Investigation of the causes of runway excursions

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ABSTRACT: The risk of runway excursion dependent on multiple factors related to operating conditions. These include Runway Contamination, Adverse Weather Conditions, Mechanical Failure, Human Error.
A multivariate analysis of historical data on accidents on runways carried out in order to quantify the effect that various factors have upon runway excursions (landing and takeoff overruns and landing and takeoff veer-offs).
In this paper, an in-depth data study was conducted of all runway excursion accidents over the period spanning 2006-2015 in 8 geographical regions to investigate the causes of runway excursion accidents. All data in this study are from the Aviation Safety Database, published by Aviation Safety Network (ASN) by Flight Safety Foundation, and have been augmented by appropriate investigative reports when available.
The technique deployed in this work is the multiple logistic regression model, often used in recent literature and proved suitable to examine and quantify the effect of various factors on accidents risk. This technique revealed interesting relationships among the variables both for landing accidents and for takeoff accidents. The goal of a logistic regression analysis is to predict correctly the outcome for individual cases using the parsimonious or least complex model.
The results of this paper show that the main cause of landing veer-off is the mechanical failure in most of the regions for any type of aircraft; the leading cause of landing overrun is human error in all regions especially for small aircrafts: the takeoff overrun mainly are caused by mechanical failure, especially for very large aircrafts. The weather conditions assume a dominant role, especially for small aircraft and for overrun accidents.

1 INTRODUCTION

A major initiative to improve safety is the increasing role of Safety Management Systems (SMS), intended as “an organized approach to managing safety, including the necessary organizational structures, accountabilities, policies, and procedures” (ICAO, 2012). ICAO has championed this initiative, which is now included in international standards for airline operations (ICAO, 2009). The basic structure involves four “pillars”: identifying safety hazards; safety risk management through remedial actions to address safety risks; continuous monitoring and assessment of the safety level sought and achieved; and programs for continuous improvement in the overall level of safety.

Another major contributor to the improved safety record can be traced to the careful investigation of past accidents to determine what led to the accidents and what needs to be done to prevent such events from occurring again. This reactive approach to improving aviation safety has been enhanced by the thorough analysis of data from numerous accidents, which has aided in the identification of recurring patterns or risk factors that are not always apparent when individual accidents are investigated. More recently, proactive approaches to determining ways to improve safety have become increasingly popular. An example of such a proactive approach is the analysis of incident data to identify areas of increased risk that may lead to an accident (Oster et al. 2013)

A large number of air accidents occur during the take-off and landing phases. Most occur beyond the designated safety and protection areas, around the runway, when an aircraft overruns the runway-end during take-off or landing, or when it undershoots the runway, with regard to the threshold, during landing.

The most common accidents that occur during these flight phases are:

- Landing overrun (LDOR – LanDing OverRun).
- Landing veer-off (LDVO – LanDing Veer-Off).

– Landing undershoot (LDUS – LandDing UnderShoot).
– Take-off overrun (TOOR – Take-Off OverRun).
– Take-off veer-off (TOVO – Take-Off Veer-Off)
– Ground collision after take-off.

Runway excursions during take-off and landing continue to be the highest category of aircraft accidents and often exceed 25% of all annual commercial air transport accidents (IATA 2011).

Runway excursions can result in loss of life and/or injury to persons either on board the aircraft or on the ground. The effect of runway excursions can result in damage to aircraft, airfield or off-airfield installations including other aircraft, buildings or other items struck by the aircraft.

A runway excursion accident is defined as an accident where an aircraft on the runway surface departs the end of the runway or side of the runway surface during take-off or landing (IATA 2011).

It consists of two types of events:
– Veer Off: A runway excursion in which an aircraft departs the side of a runway
– Overrun: A runway excursion in which an aircraft departs the end of a runway

It excludes both accidents where the aircraft did not initially land on a runway surface, and take-off excursions that did not start on a runway (e.g., inadvertent take-offs from taxiways).

The current definitions of runway overrun do not specify any distance for arrivals and departures where an incident can not be considered to be an overrun or undershoot, because it is too far out from the runway. For example, the current definitions used by Eurocontrol are:
– Overrun on Take-Off: ‘‘A departing aircraft fails to become airborne or successfully reject the take-off before reaching the end of the runway”.
– Overrun on Landing: ‘‘A landing aircraft is unable to stop before the end of the runway is reached”.

