The impact of airport characteristics on airport surface accidents and incidents

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ABSTRACT

Airport surface safety and in particular runway and taxiway safety is acknowledged globally as one of aviation’s greatest challenges. To improve this key area of aviation safety, it is necessary to identify and understand the causal and contributing factors, and their impacts. Whilst the contribution of human factors, operations, and procedures has been researched extensively, the impact of the airport and its associated characteristics itself has received little or no attention. This paper introduces a novel methodology for risk and hazard assessment of airport surface operations, and models the relationships between airport characteristics, and i) the rate of occurrences, ii) the severity of occurrences, and iii) the causal factors underlying occurrences. The results show for the first time how the characteristics of airports, and in particular its infrastructure and operations, influence the safety of surface operations.

KEYWORDS

Airport surface safety, safety data, causal factors, airport characteristics
INTRODUCTION

The safety of the airport surface and in particular the runways and taxiways (i.e. manoeuvring area) is an area of great concern. With 30% of aviation accidents being runway related (1) and numerous incidents occurring on the manoeuvring area (e.g. 2), surface operations are the most vulnerable phase of flight.

To improve this key area of aviation safety, it is necessary to identify the causal factors that underlie accidents and incidents (i.e. occurrences), and to understand their impacts. Airport surface operations require the interaction of four main stakeholders, i.e. pilots, air traffic control (ATC), airport operator, and ground handling, and function under the umbrella of regulations. The complexity of surface infrastructure and related operations makes the system vulnerable. Whilst the contribution of human factors, operational practices, and procedures has been researched extensively (e.g. 3, 4), the impact of the airport and its associated characteristics itself has received little or no attention.

A review of the literature on the causal factors that underlie airport surface safety occurrences highlighted the potential impact of airport characteristics, e.g.:

- The loss of pilot situational awareness may be caused by a complex layout of the airport surface and its related infrastructure, and eventually lead to an incursion, a situation involving the incorrect presence of an aircraft, vehicle, or person on the manoeuvring area (e.g. 3, 4);
- The physical characteristics of runways, such as runway end safety areas, runway slope, runway condition (e.g. contamination), and surface operations and maintenance (e.g. snow and ice control and removal) might contribute to an excursion, an incident whereby an aircraft leaves the paved airport surface (e.g. 2, 5);
- Airport landscaping and surrounding land use seems to influence the occurrence of wildlife and associated risk of a wildlife strike (e.g. 6, 7), and;
- Surface infrastructure, operations, and maintenance can lead to debris and eventually cause a Foreign Object Damage (FOD) (e.g. 8, 9).

Likewise, airport characteristics (e.g. markings, signage, lighting) have been identified as having an impact on airport surface occurrences during an analysis of safety data (10). All these factors can be summarized under the topic of airport characteristics, and although mentioned frequently as ‘causal factors’, quantitative studies that prove a relationship between airport characteristics and surface safety occurrences are missing in the literature.

A recent study by Galle, et al. (2010) analyzed the impact of runway geometry on the rate of runway incursions. The authors clustered 80 airports from the United States Great Lakes Region into five clusters based on runway geometry. The study compared the rate of runway incursions across the clusters and found a similar median across the groups. The study concluded that runway geometry is not a significant predictor for runway incursions (11). Whilst this study provides an initial attempt at analyzing the impact of airport characteristics on surface safety occurrences, it is however limited in several respects. The authors consider runway geometry simply as one variable and do not elaborate on the particular geometric characteristics used for the clustering. However, it maybe that only certain geometric aspects are significant (e.g. number of runways, intersecting taxiways), and Galle et al.’s study does not test for this. In addition, their study considers only runway geometry and ignores the operation of the runway. Furthermore, Galle, et al. focus on analyzing the impact of airport geometric characteristics on the rate of runway incursions. While airport characteristics may not influence the rate of occurrences, they may however impact on their severity, or their underlying causal factors, e.g. the type of human errors an airport is most likely to suffer. For instance, specific airport characteristics may influence the occurrence of pilot, ATC, or vehicle driver/pedestrian (V/PD) related factors.

This paper proposes a framework for an integrated risk assessment of airport surface operations, and analyzes the impact of airport characteristics on the occurrence of airport surface accidents and incidents and their causes in North America, Europe, and Oceania. The paper is organized in three parts. The next section provides a detailed outline of the methodology. Subsequently, the results are presented, before part three concludes the paper.

