Survivable): Incidents where all crew and passengers survive.

Nearly 90% of all aviation incidents are classified as survivable or partially survivable. Consequently, normative documents include provisions for the organization and execution of search-and-rescue operations in airport areas [4,5].

Ensuring the survival of people and mitigating the consequences of ground fires in such incidents can be achieved by adhering to the following requirements:

- fire-extinguishing efforts on an aircraft must commence before dangerous fire factors exceed maximum permissible values,
- the time for fire localization and extinguishment must not exceed set values,
- the time to localize non-communicative fires must be sufficient for the evacuation of people from an emergency aircraft.

This article models the processes occurring in the cabin of a burning aircraft during an aviation incident near an airport, with a focus on passenger evacuation. A probabilistic model for estimating passenger survivability in such incidents is proposed.

2. MODELLING PASSENGER SURVIVAL IN A FIRE ACCIDENT

The negative factors that threaten the life and health of people onboard an aircraft in distress include:

- shock overloads when an aircraft collides with the ground
- hazardous factors of fire (explosion) in case of fire on board the aircraft
- environmental factors at the scene.

These factors have varying effects on the survival of people in an aircraft accident and depend on the type of aircraft, the nature of the emergency, the duration of exposure, etc. [6]. Based on the combination of these factors, we consider ten emergency scenarios, assessing:

- conditions that impede rescue operations and evacuation (e.g., condition of the aircraft),
- the volume and location of the fire (its intensity, area of ignition),
- the ability of passengers to self-evacuate.

When developing the model, we use the security matrix adopted in the theory of risks [2]. Based on these factors, we define three groups of typical emergency situations involving a fire on the ground:

Group I (Favorable):

- the aircraft landed on the landing gear with no damage
- passengers can independently leave the aircraft
- low-intensity fire outside the passenger cabin
- aviation accident occurring on or near the airport

Group II (Unfavorable):

- the fuselage is partially damaged (landing not on the chassis).
- some passengers cannot leave the aircraft on their own.
- fire with fuel spill near the passenger cabin.
- accident location is a short distance from the airport.

Group III (Catastrophic):

- fuselage and passenger cabin are significantly damaged
- most passengers cannot leave the aircraft on their own
- fire in the passenger cabin
- accident location far from the airport.

Based on these groups, we will formulate ten possible emergency situations in terms of severity [7]. The proposed model will consist of a matrix of emergency events and the probability of passenger survival, as shown in Table 1.

Table 1: Matrix of emergency situations

Emergency situation (i)	1	2	...	...	i	$i+1$	...	...	$i-1$	i
P_i – probability of passenger survival in situation i	P_1	P_2	...	...	P_i	P_{i+1}	..	...	P_{n-1}	P_n
N_i – probability of occurrence of situation i	N_1	N_2	...	...	N_i	N_{i+1}	..	..	N_{n-1}	N_n

Let's assume that the matrix of emergency events is oriented from the most favorable situations ($i = 1$) to the most catastrophic ($i = n$):

- Favorable ($i = 1$): An aviation accident occurs near the airport's take-off strip, the passenger cabin is mostly intact, almost all passengers can self-evacuate, and there is minimal fuel spillage.
- Catastrophic ($i = n$): An aviation accident happens far from the airport, with significant damage to the passenger cabin, most passengers need forced evacuation, and there is extensive fuel spillage.

Obviously, the probability P_i of passenger survival is maximal in favorable situations and minimal in catastrophic situations, hence:

$$P_1 > P_2 > \dots P_{i-1} > P_i \dots > P_n \quad (1)$$

where

$$\sum_{i=1}^n P_i = 1.0$$

Probabilities of the occurrence of specific situations are denoted as N_i . It is logical to assume that situations closer to “favorable” (near the airport) and “catastrophic” (severe damage and fire far from rescue services) are more common, while intermediate situations are likely to be rarer.

$$N_{(1, 2, 3 \dots)} > N_i \dots < \dots N_{(i-1, i)} \quad (2)$$

$$\sum_{i=1}^n N_i = 1.0 \quad (3)$$

So the complete matrix of emergency situation events has at least 16 (2^4) situations, considering the two extremes of four factors:

- proximity to the airport: near the airport vs. far from the airport
- degree of fuselage damage: minimal vs. significant
- fuel spillage: negligible vs. extensive
- passenger evacuation capability: self-evacuating vs. requiring rescue

Such detailed statistics are not available in open sources, although in principle collecting this data would be beneficial and allow for the application of multivariate statistical analysis methods [8]. As a simplification, assuming the correlation between passenger evacuation capability, fuel spillage, and fuselage damage, we can reduce the matrix of events to nine states based on:

Therefore, supposing that capacity of passengers for self-supporting evacuation and level of fuel spread correlate with the level of fuselage destruction, let's simplify the matrix of events to nine states (3^2) as follows:

Proximity to the Airport:

- at an airport
- near an airport
- far from an airport

Degree of Fuselage Damage:

- small
- medium
- significant

Table 2: Grouped Matrix of Emergency Events

level of destruction of aircraft	Remoteness from an airport		
	at an airport $i = 1$	near an airport $i = 2$	far from an airport $i = 3$
Small, $j = 1$	P_{11}	P_{12}	P_{13}
Middle, $j = 2$	P_{21}	P_{22}	P_{23}
Considerable, $j = 3$	P_{31}	P_{32}	P_{33}

Where P_{ji} is the probability of passenger survival getting in situation ji .

We can categorize all hypothetical aviation accident scenarios with fires into three groups, accordingly marked above in green, yellow and red colors:

- I. the “Favorable” group, with high probability of passenger survival, includes the states $i = 1 \dots 4$
- II. the “Unfavorable” group, with moderate probability of passenger survival, includes the states $i = 5 \dots 7$
- III. the “Catastrophic” group, with low probability of passenger survival, includes the states $i = 8 \dots 10$.