The common taxonomy group of the ICAO commercial aviation safety team refers to: Runway excursion as veer off or overrun off the runway surface. This definition is only applicable during either the take-off or landing phase. The excursion may be intentional or unintentional (for example, deliberate veer off to avoid a collision, brought about by a runway incursion). This classification applies in all cases where the aircraft left the runway regardless of whether the excursion was the consequence of another event or not.

Arnaldo Valdés et al. (2011) developed probabilistic models of runway overruns and proposed risk models supported by historical data; they noted that runway overrun risk depends on multiple factors in relation to operating conditions including wind, runway surface conditions, landing or take-off distance required, presence of obstacles, runway distance available, existence and dimensions of runway safety areas.

Oster jr. et al. (2013) says there is still a role for careful accident investigation and there are still lessons to be learned from the few accidents that these carriers have. But with improvements in safety and major reductions in accidents, airline safety analysis will have to shift toward analysis of incident and operational data with the intent of identifying safety risks before accidents occur. There are two potential benefits from looking at these types of data. One is to address the question of why some sequences of events result in accidents while other sequences do not result in accidents. A better understanding of how potential accidents were avoided in some situations may lead to more such avoidances in the future. A second potential benefit is to identify trends in or the emergence of potentially hazardous sequences of events before they result in an accident. Here again, by identifying such trends, it may be possible to take corrective action before an accident occurs.

Distefano et al. (2014) proposes a risk assessment procedure in which the probability of each accident is proportional to the cumulative probability of the causes identified for the accident.

Čokorilo et al. (2014) has produced a model in order to estimate the frequency of aviation accidents in different environmental conditions and was based on the physical characteristics of the aircraft. The data were processed and then aggregated into groups, using cluster analysis based on an algorithm of partition binary ‘Hard c means.’

Ayres jr. et al. (2012) shows that location models could be improved if greater attention was paid to causality but data difficulties exist, for example, on meteorological influences on overrun distance and that this is often mis-recorded in accident dockets so lateral deviations are more difficult to model; while in consequence modelling the variation in aircraft type, wingspan and speed ought to be included as well as pavement type variations that will affect deceleration.

Wagner et al. (2014) focuses his work on predicting if the excursion will generate fatalities: human errors are the strongest associated feature with fatal excursions, another feature strongly associated with fatal excursions is adverse weather conditions, fatal excursions occur more frequently on commercial flights than other categories of aircraft operation, and overruns are the most fatal category of runway excursions.

The risk of runway excursion dependent on multiple factors is related to operating conditions. The goal of this paper is to identify risk factors for type of accident of runway excursion in relation to certain elements such as the aircraft type and geographical region. The low accident rate of aviation means that no particular airport has sufficient accident occurrences in the recent past to support an accident frequency model with reasonable statistical confidence (Piers, 1994; Hale, 2001). Therefore, this study is based on a large database of relevant accident cases. The results of the current study can be used by a broad range of civil aviation organizations for risk assessment and cost-benefit studies of actions improvements.

2 RUNWAY EXCURSION DATA

The primary data source used in this work is a database created by Aviation Safety Network (ASN). The Aviation Safety Network is a private, independent initiative founded in 1996. On line since January 1996, the Aviation Safety Network covers accidents and safety issues with regards to airliners, military transport planes and corporate jets.
The ASN Safety Database contains detailed descriptions of some 15.800 incidents, hijackings and accidents to airliner, military transport category aircraft and corporate jet aircraft safety occurrences since 1921. Most of the information are from official sources (civil aviation authorities and safety boards), including aircraft production lists, ICAO ADREPs, and country's accident investigation boards.
For the purposes of this paper, it created a database containing solely runway excursion accidents, in a period between 2006 and 2015, for all categories of aircraft, and in all world regions.
Runway excursions are categorized into the following categories: landing overrun (LDOR), landing veer off (LDVO), take-off overrun (TOOR), and take-off veer off (TOVO). The four runway excursion categories are mutually exclusive.
In this database for every event are recorded information about:

- date
- airport
- airport's country
- accident type
- phase of flight
- potential cause
- n° of fatalities
- n° of occupants
- aircraft type
- nature of flight
- aircraft damages and
- dynamic event.

Figure 1 shows the distribution of events contained in the database as a function of the type of accident.