METHODOLOGY

The safety of airport surface operations is modeled in three steps and Figure 1 provides a detailed outline of the methodology. First, accident and incident data from North America, Europe, and Oceania is collected and analyzed for its causal factors. The corresponding airport characteristics data is subsequently collected using a survey methodology. Last, the relationships between airport characteristics and safety occurrences are modeled, and safety mitigation strategies outlined.
Safety Data Collection and Analysis

Safety data selection
- Traffic statistics to identify relevant regions in terms of air traffic
- Consultation with subject matter experts (SMEs)
  - Federal Aviation Organisation (FAA) Runway Safety Program Manager, Regional Runway Safety Manager, and
  - The European Organisation for the Safety of Air Navigation (EUROCONTROL) Head of Safety Unit, Retired Head of Safety Regulation, Senior Safety Expert
- Countries reflecting different national air traffic movement characteristics, topographies, and meteorological conditions

Safety data collection
- Safety data from four countries are collected:
  - United States (U.S.)
  - United Kingdom (UK)
  - Norway (NO)
  - New Zealand (NZ)
- Safety data from the regulatory bodies of the four countries are selected, because:
  - Accident/incident reporting is mandatory in each of the countries
  - The common viewpoint (i.e. regulatory) ensures standardisation

Safety data analysis
- Analysis of the descriptive narratives of accidents/incidents for causal factors
- Data coding using a new taxonomy of causal factors underlying airport surface safety occurrences developed by Wilke and Majumdar (2012) (12)

Airports survey

Identification of airport characteristics with potential impact on surface safety
- The airport characteristics to be considered in this research are derived from:
  - Process model of airport surface operations (14)
  - Literature findings
  - Analysis of safety data (10)

Definition of measurement variables and questionnaire design
- Measurement variables are derived from:
  - Subject matter literature
  - Safety data (10)

Validation with SMEs
- To ensure content validity the questionnaire is validated with:
  - Senior safety experts from EUROCONTROL and the FAA as outlined in Step 1
  - Vice President Safety and Regulatory Affairs at Airports Council International (ACI)
  - SMEs from a major U.S. airport operator

Sampling
- Target sample size: 57 towered airports in the U.S., UK, NO, NZ

Survey methodology
- Internet-mediated questionnaire
- Data collection through the researcher using Aeronautical Information Publication (AIP)

Pilot survey
- 1 U.S. and 1 European airport

Revision of pilot
- Minor amendments in the questionnaire design

Full survey
- Distribution of the questionnaire over reference organisations:
  - FAA Regional Runway Safety Managers
  - UK Civil Aviation Authority (CAA)
  - Avinor (Norwegian ANSP)
  - NZ Pilots Association

Data analysis
1) High-level analysis and data distribution
2) Tests for associations between:
  - Airport characteristics and accident/incident rates
  - Airport characteristics and the severity of occurrences
  - Airport characteristics and causal factors underlying occurrences
3) Logistic regression to model the relationships between:
  - Airport characteristics and severity
  - Causal factors and severity
  - Airport characteristics and causal factors

Figure 1 Methodology outline

Safety Data Collection and Analysis

Safety data from the regulatory authorities of the following four countries was collected: United States (U.S.), United Kingdom (UK), Norway (NO), and New Zealand (NZ). The requirements for data collection have been derived based on the limitations of previous research on airport surface safety, outlined in Wilke and Majumdar (2012) (12). Particular care was taken to include only countries known for a good safety culture (in North America, Europe, Oceania) in order to ensure a high reliability, continuity, and completeness of the data. Regulatory safety data was selected as the reporting of accidents and incidents is mandatory in each of the four considered countries (e.g. 13) and therefore the chosen databases should encompass all the reports made by the
relevant aviation stakeholders. In addition, a common viewpoint, i.e. regulatory, ensures a standardized data collection.

Safety data of the most prominent airport surface safety occurrence types (i.e. incursions\(^1\), excursions\(^2\), and FOD\(^3\)) were collected from each country and the following databases were available:

- Federal Aviation Administration (FAA) Incursion (RI) database and Accident/Incident Data System (AIDS) for excursions and FOD;
- United Kingdom Civil Aviation Authority (UK CAA) Mandatory Occurrence Reporting Scheme (MORS);
- Civil Aviation Authority – Norway (CAA – Norway) European Coordination Centre for Accident and Incident Reporting Systems (ECCAIRS); and
- Civil Aviation Authority New Zealand (CAA New Zealand) Aviation Safety Monitoring System (ASMS).

The data was normalized using the annual number of movements per airport.

Subsequently, the accidents and incidents were analyzed for their causal factors. To do so, the descriptive narrative of each occurrence report was analyzed and one or more causal factors extracted. The safety data was coded using a new taxonomy of causal factors developed by Wilke and Majumdar (2012) (12).

This taxonomy classifies the causal factors on the highest level into the five categories of: aircraft operations (i.e. aircraft-technical failure and pilot human-related factors), ATC (i.e. ATC-technical failure and ATC human-related factors), airport operations (i.e. technical failures, V/PD human-related factors and factors related to the airport physical infrastructure), environment, and regulations.

### Airports Survey

To collect the corresponding airport characteristics data, an airports survey was conducted and the following paragraphs specify the details.

**Airport Characteristics and Measurement Variables**

To identify the airport characteristics with potential impact on surface safety and their measures, a process model of airport surface operations has been developed. The model shows the physical airport surface infrastructure, introduces the aviation stakeholders involved in surface operations, and defines the interactions between stakeholders and infrastructure (14). An initial list of relevant airport characteristics was derived from the process model, and verified with the factors identified in the literature, and the findings from an analysis of safety data (10). The list of airport characteristics and measures was subsequently validated with subject matter experts (SMEs) from the European Organisation for the Safety of Air Navigation (EUROCONTROL), the FAA, a senior safety expert from Airports Council International (ACI), and SMEs from a major U.S. airport authority.