The probabilities of these situations (I, II, III) are designated as N_I , N_{II} and N_{III} .

Table 3: Matrix of Grouped Emergency Situations

Type of emergency situation ($\bullet$)	I	II	III
Probability $I(\bullet)$ of occurrence of emergency situation ($\bullet$)	N_I	N_{II}	N_{III}
Probability of passenger survival $P(\bullet)$ in emergency situation ($\bullet$)	P_I	P_{II}	P_{III}

Thus, the total probability of a passenger surviving an aircraft accident involving a fire on the ground can be calculated using the formula:

$$P_{total} = \sum_{l=1}^{l=3} P_l N_l \quad (4)$$

This formula estimates the average probability of survival for a passenger involved in a plane crash with a fire. When assessing the hazard level of an aviation accident, it is necessary to quantify the danger of emergency factors on passengers. Let's now consider one possible approach to solving this problem.

3. AN APPROACH TO QUANTIFYING PASSENGER SURVIVAL IN AIRCRAFT FIRES IN THE AIRFIELD AREA

To develop a model that specifies Available Safe Egress Time (ASET) for evacuating passengers from the burning cabin of an aircraft, we analyze accident statistics from ICAO member countries. These statistics indicate that one of the principal causes of severe injuries in aircraft fires is poisoning by products of complete and incomplete combustion, as well as toxic substances [9].

To address this, we introduce the concept of a critical level K_K , which specifies a “dose” of dangerous factors for passengers in the burning cabin of an aircraft. There are many risk factors for passengers in such scenarios, and quantifying each is highly complex. Therefore, we introduce a complex criterion focusing on two main factors: toxic K_{kv} and thermal K_T .

The coefficient K_{kv} represents the “dose” of toxic substances released in the burning cabin, whereas the coefficient K_T represents the thermal dose. Consequently, the complex coefficient specifying the critical level of hazard in the burning cabin over time is:

$$K_K = -K_{KV} + K_T \quad (4)$$

Toxic substances are understood as those that negatively affect the human body and the environment. The toxicity of combustion products is defined by three factors:

1. specific coefficients of selected toxic gases,
2. partial densities of gases,
3. the duration of exposure to humans.

To estimate the index of toxicity, we calculate the total index of toxicity (K_m):

$$K_M = \frac{C_{CO}}{CL_{50CO}} + \frac{C_{CO_2}}{CL_{50CO_2}} + \dots + \frac{C_i}{CL_{50i}} \quad (6)$$

where C_{CO} , C_{CO_2} , C_i are the average concentrations of gases obtained from tests (mg/m^3), and CL_{50CO} , CL_{50CO_2} , CL_{50i} are the average lethal concentrations of gases under 30-minute isolated exposure to experimental animals.

Based on this index, materials can be categorized into four danger levels: extraordinarily dangerous, highly dangerous, mildly dangerous, and low-hazard [1]. Many researchers consider four of the most dangerous gases in fire conditions: carbon monoxide (CO), carbon dioxide (CO_2), hydrogen chloride (HCl), and hydrocyanic acid (HCN). [1,10]

The total complex coefficient K_{kv} involving four separate coefficients for CO , CO_2 , HCl , and HCN is then:

$$K_{kv} = K_{CO} + K_{CO_2} + K_{HCl} + K_{HCN} \quad (7)$$

Determining these coefficients is very challenging. In practice, empirical analytical dependencies, based on statistical data and natural experiments, are used to compare results for such complex problems as combustion.

During any fire, thermal energy is released. The quantity of released heat depends on air-ventilation conditions, the thermophysical properties of surrounding materials, and fire load components. The “temperature dose” (K_T) can be defined as the ratio of the time a person spends in the burning plane cabin to the time until death at a given temperature:

$$K_T = \frac{\tau_T}{\tau_{CT}} \quad (8)$$

Where τ_T is the time of presence in temperature $T(c)$ and τ_{CT} is the time until death at temperature $T(c)$. As the fire develops, the temperature of the gaseous medium in the passenger compartment changes. The maximum permissible ambient temperature is considered to be 70°C . In case of fire, the rise in temperature in a closed room follows a monotonic dependence and reaches its limit value almost after one and a half minutes.

4. CONCLUSIONS

In this study, we developed a probabilistic model to assess passenger survival in aircraft fire incidents, particularly near airport areas.

1. The proposed model provides a method to assess the risk of fatal outcomes for passengers in fire situations by evaluating different aircraft types and airline companies. It also facilitates the compilation of an insurance fund for compensating the families of deceased and injured passengers.
2. Mathematical modeling, which identifies the values of T_R (response time) and T_p (evacuation time) in various development scenarios, allows us to compare the dynamics of critical conditions in the cabin of a burning aircraft. To quantify the critical level in such scenarios, many fire risk factors need to be considered. A complex criterion containing two primary factors – toxicity (K_{KV}) and temperature (K_T) – is needed. The K_{KV} coefficient indicates the toxic dose of substances released in the burning aircraft cabin, while the K_T coefficient represents the temperature dose.
3. Assuming a person is exposed to toxic doses of four major combustion products – carbon monoxide (CO), carbon dioxide (CO_2), hydrogen chloride (HCl), and hydrogen cyanide (HCN) – the total complex factor K_{kv} is derived. This factor characterizes the dose of toxic substances in a burning cabin and consists of individual factors representing the effects of each of these substances separately.

By employing this model, stakeholders can better understand the risks and develop strategies to enhance passenger safety during aircraft fire incidents. This approach can also guide improvements in aircraft design, emergency procedures, and crew training, ultimately contributing to higher survival rates in aviation accidents involving fires.

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