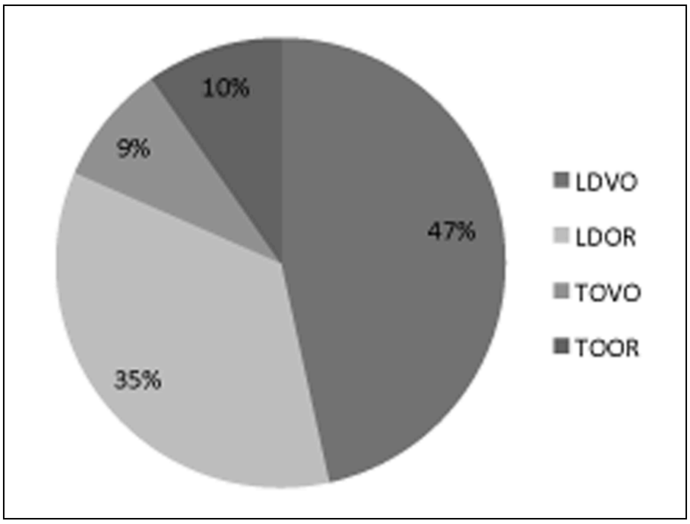

Figure 1. Distribution of events by type of accident

4.1 *Data preparation*

In order to make statistically significant data to be analysed fields suitable to regroup together the elements of some records of the database have been created.
The following are the criteria used for the definition of new fields.

2.1.1. *Geographical regions*
The airport's countries where there was the runway excursion were grouped as recited in the IATA classification of the geographic regions (IATA 2011):

- AFI: Africa,
- ASPAC: Asia Pacific,
- CIS: Commonwealth of Independent States,
- EUR: Europe,
- LATAM: Latin America & the Caribbean,
- MENA: Middle East & North Africa,
- NAM: North American, and
- NASIA: North Asia.

Table 1 shows the number of events by type of accident in each geographic regions.

Table 1. Distribution of events by type of accident in geographic regions

	LDVO	LDOR	TOVO	TOOR
AFI	18	17	3	6
ASPAC	43	21	5	2
CIS	8	5	3	6
EUR	25	16	6	3
LATAM	21	31	4	8
MENA	21	12	1	3
NAM	44	35	12	10
NASIA	2	0	0	0

2.1.2. *Risk factors*
The following four classes of risk factors have been defined which includes all the causes of the events recorded in the database:

-Aircraft System Faults:

- Engines
- Brake (wheel brakes, spoilers or
- reversers)
- Hydraulic
- Electric
- Main gear
- Tire
- Other

-Human errors:
- Incorrect Flight Planning
- Communication/Coordination
- Pilot error
- Visual Illusion
- Fatigue
- Excessive speed
- Loss of control
- Other

-Weather Conditions:
- Low Visibility
- Rain
- Wind Shear
- Tailwind
- Crosswind
- Ice
- Low Ceiling
- Strong Wind
- Turbulence
- Freezing Rain
- Other

-Runway Conditions:
- Wet
- Contaminated - Standing water
- Contaminated - Rubber
- Contaminated - Oil
- Contaminated - Ice
- Contaminated - Slush
- Contaminated - Snow
- FOD
- Wildlife Hazards
- Down Slope

When the accident report does not mention the potential cause, this was referred to as unknown.
Table 2 shows the number of events by type of accident in relation to the class of risk factors.

Table 2. Distribution of events by type of accident and by risk factor

	LDVO	LDOR	TOVO	TOOR
Aircraft System Faults	53	25	5	13
Human errors	49	42	12	8
Weather Conditions	38	15	6	4
Runway Conditions	12	11	1	5
Unknown	30	44	10	8

2.1.3. *Aircraft classes*
The accidents were analysed according to the different classes of aircraft operations represented in: general aviation (GA), corporate aircraft (CA), Commuter aircraft (Com A) and transport aircraft (TA) - to address these different operational perspectives. The aircraft operation classes are defined as:

– General aviation aircraft (GA): typically these aircraft con have one (single engine) or two engines (twin engine). Their maximum gross weight is usually below 14.000 lb.
– Corporate aircraft (CA): typically these aircraft can have one or two turboprop driven or jet engines (sometimes three). Their maximum gross mass is up to 90.000 lb.
– Commuter aircraft (Com A): usually twin engine aircraft with a few exceptions such as the De Havilland DHC-/which has four engines. Their maximum gross mass is below 70.000 lb.
– Transport aircraft (TA):
  -Short-range (S-R): their maximum gross mass is usually below 150.000 lb.
  -Medium-range (M-R): these are transport aircraft employed to fly routes of less than 3.000 nm (typical). Their maximum gross mass is usually below 350.000 lb.
  -Long-range (L-R): these are transport aircraft employed to fly routes of less than 3.000 nm (typical). Their maximum gross mass usually is above 350.000 lb.