The airport characteristics were presented and the SMEs were asked to systematically assess and comment on their validity (e.g. to assess whether the list in their opinion contained all relevant airport characteristics or missed important aspects). All SMEs were senior safety experts with a minimum of 20 years of relevant experience.

The identified characteristics can be summarized into 8 categories:

- Airport location and surrounding land use,
- Traffic characteristics,
- Airport surface design (i.e. geometry),
- Equipment and installations,
- Visual navigation aids,
- Airport surface operations and maintenance,
- Regulations, and
- Human aspects.

**TABLE 1** contains the measurement variables and discusses how these potentially impact on airport surface safety. Some factors are highlighted as 'excluded'. These are variables that could affect surface safety, but are not considered in this study for the following reasons:

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\(^1\) An incursion is defined as any occurrence at an aerodrome involving the incorrect presence of an aircraft, vehicle, or person on the maneuvering area (Definition adapted from 4).

\(^2\) An excursion is defined as an occurrence (accident or incident) where an aircraft on the ground departs from a runway or taxiway. Excursions may occur on take-off, taxing or landing, and be either intentional or unintentional (Definition adapted from 15).

\(^3\) A FOD is defined as any damage attributed to a foreign object that can be expressed in physical or economic terms, which may or may not degrade the product's required safety and/or performance characteristics (Definition adapted from 16).
The airport characteristic is assumed to influence the level of wildlife (e.g. airport surrounding land use). Occurrences in relation to wildlife are not considered, as the reporting of wildlife strikes is not mandatory in all of the considered countries and current data collection mechanism seem inconsistent; Data collection is expected to give unreliable results (e.g. meteorological conditions); Normal airport surface operations are assumed (e.g. the infrastructure is assumed to be in working conditions, failure rates are not considered); Runway/taxiway specific characteristics (e.g. type of Instrument Landing System (ILS)) are excluded, as safety data would have to be correlated to specific locations at airports. Such information is not consistently collected in the safety data.

**TABLE 1 Measurement Variables**

<table>
<thead>
<tr>
<th>Airport characteristics</th>
<th>Measurement variables</th>
<th>Impact on safety</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Airport location and surrounding land use</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Airport location</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Airport surrounding land use that causes disruptions to aviation</td>
<td>Excluded: - Airport surrounding land use possibly influence the level of wildlife strikes</td>
<td>• Certain airport surrounding land uses influence the presence of wildlife (wildlife attractants)</td>
</tr>
<tr>
<td>• Meteorological conditions</td>
<td>Excluded: - Any average airport in North America and Europe will experience all meteorological conditions - Data collection (e.g. number of days certain meteorological conditions impact on normal surface operations) will lead to unreliable estimations</td>
<td>• Weather influences operations and safety (e.g. snow / ice, fog, heavy storm, cross-winds)</td>
</tr>
<tr>
<td><strong>2. Traffic characteristics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Traffic characteristics</td>
<td>• Number of movements per year</td>
<td>• Traffic volume, in particular during peak hours, increases the potential of occurrences</td>
</tr>
<tr>
<td></td>
<td>• Peak number of operations during peak hours</td>
<td>• High number of airlines increases coordination; low number of airlines ensures that all flight crews are trained equally</td>
</tr>
<tr>
<td></td>
<td>• Primary type of traffic handled at the airport</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Number of airlines that have their home base at the airport</td>
<td></td>
</tr>
<tr>
<td><strong>3. Manoeuvring area physical characteristics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Manoeuvring area design</td>
<td>• Number of runways (RWY)</td>
<td>• Airfield layout and complexity can lead to confusion</td>
</tr>
<tr>
<td></td>
<td>• Number of taxiways (TWY)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Number of conflict points: - (RWY/RWY) - (RWY/TWY) - (TWY/TWY)</td>
<td></td>
</tr>
<tr>
<td>• Landscaping</td>
<td>Excluded: - Airport landscaping possibly influences the level of wildlife strikes - Data collection would require site visits</td>
<td>• Landscaping influences the presence of wildlife (wildlife attractants)</td>
</tr>
<tr>
<td><strong>4. Equipment and installations</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Equipment status</td>
<td>• Number of communication channels</td>
<td>• No of communication channels and frequencies can lead to e.g. frequency confusion</td>
</tr>
<tr>
<td></td>
<td>• Number of frequencies</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Excluded: - Type of landing system, as this is runway / taxiway specific data</td>
<td></td>
</tr>
<tr>
<td>• Adequacy</td>
<td>• Adequacy of equipment / installations to support the operations based upon them*</td>
<td>• Inadequate equipment can lead to safety challenging situations</td>
</tr>
<tr>
<td><strong>5. Visual navigation aids (markings, signage, lighting)</strong></td>
<td><strong>6. Manoeuvring area operations &amp; maintenance</strong></td>
<td></td>
</tr>
<tr>
<td>----------------------------------------------------------</td>
<td>-------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td><strong>Equipment status</strong></td>
<td><strong>Operational scenario</strong></td>
<td></td>
</tr>
</tbody>
</table>
| Excluded: - This study considers certified airports, hence, visual navigation aids are assumed to be compliant to ICAO Annex 14 | Use of runways as taxiways
Excluded: - Operational scenario (i.e. runway operational practice), as this is runway specific information |
| **Adequacy** | **Manoeuvring area inspection** |
| • Adequacy of visual navigation aids to support the operations based upon them* | Number of runway condition checks per day |
| • Number of reports / complaints about confusing visual navigation aids | **Surface conditions - adequacy** |
| **Infrastructure / equipment failure (operational readiness)** | **Infrastructure maintenance** |
| Excluded: - See ‘Equipment and installations – equipment failure’ | **Construction management** |
| **Inadequate infrastructure / equipment failure can lead to safety challenging situations** | **Vehicle management** |
| **Adequacy of visual navigation aids to support the operations based upon them** | Requirement of clearance for vehicle drivers |
| • Number of reports / complaints about confusing visual navigation aids | **Vehicle equipment with radio communication** |
| **Infrastructure / equipment failure (operational readiness)** | Subcontractors working on the manoeuvring area |
| Excluded: - See ‘Equipment and installations – equipment failure’ | **Wildlife hazard management** |
| **Inadequate infrastructure / equipment failure can lead to safety challenging situations** | Excluded: - Existence of a wildlife hazard management plan |
| **Surface conditions - adequacy** | **Presence of wildlife imposes a risk on surface operations** |
| **Inadequate infrastructure / equipment failure can lead to safety challenging situations** | 7. Regulations |
| **Vehicle management** | **Regulations** |
| **Vehicle equipment with radio communication** | Engagement in pro-active safety assessments apart from regulatory requirements
Excluded: - Compliance with regulatory requirements: airports are audited regularly, hence, compliance is assumed |
| **Subcontractors working on the manoeuvring area** | **Regulatory compliance impacts on safety. As all airports are required to be compliant, it is of particular interest whether they engage in pro-active safety assessments** |
| **Wildlife hazard management** | 8. Human aspects |
| Excluded: - Existence of a wildlife hazard management plan | * |
Sampling

The population of airports sampled in this survey was those airports with diverse characteristics, including for instance manoeuvring area design, equipment status, and operational practices. This sample aimed to be representative of the measurement variables.

The survey focused on towered airports in the U.S., UK, NO, and NZ, giving a population size of 616 airports (17-20). Any sample of airports needs to be representative of the population and contained within manageable proportions given the available resources. Salant and Dillman (21) propose a sample size of 57 for a population with 750 members to make estimates with an error of no more than +/- 10 %, at the 95 % confidence level. For a population of 500 members a sample of 55 is proposed. The target sample for this study was 57 responses, representing 9.25 % of the population.

Survey Methodology

An internet-mediated questionnaire survey was adopted based on the need to collect a sample of 57 airports with a geographical dispersion covering four countries. In addition, the use of an internet survey enabled the relevant airport personnel to be addressed directly.

There were considerations related to the collection of data regarding the physical characteristics of the manoeuvring area (e.g. the number of runways, taxiways, and intersections). Discussions with an SME from ACI revealed considerable inconsistencies in the ways airports count these within any country, and this may be in addition to any variation between countries. To ensure a standardized and consistent way of data collection that will lead to more reliable results such data was collected by the researcher using aeronautical information publication (AIP), i.e. aeronautical charts. A similar decision was made for other public available information, i.e. airport equipment and installations. In addition, data collection by the researcher helps to control the length of the questionnaire. Hence, a combined approach of internet-mediated questionnaire survey and data collection using AIP and aeronautical databases was applied for data collection.

The questionnaire was validated with the same SMEs from EUROCONTROL, the FAA, ACI, and a major U.S. airport authority as introduced in before. It was refined over several iterations to only include essential questions that enabled meaningful statistical results.

Pilot Survey

Prior to conducting the full survey, a small-scale pilot survey was conducted both to verify the clarity of the questions posed and to assess the time necessary to complete the questionnaire. One airport in the U.S. and one European airport were surveyed. The results of the pilot survey led to only minor amendments in the design of the questionnaire, e.g. rephrasing some of the questions for clarity. Such changes were incorporated in the final design of the questionnaire.

Full survey

The questionnaires were distributed to all the airports in the target population. This decision was based on the expected low response rate of internet-based surveys, i.e. 11-30 % (21, 22). The questionnaires were distributed over reference organizations in:

- the U.S. where the FAA Regional Runway Safety Managers distributed the survey;
- NZ where the New Zealand Airports Association assisted with the data collection, and;
- NO where the survey was distributed by Avinor, the Norwegian ANSP, an organization that is also responsible for the operations of airports in the country.

In addition, professional networks (e.g. Transportation Research Board (TRB) of the National Academies) were exploited to gain more responses. The questionnaire was distributed to relevant personnel in senior positions in the operations departments of the airport authorities (e.g. Head of Airfield Operations). In the UK,
the UK CAA provided the contact details of UK airport operations directors, who were subsequently contacted directly.