Table 3 shows the number of events by type of accident in relation to the aircraft class.

Table 3. Distribution of events by type of accident and aircraft class

	LDVO	LDOR	TOVO	TOOR
GA	29	25	4	7
CA	39	31	14	14
Com A	48	33	6	10
S-R	45	34	8	3
M-R	14	11	2	1
L-R	7	3	0	3

2.1.4. *Nature of flight*
Nature of flight was reported in ASN database; the following are the items used for the analysis:

– Ambulance,
– Cargo,
– Domestic Non Scheduled Passenger,
– Domestic Scheduled Passenger,
– Executive,
– Ferry/positioning,
– International Scheduled Passenger,
– International Non Scheduled Passenger,
– Private,
– Other (Agricultural, Training, Test, Parachuting), and
– Unknown

Scheduled services are flights scheduled and performed for remuneration according to a published timetable, or so regular or frequent as to constitute a recognizably systematic series, which are open to direct booking by members of the public,
A non-scheduled air service is a commercial air transport service performed as other than a scheduled air service. A charter flight is a non-scheduled operation using a chartered aircraft.
Table 4 shows the number of events by type of accident in relation to the nature of flight.

Table 4. Distribution of events by type of accident and nature of flight

	LDVO	LDOR	TOVO	TOOR
Ambulance	3	2	2	2
Cargo	27	15	4	5
Domestic Non Scheduled Passenger	15	5	2	0
Domestic Scheduled Passenger	72	48	10	14
Executive	11	14	3	4
Ferry/positioning	7	11	2	5
International Scheduled Passenger	19	13	1	1
Military	7	9	4	2
Private	11	11	2	2
Other	3	6	3	1
Unknown	7	3	1	2

3 STATISTICAL APPROACH FOR EXCURSION DATA ANALYSIS

In many transportation applications discrete data are ordered, for example to analyse categorical frequency data (e.g., accident, serious incident, incident).
Although these data are discrete, application of the standard or nested multinomial discrete models does not account for the ordinal nature of the discrete data and thus the ordering information is lost. To address the problem of ordered discrete data, ordered probability models have been developed.
Ordered probability models (both probit and logit) are a form of discrete outcome models that relate dependent variables on an ordered discrete scale to a series of predictor variables. Ordered probability models are derived by defining a latent variable z as a basis for modelling ordinal ranking data. This unobserved variable can be specified as a linear function for each observation such that:

$$z = \beta X + \varepsilon \tag{1}$$

where X is a vector of variables determining the discrete ordering for observation n, β is a vector of estimable parameters, and ε is a random disturbance. Using this equation, observed ordinal data, y, for each observation are defined as:

$$y = 1 \text{ if } z \leq \mu_0$$

$$y = 2 \text{ if } \mu_0 < z \leq \mu_1$$

$$y = 3 \text{ if } \mu_1 < z \leq \mu_2$$

$$y = \ldots$$

$$y = I \text{ if } z \geq \mu_{i-1},$$

where the μ are estimable parameters (referred to as thresholds) that define y, which corresponds to integer ordering, and I is the highest integer ordered response. Note that during estimation, non-numerical orderings such as never, sometimes, and frequently are converted to integers (for example, 1, 2, and 3) without loss of generality.
The μ are parameters that are estimated jointly with the model parameters (β). The estimation problem then becomes one of determining the probability of I specific ordered responses for each observation n. This determination is accomplished by making an assumption on the distribution of ε. If ε is assumed to be normally distributed across observations with mean = 0 and variance = 1, an ordered probit model results with ordered selection probabilities as follows:

$$P(y = i) = \Phi(\mu_i - \beta X) - \Phi(\mu_{i+1} - \beta X),$$

where μ_i and μ_{i+1} represent the upper and lower thresholds for response category i and Φ (…) is the cumulative normal distribution.
Estimation is done using maximum likelihood methods. For this study, XLSTAT software was used to estimate separate ordered probit models in order to examine the risk factors of the runway excursions depending on the flight nature and in relation to different geographic regions of occurrence and the aircraft class involved. Runway excursions risk factors are assessed on a five-point scale.
When interpreting the results of the ordered probit models, a positive value for particular β implies that if the condition corresponding to that parameter is true (e.g., the runway excursions category is LDVO) the probability of the highest ordered discrete category (e.g., risk factor: aircraft system faults) will increase and the probability of the lowest category (e.g., risk factor: runway conditions) will decrease.
Assessing the impacts on intermediate categories is more difficult because these results are conditional based upon the threshold values (μ). As such, to examine the effects of a specific variable on one of the interior categories, marginal effects are computed as the change in the estimated probabilities when a specific indicator variable is changed from zero to one with all other variables held equal to their means. These marginal effects can be interpreted as the change in the probability of a particular prefer-

ence category, P(y=i), given a change in the respective variable.

Ordered probability models were developed in order to gain greater insight as to how differences in geographic regions, aircraft type, and other factors influenced the cause of the runway excursion.

4 RESULTS AND DISCUSSION

Table 4 presents the parameters of the ordered probit model that has been developed for the estimation of the probabilities of the causes that generate the runway excursions. Coefficient estimates are provided for this model, along with standard errors, as well as confidence intervals for each variable. The modelling results allowed to infer interesting considerations, both general and in relation to individual types of accidents.

The comments relating to each type of accidents will be performed with reference to a subdivision of accidents in relation to the different geographic regions of occurrence.

For each type of runway excursion in each geographic region has been identified the cause that has the highest probability of generating the event.

Table 4. Ordered Probit Model (normalized coefficients).

Variable	Coeff.	Std. Error	95% Confidence interval
Event			
LDVO	0.000	0,000	
LDOR	-0.201	0,061	(-0.320, -0.081)
TOVO	-0.117	0,059	(-0.232, -0.002)
TOOR	-0.015	0,060	(-0.134, +0.103)
Airport's country			
NAM	0.000	0,000	
EUR	0.023	0,066	(-0.106, +0.151)
LATAM	-0.076	0,069	(-0.211, +0.058)
AFI	-0.190	0,067	(-0.321, -0.058)
ASPAC	-0.192	0,070	(-0.329, -0.055)
CIS	-0.116	0,062	(-0.237, +0.006)
MENA	-0.126	0,067	(-0.256, +0.005)
NASIA	-0.083	0,058	(-0.197, +0.030)
Aircraft class			
GA	0.000	0,000	
CA	-0.040	0,076	(-0.189, +0.109)
Com A	-0.026	0,082	(-0.187, +0.135)
S-R	0.028	0,084	(-0.137, +0.194)
M-R	0.034	0,071	(-0.105, +0.172)
L-R	0.115	0,067	(-0.016, +0.247)
Nature of flight			
Ambulance	0.000	0,000	
Cargo	-0.125	0,135	(-0.390, +0.139)
Domestic Non Scheduled Passenger	-0,101	0,098	(-0.294, +0.092)
Domestic Scheduled Passenger	-0.105	0,181	(-0.461, +0.250)
Executive	-0.118	0,110	(-0.333, +0.096)
Ferry/positioning	-0.011	0,102	(-0.211, +0.189)
International Scheduled Passenger	-0.064	0,120	(-0.299, +0.171)
Military	-0.102	0,101	(-0.300, +0.096)
Private	-0.043	0,103	(-0.244, +0.158)
Unknown	-0.117	0,083	(-0.281, +0.046)
Other	-0.010	0,085	(-0.177, +0.156)

4.1 *Generality*

The weather conditions play an important role, although not predominant, for the overrun accidents (both in take-off and landing).

In NAM and EUR the probability that an overrun is due to bad weather conditions is about 16% (with 18% values for smaller aircraft); while the probability that a veer-off is due to unfavourable weather conditions is about 13% (with values 8% for larger aircraft).

In LATAM, AFI and ASPAC the probability that bad weather conditions cause all kinds of accidents is on average 17% for all types of aircraft. Only for a L-R aircraft such probability is reduced to 10% in LATAM and ASPAC.

In LATAM and AFI the probability that the various types of accidents are caused by unknown causes assumes a higher percentage than in countries of NAM and EUR, especially for small aviation. This consideration is more evident in the countries AFI even more than in those of LATAM.

In ASPAC the percentage of accidents involving large aircraft (M-R and L-R) is 5.6%. For large aircraft (L-R), the most likely cause is the mechanical failure for all types of accident; human error is manifested by a reduced rate compared to other types of aircraft.