**Data Analysis**

After the relevant data has been collected, a master file matching the airport characteristics data with the corresponding safety data was created and subsequently analyzed in 3 steps.

**High-Level Analysis and Data Distribution**

First, descriptive statistics (e.g., frequency analysis, bar charts, boxplots) were used to understand the characteristics of the sample and to identify outliers. Subsequently, the distributions of the data were analyzed. The data set contained four different data types, i.e.:

- Continuous data (e.g., normalized number of occurrences, number of taxiway segments);
- Ordinal categorical data (e.g., severity of occurrences);
- Nominal categorical data with multiple categories (e.g., causal factors, use of runways as taxiways);
- Nominal categorical data with two categories (binary) (e.g., adequacy of equipment/installations on the manoeuvring area).

Using the Kolmogorov-Smirnov test (for \( n > 50 \)) and the Shapiro-Wilk test, (for \( n < 50 \)) the continuous data were tested for normality and the majority of variables were found to be not normally distributed. The implication of this is that non-parametric statistical tests needed to be applied. Similar, categorical data required the application of non-parametric tests.

Afterwards, the data were tested for homogeneity. This is necessary in order to test whether the data collected from the four different countries originate from the same population and can be aggregated. The non-parametric Kruskal-Wallis (for continuous data) and Pearson Chi-Square (for categorical data) tests were applied.

**Analysis for Associations**

To get an initial insight into the relationships among the variables, the data were tested for associations in a second step. The data were tested for associations between the following variables:

- Airport characteristics and occurrence rates,
- Airport characteristics and the severity of occurrences, and
- Airport characteristics and the causal factors that underlie occurrences.

Depending on the nature of the data and its distribution various statistical tests were applied, as detailed in TABLE 2.

**TABLE 2 Statistical Tests**

<table>
<thead>
<tr>
<th>Data type variable A</th>
<th>Data type variable B</th>
<th>Normal distributed variables</th>
<th>Non-normal distributed variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous</td>
<td>Continuous</td>
<td>Pearson’s Correlation Coefficient (( r ))</td>
<td>Spearman’s Correlation Coefficient (( r_s ))</td>
</tr>
<tr>
<td>Continuous</td>
<td>Ordinal categorical</td>
<td>Independent T-Test (( t ))</td>
<td>Mann-Whitney U Test (( U ))</td>
</tr>
<tr>
<td>Continuous</td>
<td>Nominal categorical - binary</td>
<td>Analysis of variance (ANOVA)</td>
<td>Kruskal-Wallis (( H ))</td>
</tr>
<tr>
<td>Continuous</td>
<td>Nominal categorical - multiple categories</td>
<td>Pearson Chi Square (( \chi^2 ))</td>
<td></td>
</tr>
<tr>
<td>Categorical</td>
<td>Categorical</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Regression Analysis to Model the Functional Relationship Between the Severity of Occurrences and their Underlying Causal Factors**

As will be discussed in the results section, the data showed significant associations between the severity level of occurrences and airport characteristics, as well as the causal factors extracted from the accident/incident reports. To analyze this finding further, logistic regression was employed. Logistic regression is used to identify relationships between a categorical dependent variable (DV) and continuous and/or
categorical predictor variables (i.e. independent variables (IVs)). It allows predicting the probability of the DV occurring, i.e. the probability that a case belongs in a certain category, given known values of the IVs (23).

The relationships between airport characteristics, causal factors and the severity of occurrences were analyzed further using the example of the U.S. FAA RI database and the reasons for this are discussed in the results section. Airport characteristics data were available for 19 airports in the U.S. and the corresponding safety data covered the period from 1 October 2007 to 2009, resulting in a sample of 288 occurrences.

The FAA RI database captures runway incursions* and assigns one of four severity levels (Category (Cat) A to D) to each occurrence. Furthermore, the database contains next to runway incursion also surface incidents (i.e. taxiway incursions). As severity assessments are only conducted for incursions involving runways, the surface incidents had to be excluded from the analysis.

RESULTS AND DISCUSSION

High-Level Analysis and Data Distribution

A total of 58 airports responded to the survey, corresponding to a 9.5 % response rate, slightly above the anticipated 9.25 %. For sensitivity reasons, the airports are de-identified. Among the 58 responses, a major airport authority running five U.S. airports and a UK airport operator did not want to take part in this study due to sensitivity reasons. Overall, 52 airports filled in the questionnaire, and the distribution among the countries is as follows: 19 U.S., 14 UK, 16 NO, and 3 NZ.

The data represents a very diverse sample ranging from small airports with a low number of movements and a small number of runways and taxiway segments, and possibilities for conflicts to major airports with nearly one million annual movements and highly complex layouts. Overall, the sample captures diverse airport characteristics as desired.

Following a high-level analysis the data were analyzed for outliers. While the data does show outliers, it is questionable as to whether to exclude these. For instance, in the UK London Heathrow was shown as an outlier among several variables (e.g. average annual movements, number of taxiway segments). Likewise, Oslo Lufthavn was shown as outlier for Norway. These airports are characteristic for their countries. Both Heathrow and Oslo are the biggest airports in their country in terms of movements and passenger boardings. Both airports accommodate international flights and serve as main hubs for their country. If removed the typical characteristics of the national airport infrastructures would consequently be removed. Thus, it was decided to create two data sets, one including outliers and one excluding outliers. The statistical tests were run on both data sets in order to see whether these outliers influence the results.