In CIS occurred only 5.6% of total accidents; the predominant cause for all incident types and for all types of aircraft is human error (from 20 to 30%); the probability that accidents are caused by unknown factors is about 25%. The mechanical failure is relevant in the case of LDVO, while the weather conditions are the potential cause of 18% of accidents on average for all types of aircraft.

In NASIA there were only 2 LDVO accidents; for them the unknown cause is the most likely (43%).

4.2 *LDVO (Landing Veer-Off)*

In EUR and NAM, the main causes of this type of accident are those related to mechanical failure, regardless of the type of aircraft and the flight nature. For example, the LDVO for GA aircraft and "Private" flight nature, has a 42% probability of being caused by mechanical failure, 31% to have as a

triggering event a human error, 13% to be caused by weather conditions and only 5% to be caused by the runway conditions.
In LATAM, AFI, ASPAC and MENA the leading cause of LDVO for small aircraft is human error, while for large aircraft in LATAM, MENA and ASPAC is the mechanical failure and in AFI is always human error.

4.3 *LDOR (Landing Overrun)*

In EUR and NAM, this accident has a higher probability of occurrence for causes related to human error (30%), regardless of the type of aircraft. It should however be pointed out that, as regards the nature of the flight, in the case of "Other" (Test, training, parachuting), the mechanical failure is the main cause of this accident type (over 30%).
In LATAM, human error is the main cause (around 27%) of LDOR for small aircraft and for aircraft of larger size (L-R) the main cause is mechanical failure (40%).
In AFI and ASPAC, the main cause of LDOR for small aircraft is human error (about 20%); the unknown causes, however, assume a high percentage (between 40 and 50%) for all types of aircraft.
In NEMA, the main cause of LDOR is human error (approximately 25%) for small aircraft, while the unknown causes contribute in a high percentage (between 30 and 40%) for all types of aircraft, with the exception of L-R mainly caused by mechanical failure (33%).

4.4 *TOVO (Take-Off Veer-Off)*

In EUR and NAM, the TOVO has an equal probability of occurring from causes related to human error and mechanical failure in the case of small aviation (GA and CA); for larger aircraft (com-A and S-R), the probability that the human error is the main cause grows slightly, while for large aircraft (M-R and L-R) this type of accident is infrequent.
In LATAM the main cause of TOVO is human error (around 27%), although the percentage of unknown causes is very high for all types of aircraft.
In AFI and ASPAC, accidents during take-off involve only small aviation (CA, Com A); for such aircraft, the most likely cause of TOVO is human error (20%) followed by the bad weather conditions (17%). Also in this case the unknown causes are in high proportion (45%).

4.5 *TOVO (Take-Off Overrun)*

In NAM and EUR accidents of this type are quite rare (9.9% in NAM and 6% in EUR); the mechanical failure is certainly the most likely cause, especially for very large aircraft.
Also in AFI and ASPAC the TOOR type accidents are not very frequent (13,63% in AFI and 12.4% in ASPAC) and involve only small aircraft (CA, Com A); for these aircraft the most likely cause of such accidents is human error (about 26%) followed by the bad weather conditions (18%). The probability of unknown causes is high in percentage (30%).
In CIS the incidents of this type are quite frequent (27,27%) and the likely cause is human error (25 - 30%) in the case of small and medium-sized aircraft. The large aircraft have not recorded any such incident.
In LATAM the frequency of these accidents is very low (2.8%) and the most likely cause is the mechanical failure (about 35%) for small aircrafts, and even 62% for aircraft type L-R. The probability that the TOOR is due to unknown causes is instead quite low.

5 CONCLUSION

Aviation safety analysis historically has emphasized accident data. For the most part, the aviation industry and government regulators have used data reactively to identify the causes of aircraft accidents and to take steps to prevent these types of accidents from recurring. But there are still lessons to be learned from the few accidents that these carriers have. With improvements in safety and major reductions in accidents, airline safety analysis will have to shift toward analysis of incident and operational data with the intent of identifying safety risks before accidents occur.

This paper shows how the same event may be caused by different risk factors in relation to different geographic regions or types of aircrafts.

This results represent a very proactive tool for future aviation safety analysis.

Future work includes efforts on improving predictive performance with statistic methods that address imbalanced data more effectively. Further, it will be considered the consequences of the events in terms of damage to the aircraft and/or persons.

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