Before modeling, the data were also tested for homogeneity and their consequent potential for aggregation. The non-parametric Kruskal-Wallis and Pearson Chi-Square tests were applied to test whether samples originate from the same population. The homogeneity of the four countries in terms of airport characteristics, normalized number of occurrences, and causal factors was tested and the results indicated that the difference among the countries is significant at the 95 % level (Kruskal Wallis p < .05; Pearson Chi-Square p < .05). Thus, both, safety data and airport characteristics data from different countries, should not be aggregated. This confirms the results of a prior conducted data quality assessment, which has been published elsewhere (25).

Analysis for Associations

The data were tested for associations between airport characteristics and i) the rate of accidents/incidents per occurrence type, ii) the severity of accidents/incidents per occurrence type, and iii) the causal factors that underlie occurrences.

As the data cannot be aggregated across countries, each country was analyzed separately. In NZ, only three airports responded to the questionnaire survey and with only three data points, statistical analysis was not possible. As the airport characteristics may influence the three considered occurrence types differently, each accident/incident type was analyzed separately. Furthermore, a data quality assessment concluded that excision and FOD data in the U.S. are underreported due to missing regulatory requirements for incident reporting (25), and therefore, this data was excluded from the assessment.

Due to a change of definitions, an analysis for associations between airport characteristics and severity levels in the U.S. was only possible for runway incursions reported after 1 October 2007. The frequency analysis showed that high-severity categories A and B occurred only four times during the considered time period. This amount was too small to be used for statistical analysis, and thus the data were analysed for

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* A runway incursion is defined as any occurrence involving the incorrect presence of an aircraft, vehicle, or person on the protected area of a surface designated for the landing and take-off of aircraft (4).
The results show that most airport characteristics are not associated to the rate of airport surface safety incidents. However, a few airport characteristics seem to have significant associations with the rate of incidents. The table below shows the summary of significant associations.

**Table 3: Summary Significant Associations**

<table>
<thead>
<tr>
<th>Airport Characteristic</th>
<th>Rate of Incursions</th>
<th>Rate of Excursions</th>
<th>Rate of FOD</th>
<th>Severity Association</th>
<th>Causal Factors Association</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average annual movements</td>
<td>-</td>
<td>✓</td>
<td>-</td>
<td>✓</td>
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* A taxiway segment is a piece of taxiway between a conflict point A and B.
** A conflict point is a point on the airport surface where two parties (e.g. pilot, V/PD) could conflict with each other, e.g. a crossing.
N/a: The test statistic could not be computed, as one of the variables is a constant.

The results show that most airport characteristics are not associated to the rate of airport surface safety occurrences, which confirms the conclusions from Galle, et al. (2010) (11). The lack of associations indicates that the rate of accidents and incidents is not influenced by the prevailing characteristics at a given airport, such as e.g. manoeuvring area geometry.
Nonetheless, although airport characteristics are not associated to occurrence rates, they are associated to the severity of occurrences, and in particular the physical airport surface design (i.e. geometry). Moreover, it was found that airport characteristics are associated to those factors that were found to have caused the occurrences. Although there are differences across the countries, the major findings are consistent and the data indicates that:

- A non-standard use of runways as taxiways, and inadequate visual navigation aids (i.e. at airports that experienced complaints about lighting, marking, signage) are associated with pilot-related factors;
- A complex manoeuvring area geometry is associated with pilot and ATC-related factors;
- A lack of radio in vehicles, V/PD free-range operations, the existence of subcontractors on the manoeuvring area, and their associated inadequate level of training are associated with ATC-related factors; and
- Inadequate subcontractor training, and a non-engagement of airports in pro-active safety assessment are associated with V/PD-related factors.

The observed differences between the analyzed countries could be a result of differing distributions of reported occurrence types in the considered countries, and associated differing distributions of causal factors ($\chi^2 = 419.53, p (2-tailed) < .001$).

**Analysis of Relationships**

### The Relationship Between Airport Surface Geometry and Severity

To model the relationships between airport characteristics, occurrence severity, and causal factors the U.S. FAA RI database was chosen for analysis. This database was selected, as i) the U.S. airports showed the greatest diversity in terms of airport characteristics and ii) the prior analysis revealed associations between airport characteristics, causal factors, and severity in the U.S. As the previous section indicated associations particularly between airport surface geometry and severity, the impact of the surface design characteristics on the severity of runway incursions was analyzed further.

First, the impact of each geometric variable on severity was modeled individually and the majority of tested variables were significant predictors for the severity of runway incursions. The airport characteristics that predicted severity best were the number of runways and taxiway segments and the number of conflict points, in particular type 3 RWY/TWY and type 4 TWY/TWY.

Building on these results cluster analysis was applied to group airports in terms of their complexity defined by traffic volume and airport surface design (i.e. geometry). The aim was to come up with airport complexity categories that could be related to safety. This would provide a new categorization of airports in terms of their probability to experience high or low severity runway incursions based on airport complexity levels. Cluster analysis was performed using various combinations of airport characteristics and available clustering methods. Although the clusters differed depending on the input variables and clustering method each categorization showed the same feature. In none of the analysis was it possible to describe the clusters exclusively. For instance, clusters of airports with a small number of runways could similarly show a low, medium, or high number of taxiway segments and conflict points, whereas clusters with a high number of runways also showed a mix of low, medium, or high number of taxiway segments and conflict points. Overall, the airports were too different in terms of their characteristics and therefore it was not possible to categorize them in terms of complexity. Hence, airport data should not be aggregated. This shows that it is not the total complexity of an airport that influences the severity of occurrences; in fact it must be individual characteristics.

Therefore, the further analysis dissected the total of airport characteristics into its elements and analyzed which features are the main drivers for severity. The physical design of the airport surface comprises three elements: the runways, taxiways and intersections (referred to as conflict points). Depending on the number of segments in conflict with each other different types of conflict points can be distinguished (i.e. type 2 to 6). These conflict points again can occur in three variations, that are RWY/RWY, RWY/TWY, and TWY/TWY. Using logistic regression these elements are modeled in three levels as shown in Figure 2.

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5 A type 3 RWY/TWY conflict point is an intersection of three runway and taxiway segments.
6 A type 4 TWY/TWY conflict point is an intersection of four taxiway segments.
The results of the can be summarized as follow:

- On level 1 the number of runways was a significant predictor for the severity of runway incursions. The odds of having Cat C instead of D runway incursions are 1.666 times higher when the number of runways increases by one unit;
- Testing the airport characteristics on the second level, the total number of RWY/RWY conflict points was found to be a significant predictor for the severity of runway incursions. The change in odds of getting Cat C instead of D is 1.177 when the number of RWY/RWY conflict points increases by one unit;
- On the third level the elements of the number of RWY/RWY conflict points did not significantly predict severity. That is, airports are not significantly more likely to experience Cat C occurrences when the number of RWY/RWY (type 2, 3 or 4) conflict points increases;
- The number of type 3 RWY/TWY conflict points is a significant predictor for severity, and in particular a unit increase in type 3 RWY/TWY conflict points increases the odds of getting Cat C instead of D about 1.115 times;
- The number of type 4 TWY/TWY conflict points was also found significant at the third level of analysis leading to a change in odds of 1.063; and
- When dissecting the number of conflict points further (analysis level 3b), the number of type 4 RWY/RWY conflict points was a significant predictor for the total number of type 4 conflict points, and the odds of having Cat C instead of D are 1.258 times higher when the number of type 4 RWY/RWY conflict points increases by one unit.

To summarize, the analysis has proven that airport characteristics do have an impact on the severity of runway incursions. While it is not the overall complexity of an airport that influences the severity of occurrences, it is only certain elements of an airport's geometry that seem to create a problem.

The Relationship Between Causal Factors and Severity

After having modeled the impact of airport characteristics on severity, the relationship between the causal factors underlying occurrences and severity was modeled. The results show that the causal factors are a significant predictor for the severity of runway incursions in the U.S. In particular, the contribution of ATC to high severity occurrences (i.e. Cat C) stands out. ATC is found to be 13.70 times more likely than pilots, and 20.41 times more likely that V/PD to lead to a high severity occurrence. A more detailed analysis as to which ATC factors are most crucial was not possible, as in fact 90.4 percent of all occurrences to which ATC contributed were classified as high severity. Also, the FAA RI database contained four occurrences with severity classifications A and B that were not considered in this analysis due to their low frequency of occurrence. ATC was the primary cause for three of them. An analysis on a lower level revealed in addition that pilot communication, and human reliability related factors (i.e. situations in which the pilot did something he was not supposed to do) were significant contributors to high severity.

Often, occurrence reports allow the extraction of more than one causal factor from the narrative. This can be a combination of factors caused by a single stakeholder (e.g. a pilot made several mistakes) or a combination of factors between different parties (e.g. pilot – ATC interaction). Further testing showed that occurrences caused by a combination of at least two parties are 5.13 times more likely to be high severity than occurrences caused by a single stakeholder. The most frequent factor combination leading to high severity is an ATC and pilot interaction that involved communication errors.

The Relationship Between Airport Surface Geometry and Causal Factors
In a next step, it was analyzed whether a relationship between airport surface geometry and causal factors exists. First, the impact of the airport as a whole on the occurrence of causal factors was analyzed. Using crosstabulation, no pattern could be identified and the causal factors were found to occur across all airports. Subsequently logistic regression was employed to analyze whether the individual airport characteristics (e.g. number of runways, taxiway segments, conflict points) influence the causal factors. Although most models showed a significant improvement to the baseline model, their overall fit was poor leading to the conclusion that airport geometric characteristics are not a significant predictor for the causes of runway incursions.

Whilst the airport characteristics may not influence the total of causal factors, they might influence particular operations and predict their associated failures. Thus, further analysis split the factors into pilot, ATC, and V/PD-related and repeated the analysis for each stakeholder individually. Again, airport characteristics did not significantly predict the causal factors.

Although the last part of the analysis split the causal factors by stakeholder operations the data might still be too aggregated. Therefore, further analysis at the factor-level related individual runway incursions and their associated causes to the specific locations at the airports where they occurred. The ten most frequent causal factors that could be related to the physical characteristics of an airport were chosen for further analysis. For instance, the layout of the manoeuvring area could cause or contribute to the factors ‘ATC misjudgement of timings that lead to a situation that was too tight’ or ‘pilot taxi error’, whilst an error in the communication process may not be related to the physical design of the airport surface. The descriptive narratives of the corresponding occurrence reports of 272 causal factors were analysed and by means of airport charts the exact locations of the incidents determined.

This detailed analysis assigned each causal factor a corresponding occurrence location. All incidents occurred at a runway or a runway intersection, i.e. RWY/TWY or RWY/RWY conflict points, and the analysis revealed causal factors associated to the following locations:

- ATC factors related to only runways (e.g. ATC cleared an aircraft to start its take-off roll while another aircraft still occupied the runway);
- ATC factors related to RWY/TWY conflict points, in particular type 3 and 4 (e.g. ATC cleared an aircraft to cross a runway whilst a second aircraft was on final approach);
- V/PD factors related to runways and all types of RWY/TWY conflict points (e.g. V/PD entering runways without authorization in various locations);
- Pilot factors related predominantly to type 3 and 4 RWY/TWY intersections (e.g. pilot crossing a runway at the approach end in a type 3 RWY/TWY conflict point, or pilot crossing in the middle of a runway in a type 4 RWY/TWY conflict point; similarly, hold lines can be crossed at the approach end of a runway before line up or during taxiing when the pilot was instructed to hold short of a runway).

The most critical operations at the analysed airports were related to runway crossings that were either unauthorised crossings initiated by the pilot, or ATC authorised crossings that were planned too tightly. In addition, take-offs and landings without clearance were identified that were particularly crucial at intersecting runways, or in situations where another aircraft crossed the active runway. The airports that have intersecting runways (i.e. RWY/RWY conflict points) showed problems associated to those, for instance, two aircraft land / start the take-off roll at the same time at an intersecting pair of runways. Other common failures included taxi errors at RWY/RWY conflict points. Overall, the runway incursions occurred most frequently at the runways, type 3 and 4 RWY/TWY conflict points and type 4 RWY/RWY conflict points, which corresponds to the airport characteristics identified earlier on as best predictors for the severity of runway incursions. Overall, the analysis built up evidence that there is a link between the characteristics of an airport and the causes for surface accidents and incidents. This proves that in order to understand occurrences better data should not be aggregated, but analysed in its elements. In order to model this link incursions need to be investigated more specific in order to assign the causal factors adequately.

Based upon the results the following recommendations for the mitigation of runway incursions are given:

- The critical role of ATC needs to be addressed through continuous training;
- Also, problems in the communication process (e.g. readbacks) between pilots and ATC need to be addressed and continuously trained;
- Future airport design should avoid RWY/RWY conflict points and limit the number of type 3 and 4 RWY/TWY conflict points;
- Existing airports with a high number of RWY/RWY and RWY/TWY conflict points should evaluate alternative operating scenarios to avoid in particular runway crossings;
- Acknowledging that changes in the operating scenarios of existing airports may lead to time and cost inefficiencies, the results support the case for new technologies such as Runway Status Lights (RWSL) and the Final Approach Runway Occupancy Signal (FAROS). RWSL identify any possible conflict with other surface traffic and warn pilots when it is unsafe to cross, enter or begin take-off on a runway via a series of red lights embedded in the pavement. FAROS provides a notification to pilots on final
CONCLUSIONS

This paper introduced a methodology for risk and hazard assessment on the airport surface and modeled the relationship between airport characteristics, the severity of occurrences, and the causal factors underlying accidents/incidents. The methodology and findings support the risk management of airports in the context of Safety Management Systems (SMS). The methodology is not limited to hazard assessments on the airport surface, but transferrable to all aspects of airports, and aviation in general, e.g. to analyze the impact of airspace characteristics on safety occurrences.

Two major findings can be summarized. The first finding concerns the quality of reporting systems. The study concluded that reporting levels are significantly different across the analyzed organizations. In addition, the airport infrastructure and operations in regard to the collected variables were found significantly different among the countries. Overall, it can be concluded that safety and airports data from different countries cannot be aggregated due to their different underlying distributions. Aggregating such data will lead to unreliable results. This in turn indicates that data-based safety mitigation strategies (e.g. statistical models) can only be valid for individual organisations.

Second, it was found that the severity of occurrences can be predicted. In particular, airport geometric complexity and the causal factors that underlie accidents/incidents (e.g. human factors) were found to be significant predictors. With this, this study proves for the first time that a relationship between airport characteristics and safety occurrences exists. The results are recommended to be used for the development of in-service mitigation measures (e.g. operational practices) or for airport planning to design out risks during the planning process of an airport (e.g. airport surface geometric complexity).

ACKNOWLEDGEMENT

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